Design, Thermal Performance, and Environmental Safety Analysis of a 304 Stainless Steel Al-Quran Disposal Incinerator for State Religious Authorities

Hasib, H.*, Hamid, R.A. and Yahaya, S.H.

Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia

***Corresponding Author**

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ABSTRACT

The respectful disposal of damaged Quranic texts presents a crucial socio-religious and environmental management issue for Islamic religious authorities. In Malaysia, the Department of Islamic Development Malaysia (JAKIM) guidelines specify controlled burning as an approved method. However, existing disposal incinerators operated by state authorities, such as Jabatan Agama Islam Melaka (JAIM), face significant operational issues, including excessive toxic smoke emissions, ergonomic limitations, ash loss due to wind scattering, and performance degradation from 300 kg/day to 150 kg/day after two years. This study presents the design, Finite Element Analysis (FEA), and Computational Fluid Dynamics (CFD) simulation of a redesigned 304 stainless steel Al-Quran disposal incinerator. Concept selection using the Pugh Matrix identified an optimized design incorporating an air blower, smoke filter, dust compartment, and hydraulic lift table. CFD simulations demonstrate that forced aeration elevates internal combustion temperature from 617 °C (blower off) to 1,725 °C (blower on), increasing thermal efficiency and reducing total burning time for 150 kg of paper to under 24 hours. Static FEA using the Von Mises Yield Criterion indicates that while the structure safely supports 300 kg under ambient conditions (FOS = 1.0), thermal stresses at 1,725 °C limit the safe structural payload to 150 kg (FOS = 1.1). To mitigate high-temperature sensitization (425–870 °C) and intergranular corrosion, protective enamel or Ni-Cr composite coatings are evaluated. This integrated engineering solution successfully harmonizes religious sanctity, environmental safety, and operational sustainability for public religious governance.

Keywords: Al-Quran disposal, 304 stainless steel, incinerator design, Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), public environmental safety, Islamic governance

INTRODUCTION

The respectful and legal disposal of worn, damaged, or unreadable copies of the Holy Al-Quran is a fundamental obligation within Islamic jurisprudence. In accordance with Islamic rulings and guidelines promulgated by the Department of Islamic Development Malaysia (JAKIM), approved methods for disposing of Quranic materials include controlled burning or burial in designated clean locations [1]. Improper disposal methods that contradict Islamic law are regarded as severe acts of disrespect towards sacred scriptures [2]. In Malaysia, state religious authorities—such as Jabatan Agama Islam Melaka (JAIM)—are entrusted with collecting worn Quranic materials from mosques, Islamic institutions, and the public to ensure centralized, dignified processing [1].

The standardized operational procedure in Melaka involves accumulating collected materials, shredding the paper until text becomes unreadable, weighing the shredded mass, and subjecting it to incineration. Following combustion, the residual sacred ash is collected, cemented, and respectfully scattered into open oceanic waters [1]. However, the existing incineration infrastructure utilized by JAIM presents substantial

socio-environmental and operational challenges. First, conventional units release excessive dark smoke containing harmful particulate matter, nitrogen oxides (NOx), acid gases, and carcinogenic dioxins into surrounding communities [3]. Second, environmental exposure to rain and sunlight accelerates thermal and mechanical degradation, causing operational capacity to drop from an initial 300 kg/day down to 150 kg/day within two years. Third, poor ergonomic design—including an undersized ash discharge door measuring only 30 cm in height—forces operators into strenuous bending postures and exposes residual ashes to wind dispersal, creating public concern regarding sacred text desecration during ash transfer.

To resolve these interdisciplinary challenges, this study presents a comprehensive engineering redesign and numerical simulation of an Al-Quran disposal incinerator constructed from 304 stainless steel. By integrating forced-air aeration (blower system), multi-stage particulate filtering, an automated dust compartment, and a hydraulic lift table, the proposed system aims to achieve complete combustion, mitigate environmental pollution, preserve ergonomic safety, and maintain structural integrity under high operational temperatures.

METHODOLOGY

Conceptual Design and Selection Matrix

Three initial conceptual designs (Table 1) were developed using SolidWorks CAD software, incorporating varied geometric configurations and airflow mechanisms. To objectively select the optimal design against stakeholder and customer requirements, a decision matrix based on the Pugh Matrix method was established (Table 2). Design criteria evaluated included combustion capacity, smoke reduction efficiency, ergonomic posture safety, wind-shielding during ash collection, and structural robustness.

