

LIU, X., ZHU, G., ASIM, T. and MISHRA, R. 2024. Design of a novel α -shaped flue gas route flame incinerator for the treatment of municipal waste materials. *Waste and biomass valorization* [online], 15(4), pages 2483-2498. Available from: <https://doi.org/10.1007/s12649-023-02291-5>

Design of a novel α -shaped flue gas route flame incinerator for the treatment of municipal waste materials.

LIU, X., ZHU, G., ASIM, T. and MISHRA, R.

2024



Design of a Novel α -Shaped Flue Gas Route Flame Incinerator for the Treatment of Municipal Waste Materials

Xiaozhou Liu¹ · Guangyu Zhu¹ · Taimoor Asim² · Rakesh Mishra³

Received: 18 May 2023 / Accepted: 16 September 2023 / Published online: 27 October 2023
© The Author(s) 2023

Abstract

In order to improve the combustion characteristics of municipal waste materials and reduce excess pollutants generated during the incineration process, this study develops a novel waste incinerator with an α -shaped flue gas route. This has been achieved through the application of momentum vector synthesis theory in order to modify the secondary air structure in a conventional incinerator, resulting in enhanced combustion efficiency of the incinerator. Computational Fluid Dynamics (CFD) based cold state test results demonstrate that with appropriate modifications to the design of the incinerator, the flue gas propagates through a longer α -shaped route rather than conventional L-shaped route. Hot state tests have been carried out on a full scale 750 tons/day waste incinerator. Test results show that the temperature of the flue gas increases by 138% under the front arch when secondary air supply is being incorporated into the design of the incinerator, resulting in better combustion of the municipal waste materials, lower emissions and higher thermal efficiency of the incinerator. The results obtained in this study confirm the rationality and feasibility of momentum flow rate method for better design of waste incinerators.

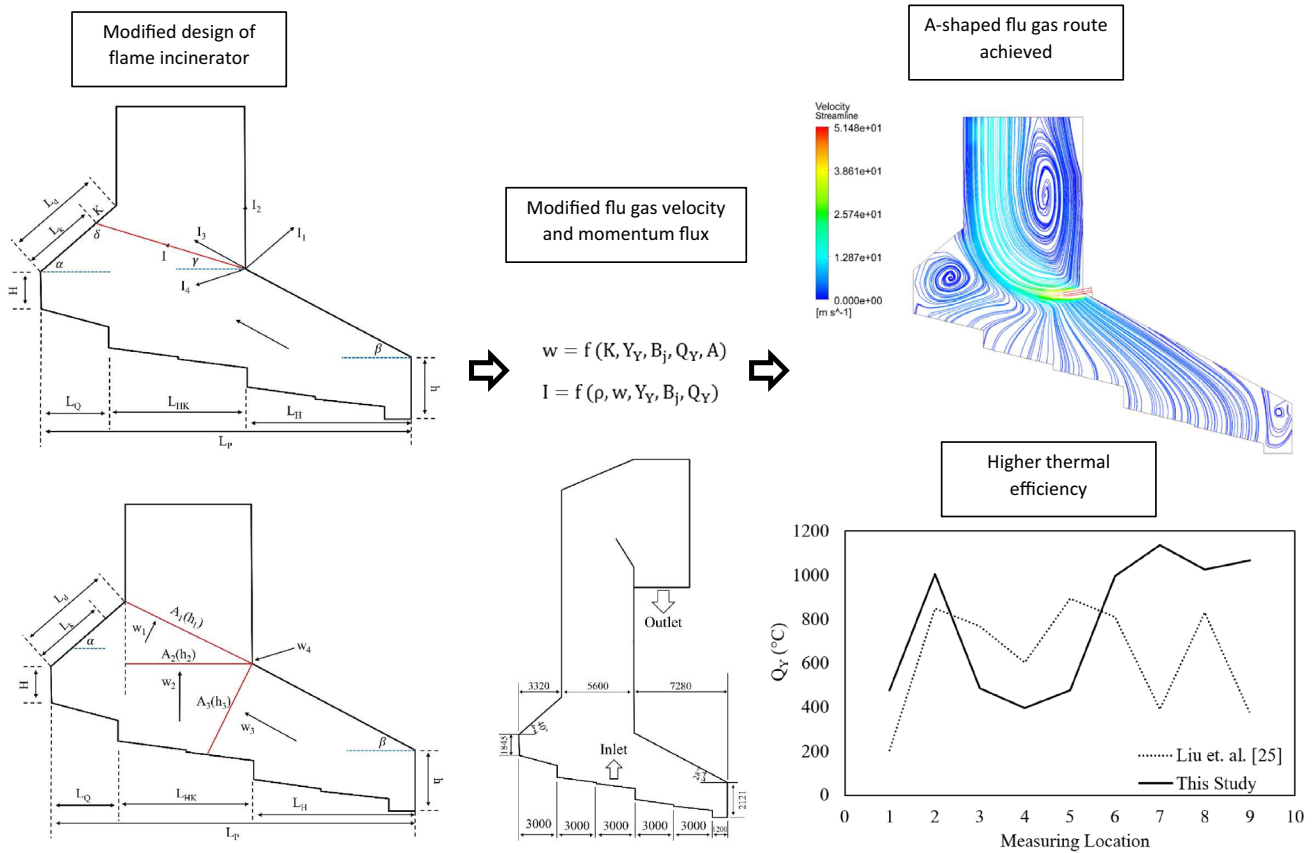
✉ Taimoor Asim
t.asim@rgu.ac.uk

¹ Guangdong University of Technology, Guangzhou 510006, China

² School of Engineering, Robert Gordon University, Aberdeen AB10 7GJ, UK

³ School of Computing and Engineering, University of Huddersfield, Huddersfield HD1 3DH, UK

