Design and Thermal–Structural Performance Evaluation of a Community Scale Waste Incinerator for Environmental Applications Using Numerical Simulation

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Abstract. The increasing generation of municipal solid waste in urban and community areas has encouraged the development of decentralized waste treatment technologies. Small-scale incinerators offer potential advantages in reducing waste volume, but their implementation requires adequate thermal and structural performance evaluation to ensure safe and reliable operation. This study evaluates the thermal and structural performance of a community-scale waste incinerator using numerical simulation. A three-dimensional incinerator model consisting of a primary combustion chamber, chimney, supporting frame, and ash removal system was developed and analyzed using Autodesk Inventor. Thermal simulation was conducted to evaluate temperature distribution, while structural simulation was used to assess von Mises stress, deformation, and safety factor. The results show that the maximum temperature reached 1201 0C in the primary combustion chamber, while the chimney temperature was 205 0C and the outer surface temperature ranged from 80 to 110 0C. Structural analysis indicated that the maximum von Mises stress was 264.58 MPa, which remained below the material yield strength of 400 MPa, with a minimum safety factor of 1.51. The maximum deformation was only 0.00113 mm, indicating negligible geometric instability. Overall, the proposed incinerator design demonstrates acceptable thermal concentration, structural safety, and potential applicability for community-based environmental waste treatment.

1 Introduction

The increasing volume of municipal solid waste has become a major environmental challenge in urban and residential areas. Limited landfill capacity and the low efficiency of conventional waste management systems have encouraged the development of alternative treatment technologies that are more effective, decentralized, and applicable at the community scale. Waste incineration is one of the thermal treatment technologies that can

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significantly reduce waste volume while supporting decentralized waste management practices [1–3].

However, small-scale incinerators are often developed empirically without adequate engineering-based performance evaluation. This condition may lead to non-uniform temperature distribution, incomplete combustion, excessive heat loss, and structural failure due to thermal and mechanical loads. Previous studies have shown that numerical simulation is an effective tool for analyzing combustion behavior, temperature distribution, and operational parameters in municipal solid waste incineration systems [4–7].

Recent studies also indicate that the optimization of combustion conditions, air supply, and furnace geometry strongly affects thermal performance and emission characteristics in waste incineration systems [8–11]. Numerical modeling has been widely applied to evaluate combustion, heat transfer, NOx formation, dioxin dynamics, and full-process behavior in municipal solid waste incinerators [12–15]. Therefore, integrating product design with numerical simulation is important to improve the reliability of small-scale environmental technologies before fabrication and field implementation.

Unlike previous studies that mainly focused on combustion optimization, emission analysis, or large-scale municipal solid waste incineration systems, this study emphasizes the integration of product-oriented engineering design with thermal–structural performance evaluation for a community-scale waste incinerator. The novelty of this research lies in the application of numerical simulation to simultaneously evaluate temperature distribution, von Mises stress, structural deformation, and safety factor within a compact decentralized incinerator configuration intended for environmental applications at the community level. This integrated approach provides a more practical and engineering-based framework for developing safe, thermally efficient, and structurally reliable small-scale waste treatment technologies prior to fabrication and implementation.

In addition to thermal behavior, the structural performance of incinerator components must also be evaluated because high-temperature operation can generate thermal stress and deformation in supporting structures. Finite element-based structural analysis allows the identification of critical stress locations, deformation patterns, and safety factors in engineering structures subjected to operational loads. Numerical simulation has been widely applied to evaluate combustion behavior, heat-transfer characteristics, operating parameters, and structural optimization in municipal solid waste incinerators [1–3,8]. Therefore, this study aims to evaluate the thermal and structural performance of a community-scale waste incinerator for environmental applications using numerical simulation.

2 Methodology

This study used a product design approach combined with numerical simulation. The research stages included three-dimensional modeling, material parameter definition, thermal analysis, structural analysis, and performance evaluation.

2.1 Three-dimensional model development

The incinerator model was developed in three-dimensional form using Autodesk Inventor. The model consisted of the primary combustion chamber, chimney, supporting frame, ash removal system, and external structural components. The geometric model was prepared to represent the operational configuration of a community-scale waste incinerator.

2.2 Material properties

The main material used in the simulation was heat-resistant steel. The mechanical properties applied in the structural analysis were as follows: yield strength of 400 MPa, Young's modulus of 200 GPa, and Poisson's ratio of 0.3. A refractory layer was assumed on the combustion chamber wall to improve thermal resistance and reduce heat loss to the external structure.