Table 1: Conceptual designs of the incinerators

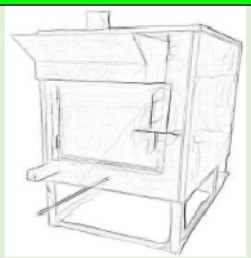
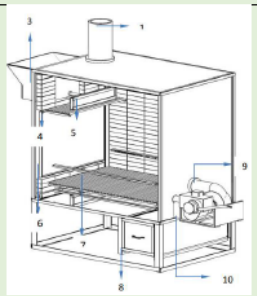
Concept Design	Description of difference
 Concept Design 1	This concept design has three differences compared to the three other concept designs. In this concept design, there is no dust compartment to quickly dispose of the dust inside the incinerator. The second difference is no additional air blower to produce more airflow. The third difference is the lack of support to withstand the 300 kg weight of Al-Quran.
 Concept Design 2	This concept design has a smaller dust compartment to dispose of the dust inside the incinerator. The second difference is the inside compartment's lack of a support bar to withstand the 300 kg weight of the Al-Quran. Meanwhile, the design change makes it hard to use and learn.
 Concept Design 3	This concept design is slightly similar to the current incinerator. It differs from the others in terms of additional mechanisms and features. The first difference is the addition of an air hole to help the burning efficiency inside the incinerator. The second difference is the bigger dust compartment size and additional support and air filter inside the incinerator.

Table 2: Conceptual Design Evaluation using Pugh Decision Matrix Method.

Selection Criteria	Datum (Current)	Concept 1	Concept 2	Concept 3 (Selected)
Combustion Efficiency & Airflow	0	+	+	++
Smoke & Emission Control	0	0	+	++
Ergonomics & Ash Transfer	0	+	+	+
Overall Rank / Evaluation	**Datum**	**Rank 3**	**Rank 2**	**Rank 1 (Selected)**

Concept Design 3 emerged as the top-ranked configuration. The finalized detailed design incorporates an electric air blower to force oxygen into the primary combustion chamber, a secondary smoke filtration cap, an enclosed lower dust compartment, and an integrated hydraulic lift table to raise ash collection vessels to comfortable standing heights (Figure 1).

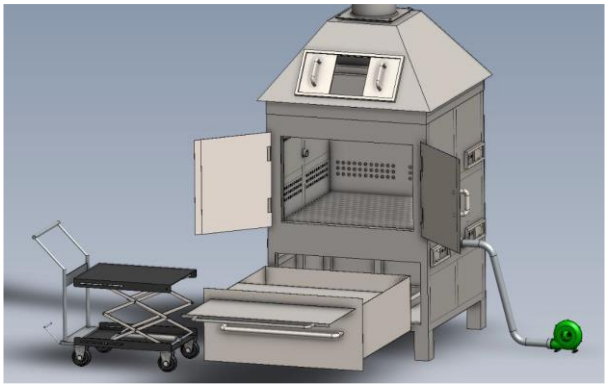
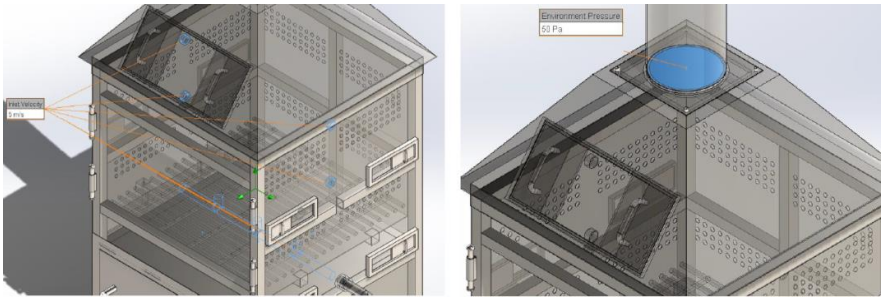


Figure 1: Final design of the Al-Quran disposal incinerator.