Graphical Abstract



Keywords α -shaped flu gas route · Flame incinerator · Momentum flux method · Computational fluid dynamics · Sewage sludge · Municipal waste

List of Symbols

A	Area (m ²)
L_d	Length of inclined section of the front arch (m)
B	Effective width of the grate (m)
L_k	Effective length of the front arch (m)
B_j	Fuel consumption (kg/s)
w	Flow velocity (m/s)
h	Height of the rear arch (m)
V	Flue gas volume (m ³)
H	Height of the front arch (m)
Q	Average temperature (°C)
I	Flue gas momentum flux (N)
K	Projection coverage constant
α	Front arch inclination angle°
L_Q	Length of grate covered by the front arch (m)
β	Rear arch inclination angle°
L_{HK}	Length of grate covered by the throat (m)
γ	Momentum synthesis angle°
L_H	Length of grate covered by the rear arch (m)
δ	Angle between I and front arch °

L_p	Effective length of the grate (m)
ρ	Density (kg/m ³)

Subscripts

1	Front arch outlet
2	Uncovered area of incinerator arch
3	Rear arch outlet
Y	Flue gas
o	Secondary air supply

Statement of Novelty

Conventional flame incinerators for the treatment of municipal waste materials are notorious for incomplete combustion leading to significant amount of emissions being released in the atmosphere. This study presents the theoretical basis for designing appropriate secondary air supply system to be integrated with conventional flame incinerators resulting in α -shaped route of the flu gas inside

the incinerator, compared to conventional L-shaped route. Full-scale hot tests on the modified incinerator show that the combustion is more profound leading to higher thermal efficiency and reduced emissions.

Introduction

The production of waste materials in China is on a rise due to its rapid urbanization and fast-growing economy [1]. Chinese National Bureau of statistics [2] have reported that the disposal and transportation of municipal waste has increased year-on-year since 2008, and as of 2020, the China's municipal waste has reached 235 million tons, with a year-on-year increase of 3.56%. This significant increase in municipal waste poses a serious threat to the Chinese economy, its further urbanization plans and to the environment. The 14th 5-year plan for the development of municipal waste sorting and treatment facilities pointed out that the overall domestic waste incineration rate in the central and western regions of China is limited, and most prefecture-level cities and counties still have large gaps in incineration capacity. Waste incineration industry has broad market space and excellent development prospects [3].

There are two main types of municipal waste materials found in China, which are solid waste (also called municipal solid waste) and sewage sludge. The solid waste further comprises of 18 primary components like rubber, paper, plastic, glass, food and garden waste etc. The composition of solid waste is affected by seasonality and geographical region, which fluctuates considerably given the waste expanse of Chinese mainland, however, the primary combustion-relevant characteristics remain largely constant. Amongst them are the low average water content and high calorific value [4]. With these physical qualities, the solid waste materials are suitable for incineration. Treatment of sewage sludge is another key challenge facing China's urban development. Presently, municipal sewage disposal plants produce a large amount of sludge. Sludge is a complex heterogeneous waste material, comprising of organic sediments, bacteria, inorganic substances and colloids. Its by-product is usually called municipal sewage sludge, which has a water content of 60% and organic content of 40%, indicating adequate combustion calorific value. As a safe and reliable sludge treatment method, incineration can fully recycle the energy of sewage sludge, kill pathogenic bacteria, reduce the occupation of land, effectively reduce environmental pollution and reduce the cost of environmental protection [5, 6]. As the sewage sludge has the characteristics of low calorific value, high water content and small air circulation area, for its efficient incineration, the route through which the flue gas pass inside the flame incinerator should be modified. This becomes further

imperative when solid waste and the sewage sludge are to be incinerated together.

In terms of waste incineration, the two main types of waste incineration power plants in China are grate furnace and fluidized bed incinerators. Amongst these, the grate furnace is most widely used, accounting for more than 75% of the incineration market, while the application of fluidized bed incinerator is gradually decreasing [7]. Compared with fluidized bed incinerators, grate incinerators have the advantages of simple raw material pretreatment, strong applicability, high reliability, low fly ash output, low operating cost and mature operation technology. However, there are some drawbacks associated with grate incinerators as well like low combustion efficiency and temperature, insufficient combustion and generation of large quantities of harmful pollutants, such as dioxins. The purpose of this study is to solve inadequate waste combustion challenge faced by grate incinerators. Before we move on to this, it would be prudent to review relevant literature in order to appraise the scientific challenges involved in this.