2.3 Thermal analysis

Thermal analysis was conducted to evaluate temperature distribution in the incinerator system. The boundary conditions included combustion chamber temperature in the range of 850–1200 °C, heat transfer to the surrounding environment, and thermal insulation through refractory lining. The main outputs were maximum temperature, chimney temperature, outer surface temperature, and overall temperature distribution.

2.4 Structural analysis

Structural analysis was performed by considering gravitational load, chamber mass, and thermal load obtained from the thermal simulation. Fixed constraints were applied at the lower frame supports to represent operational support conditions. The main outputs were maximum von Mises stress, structural deformation, minimum safety factor, and the location of critical stress concentration.

3 Results and Discussion

3.1 Temperature distribution

The thermal simulation results (Figure 1) show that the maximum temperature reached 1201 °C and was localized in the primary combustion chamber. This area represents the active combustion zone, as indicated by the high-temperature contour. The chimney temperature was recorded at 205 °C, while the outer surface temperature ranged from 80 to 110 °C.

This temperature pattern indicates that heat was concentrated in the combustion chamber, while heat transfer to the external structure was relatively controlled. The lower temperature on the outer surface suggests that the refractory lining and thermal insulation were effective in reducing heat loss and improving operational safety. This finding is consistent with previous numerical studies showing that furnace geometry, heat transfer behavior, and air distribution strongly influence the combustion stability of waste incineration systems [4,8,9].

The high temperature concentration in the combustion chamber indicates efficient heat retention and stable combustion conditions. The lower external surface temperature also suggests reduced heat loss and improved operational safety. This condition demonstrates that the proposed incinerator configuration is capable of maintaining thermal efficiency while minimizing excessive heat transfer to surrounding structural components. Furthermore, the ability of the proposed design to maintain concentrated thermal energy within the combustion chamber is important for improving combustion stability and reducing thermal inefficiency in small-scale waste treatment systems.

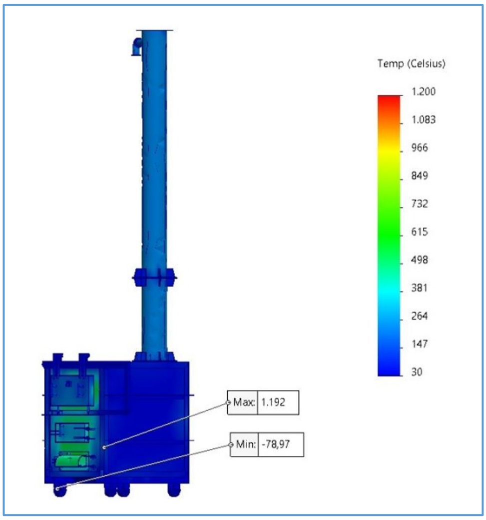

Fig. 1. Temperature distribution of the incinerator system

3.2 Von Mises stress distribution

The structural simulation results (figure 2) indicate that the maximum von Mises stress was 264.58 MPa and occurred at the connection area between the combustion chamber and the supporting frame. This location can be considered a critical point because it receives combined thermal and mechanical loads during incinerator operation.

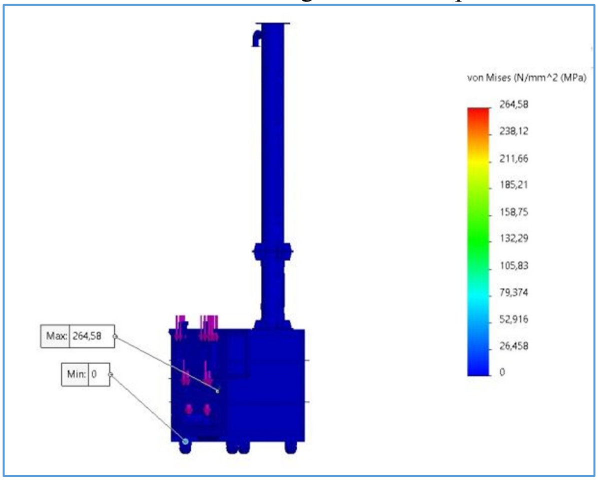

Fig. 2. Von Mises stress distribution of the structure

Compared with the material yield strength of 400 MPa, the maximum stress value remains within the safe limit. The minimum safety factor of 1.51 indicates that the structure still has an acceptable safety margin under the simulated operating condition. The stress distribution on most frame components was relatively low, indicating that the supporting frame was capable of distributing operational loads effectively. Similar engineering simulation approaches have been widely used to identify stress concentration and structural safety in high-temperature mechanical systems [1,3,8].