Computational Fluid Dynamics (CFD) Simulation Setup

To evaluate internal airflow velocity, thermal distribution, and combustion efficiency, CFD analysis was performed using SolidWorks Flow Simulation, based on the fundamental fluid conservation equations of mass, momentum, and energy [4]. Two operational conditions were simulated: (a) passive natural draft with the blower switched off, and (b) forced aeration with the blower switched on. In accordance with established thermal fluid literature, boundary conditions were defined with an inlet air velocity of 1.5 m/s for passive draft and 35.0 m/s for forced blower aeration [5][6]. The outlet boundary condition was assigned to environmental atmospheric pressure at 50 Pa static gauge pressure. The locations of these inlets and outlet are indicated in Figure 2 below:



(a) (b)

Figure 6.3: Boundary conditions for the CFD analysis; (a) the inlet velocity and (b) the environmental pressure

Finite Element Analysis (FEA) and Static Structural Parameters

Structural static analysis was conducted using SolidWorks Simulation to evaluate stress distribution, physical displacement, and safety margins under maximum paper payload conditions [7][8]. The Von Mises Yield Criterion was applied to calculate the Equivalent Stress (Se) across ductile 304 stainless steel components, defined as [9]:

$$(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2 = 2\,S_e^2 \quad (1)$$

Total three-dimensional physical displacement (U) was determined from the translational component vectors (Ux, Uy, Uz) according to Equation 2:

$$U = \sqrt{(U_x^2 + U_y^2 + U_z^2)} \quad (2)$$

The Factor of Safety (Fs) is expressed as the ratio of material yield strength (Sy) to maximum equivalent stress (Se), where structural failure occurs if Se exceeds Sy (Equation 3) [9]:

$$F_s = S_limit / S_e = S_y / S_e \quad (3)$$

Table 3 summarizes the operational parameters, thermal loads derived from CFD simulations, and mechanical payload conditions applied in the structural FEA study.

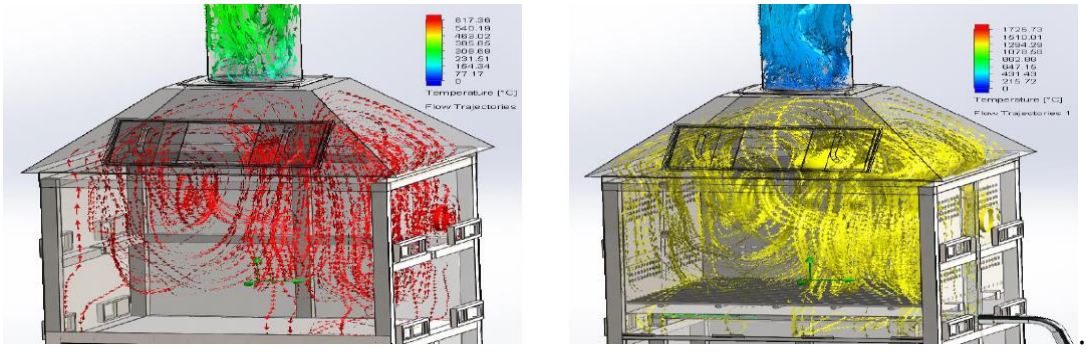
Table 3: Static Analysis Input Parameters for 304 Stainless Steel Incinerator.

Material	Applied Payload Load (kg)	Blower Off Temperature (°C)	Blower On Temperature (°C)
304 Stainless Steel	300	617	1,725
304 Stainless Steel	150	617	1,725

RESULTS AND DISCUSSION

Thermal Performance and CFD Airflow Analysis

CFD simulation results reveal dramatic differences in internal thermal generation and airflow trajectory between passive draft and forced aeration modes. In the absence of forced air (blower switched off, inlet velocity 1.5 m/s), the maximum achievable internal chamber temperature reaches 617 °C. Under forced aeration (blower switched on, inlet velocity 35.0 m/s), oxygen supply to the combustion core increases substantially, driving peak internal temperature to 1,725 °C—representing a 180% thermal increase. Streamline density vectors confirm enhanced turbulent mixing and complete combustion gas circulation (Figure 3).



(a) (b)

Figure 3: Simulated internal temperature and airflow of the new incinerator; (a) blower switched off and (b) blower switched on.

This elevated thermal output directly accelerates paper combustion rates. Under passive conditions (617 ℃), incinerating a full 300 kg batch requires approximately 36 hours. In contrast, under forced aeration (1,725 ℃), a 150 kg batch is fully incinerated in less than 24 hours. This finding aligns with fundamental combustion kinetics reported by [10], confirming that elevated flame and chamber temperatures significantly increase laminar burning velocity and rapid material turnover.