Frey et al. [8] experimentally recording flue gas composition and temperature in a grate flame incinerator and then employed a well-validated numerical model to investigate the combustion characteristics of homogeneous municipal solid waste in a conventional flame incinerator. Computational Fluid Dynamics (CFD) predicted results indicate regions of high CO concentration due to insufficient burning of the waste material. The root cause identified for incomplete combustion of the waste material is attributed to the lack of oxygen in the grate region and thus, it has been identified that secondary air supply from either side of the grate is required for complete combustion [8]. Luo et al. [9] further confirms the findings of Frey et al. [8] while studying the combustion characteristics of a V-type flame incinerator fueled with fly ash and slag. The numerical investigations show that the maximum temperature reached within the flame incinerator is 1650 K, while incomplete combustion has been detected through the analysis of CO concentration in the flame incinerator [9]. Huai et al. [10], while carrying out numerical analyses of a grate incinerator's combustion behavior, has observed that for waste materials having higher water content (like sewage sludge), the temperature within the grate is lower due to lower heat value of the fuel, which results in lower oxygen consumption. The study, though purely numerical based, proposes to add secondary air supply into the flame incinerator for enhancement in the combustion of the waste materials and thus, the thermal efficiency of the incineration process [10].

Despite the obvious environmental considerations associated with the incineration of municipal waste materials, which are a direct result of incomplete combustion, in the UK, the percentage of municipal waste being sent for incineration is on a rise. In comparison

to 9% municipal waste (2.4 million tonnes/year) being incinerated at the beginning of the century, 48.2% of the municipal waste (12.5 million tonnes/year) is incinerated across the UK in its 70 incineration facilities [11]. Thus, significant increase in focus on scientific research related to municipal waste incineration in the UK has been observed. Yang et al. [12] has carried out experimental investigations on the combustion characteristics of wood chips and municipal waste materials in a conventional incinerator. The empirical results obtained depict strong dependency on the rate of primary air supply and water content of the waste material. It has been reported that higher air supply and water content of the waste results in higher temperature in the flame incinerator and lower CO emissions [12]. Extending the scope of this study, Yang et al. [13] carried out numerical investigations on the potential of gasification of the municipal waste materials in grate incinerators. Enhancement in the combustion of the waste material is observed with the addition of secondary air supply, resulting in considerably lower concentration of CO in the incinerator. It has been advocated that in accordance with the public perception regarding incineration of municipal waste in the UK, novel technologies should be developed to mitigate the hazards posed by the flue gas [13]. Further numerical study by Yang et al. [14] reports a caveat in combustion behavior estimation for higher water content of the waste material and the use of secondary air supply. It has been reported that high water content results in considerably higher CO emissions and lower flame incinerator temperature when secondary air is supplied [14]. Swithbank et al. [15] uses the combustion data from Yang et al. [12–14] to develop a mathematical model describing the combustion of municipal waste materials in a conventional incinerator. The developed model is based on mass and momentum conservation where the waste material is modelled as a porous media [15].

The primary method to enhance combustions in a traditional incinerator is to change the arches structure, making the high-temperature flue gas to go through an α -shaped path and making full use of the waste heat of the flue gas. However, this has a huge workload, high cost and requires long-term shutdown of the incinerator, making it difficult to implement in large scale applications. Summary of the recent works in this field is given in Table 1. It can be seen that there are limited scientific developments on using secondary air to change the flow of flue gas.

Method proposed in this study is to transform the secondary air supply such that it can achieve the same goal, but keeping the workload and costs much lower. So-called secondary air refers to several strong airflow streams that are rapidly injected into the furnace from above the fire bed, having a significant effect on the airflow inside the furnace in order to enhance mixing. It can improve the thermal efficiency of waste incineration without increasing the total

amount of combustion supporting air. At the same time, the high speed and high momentum secondary air flow can also guide the flue gas into a prescribed airflow shape (α -shaped) inside the furnace, prolong the generation process of the flue gas and fly ash, and change the position of the combustion center. With the application of the secondary air structure transformation method proposed in this study, in terms of economic benefits, it can significantly improve the treatment efficiency of solid waste disposal enterprises, reduce the investment costs of enterprises, and thereby enhance the regional resource recycling and utilization capacity, and support the development of circular economy. In terms of social benefits, it can significantly reduce pollutant emissions and reduce damage to public health. Due to the improvement in production and operation efficiency, it can increase the number of local labor employment. This research method can be promoted and applied in the waste treatment industry, promoting the development of science and technology, and contributing to the development of efficient solid waste treatment technology.

From the above discussions it is clear that there is a significant gap in the scientific knowledge regarding high water content municipal waste and the use of secondary air supply in conventional waste incinerators, where the main difficulty in complete combustion arises from lower temperature, leading to higher CO emissions from the incinerator, which is also reported in a number of other research studies as well [16, 21–25]. In the present study, we also aim to develop a mathematical/theoretical model for accurate design of flame incinerator. The theoretical design model developed in this study is based on momentum flux method. Cold-state and hot-state tests carried out in the present study clearly indicate that the developed theoretical design methodology for the flame incinerator performs superior to conventional models being used, and that the novel α -shaped flue gas route flame incinerator results in complete combustion of high-water content municipal waste, with considerably lower CO emissions.