The stress concentration near the chamber-frame connection indicates the influence of thermal expansion and structural load interaction during operation. Nevertheless, the stress level remained within the allowable material limit, demonstrating acceptable structural reliability. The relatively low stress distribution observed in most structural regions also indicates that the supporting frame possesses adequate load distribution capability and structural stiffness for continuous operational conditions.

3.3 Structural deformation

The deformation simulation (figure 3) shows that the maximum deformation was only 0.00113 mm and occurred near the upper chimney region. This deformation is very small and does not significantly affect the overall geometric stability of the structure. The lower frame and supporting components showed minimal displacement, indicating good structural stiffness.

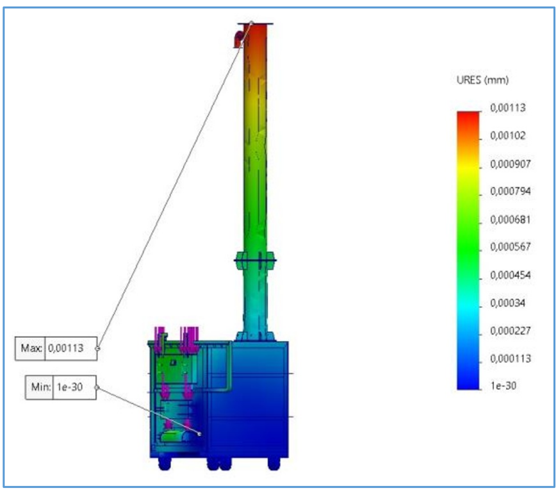

Fig. 3. Structural deformation of the incinerator

The very small deformation value suggests that the structure remained within the elastic range of the material. Therefore, the risk of permanent deformation during operation can be minimized. From a product design perspective, this result demonstrates that the incinerator structure has sufficient rigidity to support combustion operation at the simulated temperature range.

The extremely small deformation value indicates that the supporting structure possesses sufficient rigidity to withstand combined thermal and mechanical loads during operation. In addition, the minimal displacement observed in the lower frame region confirms that the structural support system effectively maintains geometric stability even under elevated thermal conditions. These findings indicate that the proposed structural configuration is mechanically reliable for community-scale waste incineration applications.

3.4 Performance evaluation

Overall, the simulation results demonstrate that the incinerator design has acceptable thermal and structural performance. From the thermal perspective, the high temperature concentration in the combustion chamber indicates that the system can generate sufficient heat for waste oxidation. From the structural perspective, the maximum stress value remained below the yield strength, and the deformation was negligible.

The integration of product design and numerical simulation provides a more systematic approach for evaluating incinerator performance compared with empirical design methods. This approach enables early identification of critical thermal and structural areas before fabrication. Therefore, the proposed incinerator has potential to be applied as a decentralized waste treatment technology for community-based environmental applications.

From an engineering perspective, the integration of thermal and structural simulations provides important insight into the operational reliability of the proposed incinerator design. The combination of stable thermal concentration, acceptable stress distribution, and minimal deformation demonstrates that the system is capable of maintaining both combustion effectiveness and structural integrity during operation. This integrated simulation-based approach can therefore support the development of safer and more efficient small-scale environmental technologies before prototype fabrication and field implementation.

4 Conclusion

This study evaluated the thermal and structural performance of a community-scale waste incinerator using numerical simulation. The simulation results showed that the maximum temperature reached 1201 °C in the primary combustion chamber, while the chimney temperature was 205 °C and the outer surface temperature ranged from 80 to 110 °C. This temperature distribution indicates that the combustion system effectively concentrated heat in the main combustion zone.

Structural analysis showed that the maximum von Mises stress was 264.58 MPa, which remained below the material yield strength of 400 MPa. The minimum safety factor was 1.51, while the maximum deformation was only 0.00113 mm. These results indicate that the structure has acceptable mechanical safety and geometric stability under the simulated operating conditions.

Overall, the proposed incinerator design demonstrates good technical feasibility from thermal and structural perspectives. The system has potential as an efficient and safe decentralized waste treatment solution for community-based environmental applications.

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