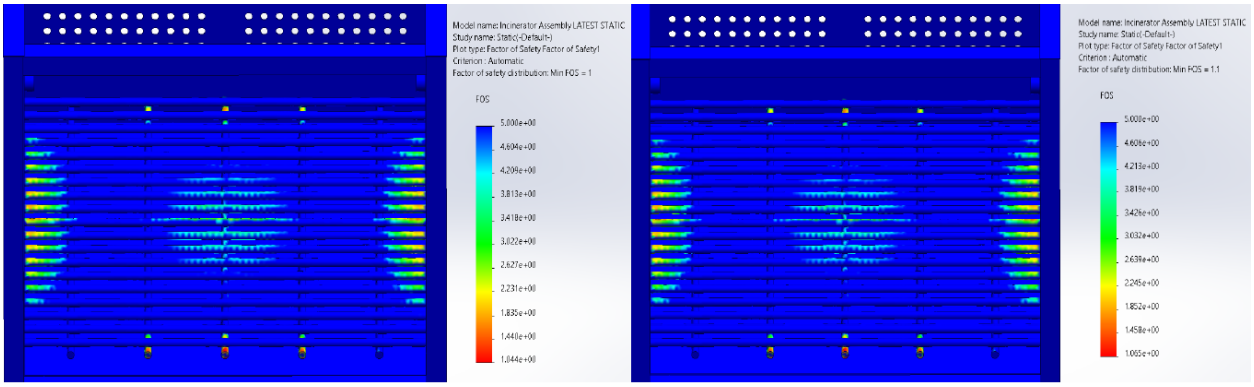
Static Structural Stress, Deformation, and Payload Limits

The FEA static simulation results for the three primary load-temperature scenarios are detailed in Table 4.

Table 4: Static Analysis FEA Results under Varying Thermal and Mechanical Payload Scenarios.

Blower Status	Chamber Temp (°C)	Payload Load (kg)	Max Von Mises Stress (MPa)	Displacement (mm)	Factor of Safety (Fs)
Off (Passive)	617	300	1.94	2.1	1.0 (Safe)
On (Forced)	1,725	300	3.84	4.4	0.5 (Unsafe/Yield)
On (Forced)	1,725	150	1.98	2.2	1.1 (Safe)

As demonstrated in Table 4, under passive blower-off conditions (617 ℃), the incinerator safely accommodates a maximum payload of 300 kg with a maximum Von Mises stress of 1.94 MPa, 2.1 mm displacement, and a Factor of Safety of 1.0. However, when the blower is activated at 1,725 ℃, applying a 300 kg payload generates excessive thermal-induced stress (3.84 MPa) and displacement (4.4 mm), reducing Fs to 0.5 and leading to structural yielding. Reducing the forced-aeration payload to 150 kg restores structural stability, yielding a maximum stress of 1.98 MPa, 2.2 mm displacement, and a safe Factor of Safety of 1.1. Hence, operational guidelines for JAIM must specify a two-mode protocol: 300 kg batching for passive overnight burns, or 150 kg batching for rapid daytime burns under forced aeration. The Factor of Safety plot is shown in Figure 4 below:



(a) (b)

Figure 4**:** Factor of Safety; (a) 300kg without blower and (b) 150kg with blower

High-Temperature Sensitization and Metallurgical Enhancements

Although 304 stainless steel is valued for its general corrosion resistance, prolonged exposure to temperatures between 425 ℃ and 870 ℃ (800–1,600 °F) triggers chromium carbide precipitation along grain boundaries (sensitization). This localized chromium depletion renders 304SS highly susceptible to intergranular corrosion (IGC) and intergranular stress corrosion cracking (IGSCC) when exposed to acidic

flue gases [11]. Furthermore, operating temperatures exceeding 1,000 ℃ during forced aeration exceed the unreinforced long-term limits of standard austenitic stainless steels.

To extend incinerator service life, protective surface coatings or alternative alloy selection are recommended. Recent material studies demonstrate that applying plasma-sprayed Ni40AA or Mo-added NiCrBSi coatings significantly enhances hot corrosion resistance in waste incineration environments [12]. Additionally, ceramic enamel coatings effectively seal the steel matrix and block chlorine/acid diffusion [13]. For internal combustion liners subject to sustained temperatures above 1,000 ℃, replacing or lining 304SS with nickel-based superalloys or ceria-doped Cr3C2-NiCr thermal coatings offers superior long-term resistance to aggressive thermal atmospheres [14][15]. The overall comparison with the old incinerator is illustrated in Figure 5.