Theoretical Design of a Novel α -shaped Flue Gas Route Flame Incinerator

The existing waste incinerators mostly have layered combustion furnace fueled with coal. In order to (i) strengthen air flow mixing in the furnace, (ii) optimize heat radiation and flue gas flow, (iii) ensure smooth ignition of fuel, and (iv) enhance the combustion efficiency of the incinerator, it is necessary to modify the route taken by the flue gas inside the incinerator. Presently, the incinerator designs are primarily based on empirical methods, such as (i) coverage method, (ii) radiation source method, (iii) empirical look-up table method, etc. These methods, however, do not consider the

Table 1 Summary of recent scientific works on traditional waste incinerators

Ref	Research contents	Key conclusions	Shortcomings
[9]	The combustion process of municipal solid waste (MSW) in "V" type Incineration furnace was studied using CFD and experiments	When the secondary air is fed into the furnace, the volatiles burn in the middle of the furnace, forming a high-temperature zone with a maximum temperature of about 1650 K	Formation of α -shaped flue gas route has not been covered
[16]	This study focuses on the effects of primary NO_x control methods and secondary NO_x suppression methods on NO_x emissions and combustion characteristics	Combustion strategy combining secondary air and over frequency air can improve combustion performance and reduce NO_x emissions	Formation of α -shaped flue gas route has not been covered
[17]	This work analysed the influence of different gas supply modes on the combustion state of municipal waste incineration	When the proportion of secondary air increases, the combustion characteristics and flame position are effectively improved	Formation of α -shaped flue gas route has not been covered
[18]	The influence of different primary air temperatures on incineration in a mobile grate incinerator was studied	As the preheating temperature of the air increases, the evaporation rate of water and the release rate of volatile substances also increase, which may lead to an increase in the local maximum temperature inside the furnace	Relying solely on adjusting the primary air to increase furnace temperature, without the formation of α -shaped flue gas route
[19]	The environmental impact, economic benefits and energy efficiency of the MSWI project were evaluated using three representative MSWI cases in the plain area	Improving boiler air volume and cross-sectional area helps adapt to hypoxic environments	Relying solely on increasing air volume capacity to improve combustion performance, without the formation of α -shaped flue gas route
[20]	A new coupling method has been proposed for modeling solid waste incineration in complex advanced moving grate (AMG) incinerators	The simulation results indicate that when the temperature rises to 1100–1400 K, a high-temperature zone appears between the bottom and the secondary air nozzle	Formation of α -shaped flue gas route has not been covered

effects of flow of flue gas in the incinerator, the geometric size of the front arch on the thermal radiation of fuel, and how the front and rear arches cooperate to ensure stable combustion.

In conventional incinerators, an L-shaped flue gas route is formed, which has the advantage of being able to treat different types of solid waste but is less efficient for municipal solid waste as it is difficult to burn. This study aims to improve the combustion characteristics of solid waste with high ignition points and poor combustion performance, thereby improving the combustion efficiency of municipal solid waste and reducing the pollutants generated during the incineration process. An effective way to achieve this goal is to transform the arches structure of the traditional waste incinerator, leading to the formation of an α -shaped flue gas route inside the incinerator. Based on momentum flow rate method, the momentum vector synthesis theory is applied to develop corresponding design formulas for the design of secondary air supply within traditional waste incinerators. Forming the α -shaped flame in a waste incinerator can significantly increase the residence time of the flue gas in the furnace arches area and ensure that the fuel is fully burned out. At the same time, due to the α -shaped route adopted by the flue gas, larger unburned fuel particles in the flue gas can be redirected back towards the fuel layer by centrifugal force to continue burning, which further improves combustion efficiency and reduce emissions. According to the calculation results of the model developed, the α -shaped flame incinerator can be obtained, which solves the problem the problem of poor combustion performance of municipal solid waste materials in incinerators.

The momentum flux method is used to re-design the flame arches and the secondary air supply in order to modify the flue gas path inside the incinerator. The key step

in this method is to synthesize the flue gas momentum at the outlet of the rear arch so as to modify the conventional L-shaped flue gas route in waste flame incinerator to an α -shaped route, as shown in Fig. 1. The resulting novel design of the incinerator is envisaged to be more suitable for mixed combustion of dewatered sludge and municipal waste.

Rationale for Choosing α -shaped Flue Gas Route

The main advantages of using an α -shaped route for the flow of flue gas inside a flame incinerator, for the combustion of municipal waste materials, are:

1. Since the water content of sewage sludge entering the flame incinerator is much higher than that of solid waste, the preheating and drying of the waste fuel must be carried out in order to easily catch fire [26]. With the formation of α -shaped route, the high-temperature flue gas is forced to turn downward under the front arch, forming a reflux area. This enhances the heat exchange between the high-temperature flue gas and the waste fuel, strengthening the heat radiation of the high-temperature flue gas to the waste fuel, which is conducive to the ignition of the fuel;
2. α -shaped flue gas route will force the combustible gas and hot carbon particles in the flue gas to fully mix with air to improve the combustion efficiency;
3. With the α -shaped route, (i) the flow of flue gas is prolonged, (ii) the residence time of high-temperature flue gas in the furnace is increased, (iii) the fly ash content in the flue gas is reduced, and (iv) the burn-out rate of waste fuel is improved [27].

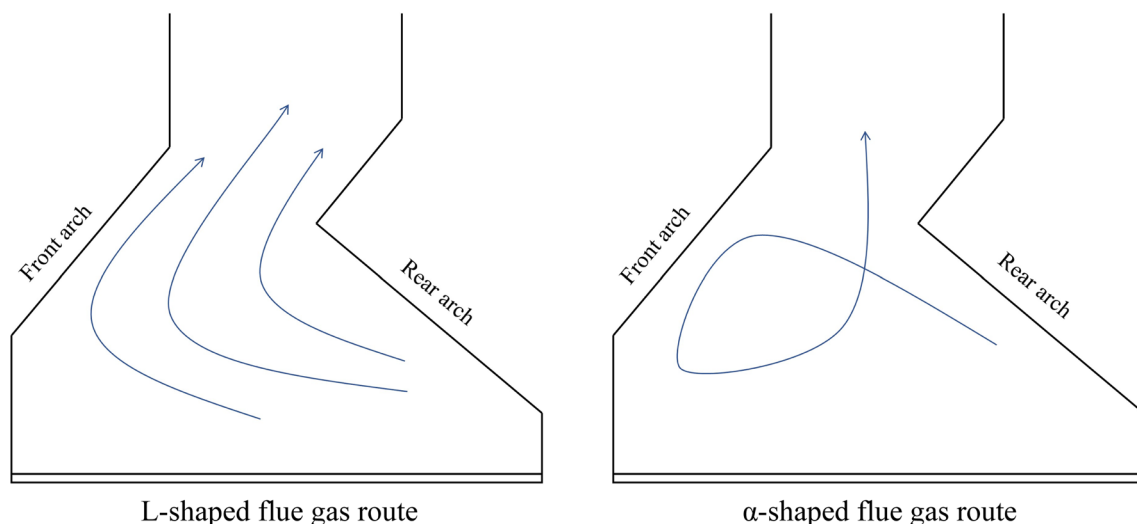


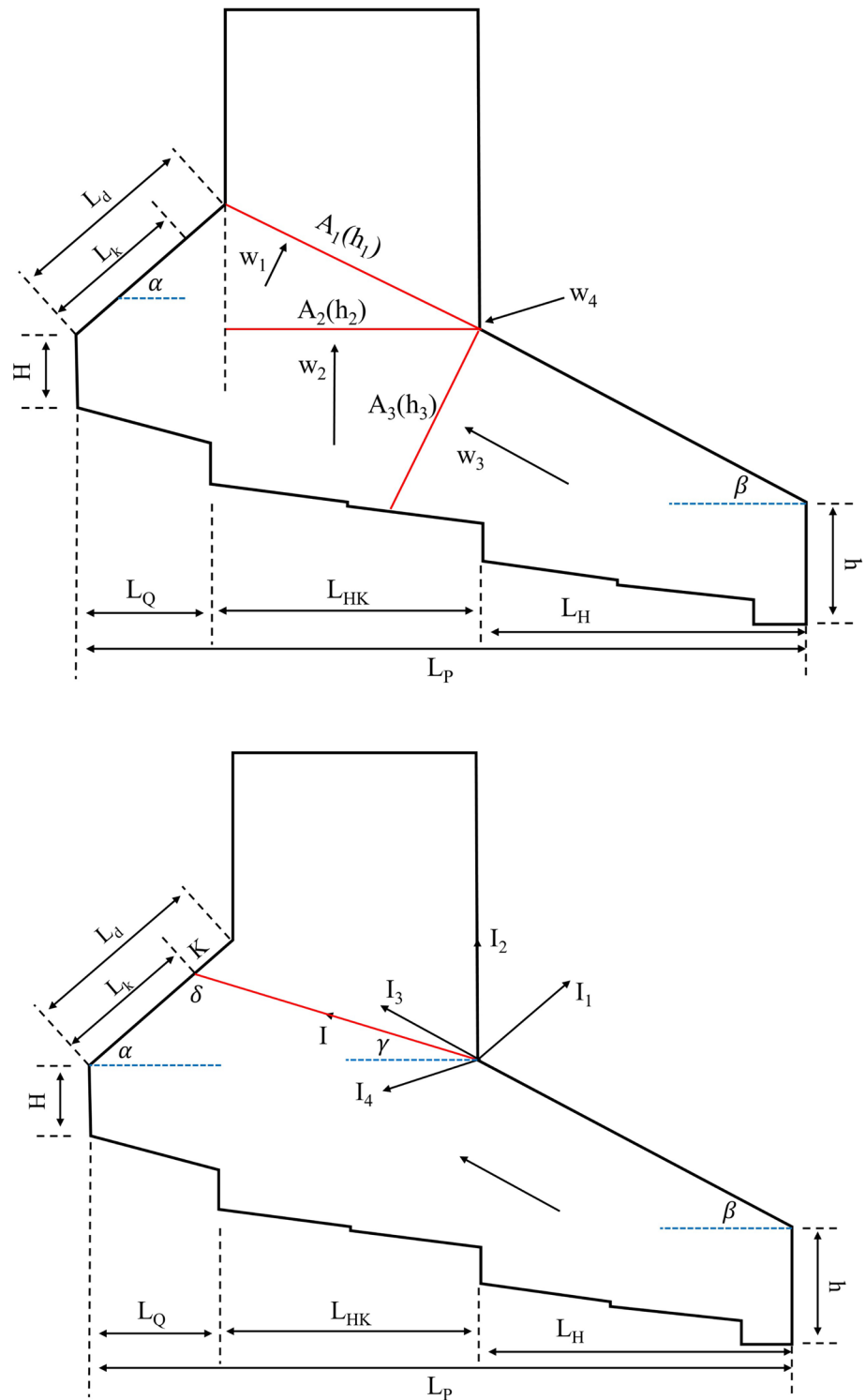
Fig. 1 Flue gas route through the flame incinerator

Key Momentum Flux Design Parameters of a Flame Incinerator

The key momentum flux design parameters for waste

incinerators are shown in Fig. 2, where A is the cross-sectional area (m^2), w is the flue gas velocity (m/s), L is the length (m) and I is momentum flux (N). The width of the incinerator is B .