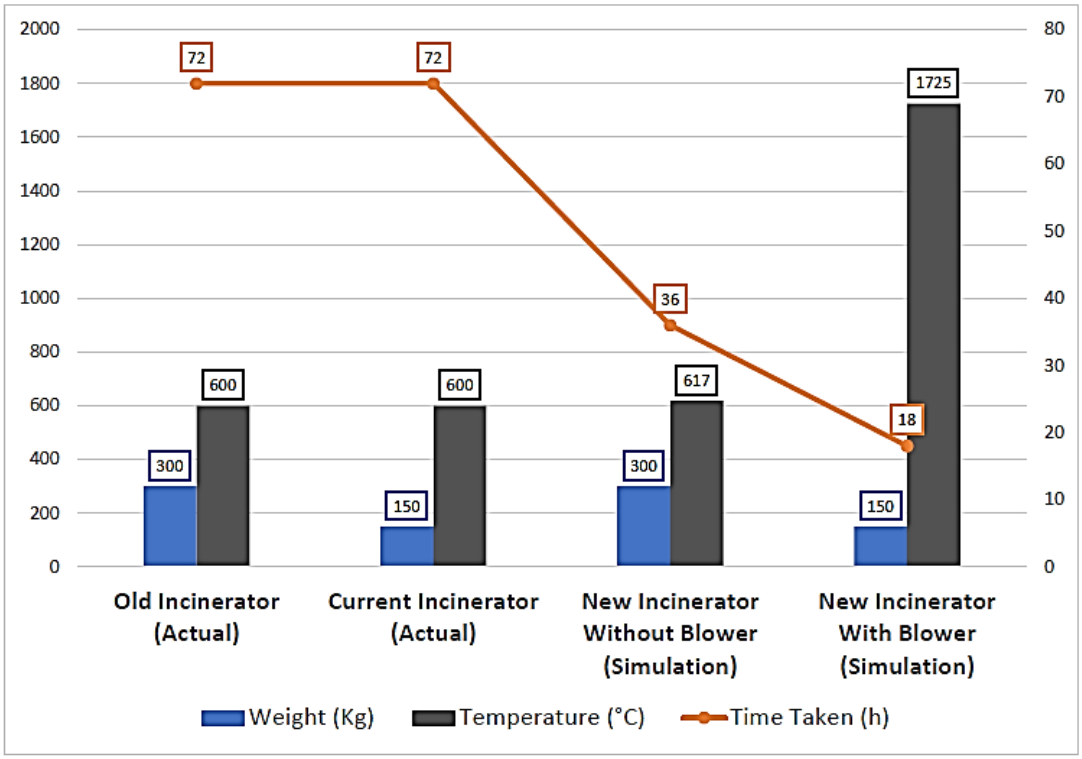


Figure 5: Performance Comparison between the old and the newly designed incinerator.

CONCLUSION

This study successfully redesigned and analyzed an Al-Quran disposal incinerator tailored for state religious administration. By integrating forced-air aeration, multi-stage filtering, and ergonomic lift mechanisms, the redesign resolves long-standing issues of toxic smoke pollution, ash scattering, and operator strain faced by JAIM. Key numerical and operational conclusions include:

- Thermal Aeration Efficiency: Blower activation elevates core combustion temperature from 617 ℃ to 1,725 ℃ (180% increase), reducing complete incineration time for 150 kg of paper to under 24 hours.
- Structural Payload Limits: Static FEA confirms safe operation at 300 kg payload during passive burning (617 ℃, FOS = 1.0) and 150 kg payload during forced aeration (1,725 ℃, FOS = 1.1). Payloads exceeding 150 kg under forced aeration cause structural yielding (FOS = 0.5).
- Ergonomic & Environmental Compliance: The hydraulic lift table and closed dust compartment eliminate operator stooping and prevent sacred ash loss during wind exposure.
- Metallurgical Preservation: Applying Ni-based or ceramic enamel protective coatings is essential to prevent intergranular corrosion caused by 304SS sensitization between 425–870 ℃.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The CAD model datasets, CFD boundary conditions, and FEA simulation mesh files generated during this study are available from the corresponding author upon reasonable request.

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