Fig. 2 Design of a flame incinerator based on momentum flux method



Flue Gas Velocity and Momentum Flux at the Rear Arch Outlet

The momentum flux method is based on momentum vector synthesis theory which considers the direction of the flue gas velocity at the rear arch outlet (w_3), ensuring that it is consistent with the rear arch inclination angle (β). Thus, w_3 is calculated according to the cross-sectional area $A_3 = h_3 B$ at the rear arch outlet as:

$$w_3 = K_3 V_Y B_j \frac{Q_Y + C}{A_3 C} \quad (1)$$

where K_3 of 0.4 and $w_3 > 2 \sim 3$ m/s is considered appropriate for flame incinerators. C is a conversion factor with a value of 273.

The flue gas momentum flux at the rear arch outlet (I_3) is calculated as:

$$I_3 = \rho_Y w_3 V_Y B_j \frac{Q_Y + C}{C} \quad (2)$$

$$\text{where } \rho_Y = 1.29 \frac{C}{C + Q_Y}$$

Flue Gas Velocity and Momentum Flux at the Front Arch Outlet

The flue gas velocity vector at the front arch outlet (w_1) is considered to be parallel to the inclination angle of the front arch (α). Considering the formation of reflux area under the front arch, the flue gas velocity vector at the front arch outlet ($A_1 = h_1 B$) is calculated as:

$$w_1 = K_1 V_Y B_j \frac{Q_Y + C}{CA_1} \quad (3)$$

where K_1 is generally 0.2 for waste incinerators.

The flue gas momentum flux at the front arch outlet (I_1) is calculated as:

$$I_1 = \rho_Y w_1 V_Y B_j \frac{Q_Y + C}{C} \quad (4)$$

Flue Gas Velocity and Momentum Flux at the Uncovered Area of the Arches

The flow velocity of flue gas in the uncovered area of furnace $A_2 = h_2 B$ determines the size and number of solid particles taken away by high-temperature flue gas. When the flue gas velocity in the uncovered area of the furnace arches is greater than 5 m/s, a large number of particles in the flue gas with an average size of 1 mm are taken away by the flue gas, which leads to incomplete combustion of the waste fuel.

Therefore, the flue gas velocity in the uncovered area of the furnace arches should not be greater than 5 m/s, which can be calculated as:

$$w_2 = K_2 V_Y B_j \frac{Q_Y + C}{CA_2} \quad (5)$$

where K_2 is generally 0.4 for waste incinerators.

The flue gas momentum flux at the uncovered area of furnace arches (I_2) is calculated as:

$$I_2 = \rho_Y w_2 V_Y B_j \frac{Q_Y + C}{C} \quad (6)$$

Momentum Flux of Secondary Air

The secondary air injected at high speed from the rear arch outlet can penetrate deep into the front arch area to provide oxygen to enhance combustion of the waste fuel. As the secondary air is injected at high speed, it has considerably greater momentum, which is very important for the formation of α -shaped flue gas route. In this study, secondary air is considered to be injected at room temperature. The momentum flux of secondary air is calculated as:

$$I_2 = \rho_0 V_0 w_0 \quad (7)$$

where w_0 of 50 m/s, based on design experience, is considered appropriate for secondary air supply.

Geometric Parameters of the α -shaped Flue Gas Route Incinerator Flame Arches

According to literature [28], in order to form an α -shaped flue gas route inside the flame incinerator, the geometric parameters of the front arch should meet the following requirements: inclination angle of the rear arch $\beta \geq 30^\circ$, angle between gas synthesis momentum I and front arch $\delta \geq 110^\circ$, the inclination length L_D and effective length L_K of front arch should meet $L_K = (2/3 \sim 4/5)L_d$ and the momentum synthesis angle $\gamma \leq 40^\circ$.

Cold-State Testing of the Novel α -shaped Flue Gas Route Flame Incinerator

Based on the aforementioned design parameters, the design of the novel α -shaped flue gas route flame incinerator has been developed and cold tested using advanced Computational Fluid Dynamics (CFD) based solver called ANSYS FLUENT®. In order to ascertain the performance supremacy of the novel α -shaped flue gas route flame incinerator over the conventional L-shaped flue gas route flame incinerator, both the flame incinerators have been

cold tested and their results (i.e. flow velocity for cold tests) compared. Hence, this section first presents the design and analysis of the conventional flame incinerator, followed by the design and performance of the novel flame incinerator.

Geometry of the Conventional Incinerator

A conventional full-scale incinerator with a capacity of 750 tonnes/day, installed in Guangdong (China), has been chosen in this study for analysis. The design of the incinerator is shown in Fig. 3a. The effective length of the grate (L_p) is 16.2 m, the width of the grate (B) is 10.8 m, the coverage length of the front arch of the grate (L_Q) is 6 m, the coverage length of the rear arch (L_H) is 7.2 m, the inclination angle of the front arch (α) is 40° , the inclination angle of the rear arch (β) is 28° , the height of the rear arch is 2.121 m, the momentum synthesis angle (δ) is 64° and the angle between the direction of combined momentum and horizontal direction (γ) is 76° . Based on these dimensions, the geometric model of the incinerator is created, as shown in Fig. 3b.

Mesh Sensitivity Analysis of the Conventional Incinerator

When Finite Volume Method (FVM) is used to analyze flow characteristics, as in the present study, spatial discretization plays an important role towards the accuracy of the predicted solution. Dividing the flow volume within the incinerator into more parts (or mesh elements) enhances the solution accuracy however, the cost of computation also increases. When the number of mesh elements reach a certain value, further increasing it doesn't

necessarily improve the accuracy of the predictions [29]. The process of identifying this optimal number of mesh elements is known as mesh sensitivity analysis (or mesh independence testing), which is an integral part of any CFD study [30].

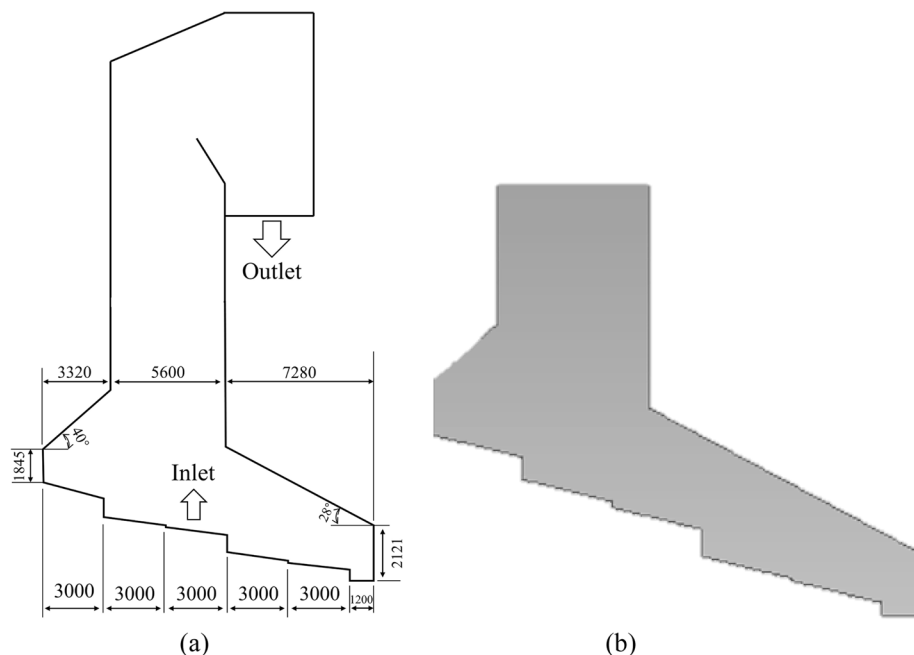
The flow domain of the incinerator has been meshed using hexahedral elements, which are extensively used in the published literature for their lower numerical error [31, 32]. Six different meshes have been generated with different element sizing in order to carry out mesh sensitivity analysis. The details of element sizing and the resulting number of mesh elements are summarized in Table 2.

Based on the numerical predictions of the flue gas velocity at the outlet of the incinerator shown in Fig. 4, it is evident that mesh M4 accurately captures the flue gas flow inside the incinerator and thus, has been chosen for further analysis.

Table 2 Mesh sizing

Mesh	Element size (mm)	No. of mesh elements
M1	310	3.7×10^4
M2	238	7.5×10^4
M3	190	1.5×10^5
M4	150	3.0×10^5
M5	120	6.0×10^5
M6	90	1.2×10^6

Fig. 3 Design of the 750 tonnes/day flame incinerator **a** geometric details **b** geometric model



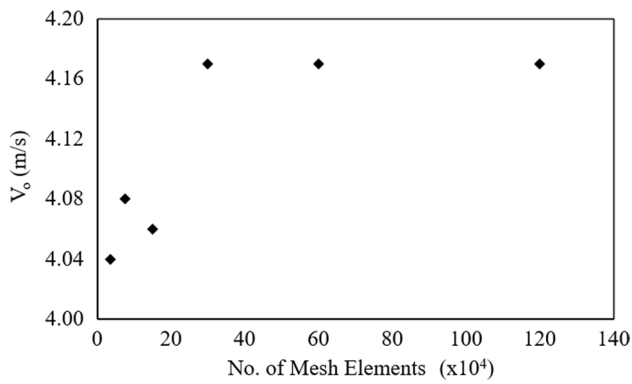


Fig. 4 Mesh sensitivity results

Table 3 Momentum flux parameters of the conventional waste incinerator

I_{1y}	I_{2y}	I_{3y}	I_y
7.24	41.31	12.66	61.21
I_{1x}	I_{2x}	I_{3x}	I_x
8.62	0	-23.82	-15.19

Operational Parameters and Boundary Conditions

For the conventional flame incinerator, the operational parameters are calculated using the momentum flux method. The momentum flux at the front arch outlet (I_1), uncovered area (I_2) and the rear arch outlet (I_3) are 26.97 N, 41.31 N and 11.26 N respectively. Moreover, the flue gas velocity at the front arch outlet (w_1), at the uncovered area (w_2) and at the rear arch outlet (w_3) are 0.7 m/s, 1.43 m/s and 1.40 m/s respectively, which have been used as the

boundary conditions in the numerical solver. The outlet of the incinerator has been modelled as a pressure outlet with 0 Pa,g pressure and the walls of the incinerator have been modeled as stationary walls observing no-slip condition. The momentum flux parameters of the conventional incinerator are summarized in Table 3.

From the momentum flux method calculations of the conventional flame incinerator, it is not difficult to see that the flue gas flow in the incinerator could not meet the requirements for the formation of α -shaped flue gas route. The angles β , δ and γ are not in-line with the recommended design of the front arch based on momentum flux method discussed in Sect. "Geometric Parameters of the α -shaped Flue Gas Route Incinerator Flame Arches". For example, the momentum synthesis angle (δ) is 64° , which is far less than recommended 110° .

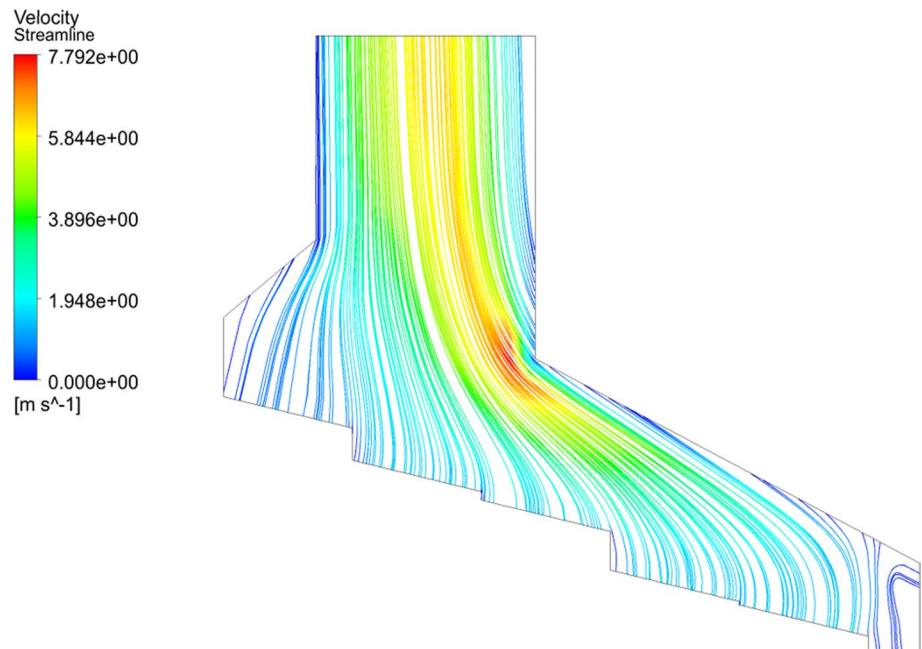
Flue Gas Route in the Conventional Incinerator

Based on the numerical simulation, the flow velocity of the flue gas has been calculated. The spatial variations in the velocity streamlines inside the incinerator are plotted in Fig. 5. It can be clearly seen that the path taken by the flue gas is L-shaped, confirming the calculations of the momentum flux method.

Design Modifications to Obtain α -shaped Flue Gas Route

The design modifications to the conventional flame incinerator have been carried out, based on the calculations from the momentum flux method, in order to obtain

Fig. 5 Flue gas velocity streamlines in the 750 tonnes/day flame incinerator



α -shaped flue gas route for enhanced thermal efficiency of the incineration process. Additionally, secondary air supply, as indicated in published literature [10, 13, 15], has been used to enhance combustion of the municipal waste in the incinerator. The combination of these two is envisaged to produce α -shaped route for the flow of flue gas. The primary design modifications are carried out on the front and rear arches of the flame incinerator.

According to the momentum flux method, in order to obtain α -shaped flue gas route, it is necessary to increase the momentum flux of air flow at the rear arch outlet, and force the high-temperature flue gas at the rear arch outlet to go deep into the front arch area i.e. making the high-temperature flue gas whirl in the front arch area to form an α -shaped route. The most effective way to enhance the momentum flux at the rear arch outlet is to install secondary air supply at the rear arch outlet and modify the geometric design of the arches accordingly. Because the secondary air has higher flow velocity and density, it can potentially enhance the momentum flux at the arch outlet. In this study, eight circular nozzles are installed at the rear arch outlet, having a downward inclination angle of 5° , diameter of 110 mm

and air flow velocity of 50 m/s. Based on the new geometry of the flame incinerator, the momentum flux calculations provide the revised geometrical parameters related to the front and rear arches of the flame incinerator. The inclination angle of the rear arch (β) remains the same as 28° as it already fulfils the requirements of α -shaped flue gas route. The modified momentum synthesis angle (δ) is 131° and the new inclination angle of the front arch (α) is 40° , as per momentum flux method calculations to obtain α -shaped flue gas route. Similarly, the revised angle between the direction of combined momentum and horizontal direction (γ) is 8.62° . For the novel α -shaped flue gas route flame incinerator, the momentum flux parameters are also re-calculated, as summarized in Table 4. It is noteworthy that the flue gas velocities w_1 , w_2 and w_3 remain the same as 0.7 m/s, 1.43 m/s and 1.40 m/s respectively.

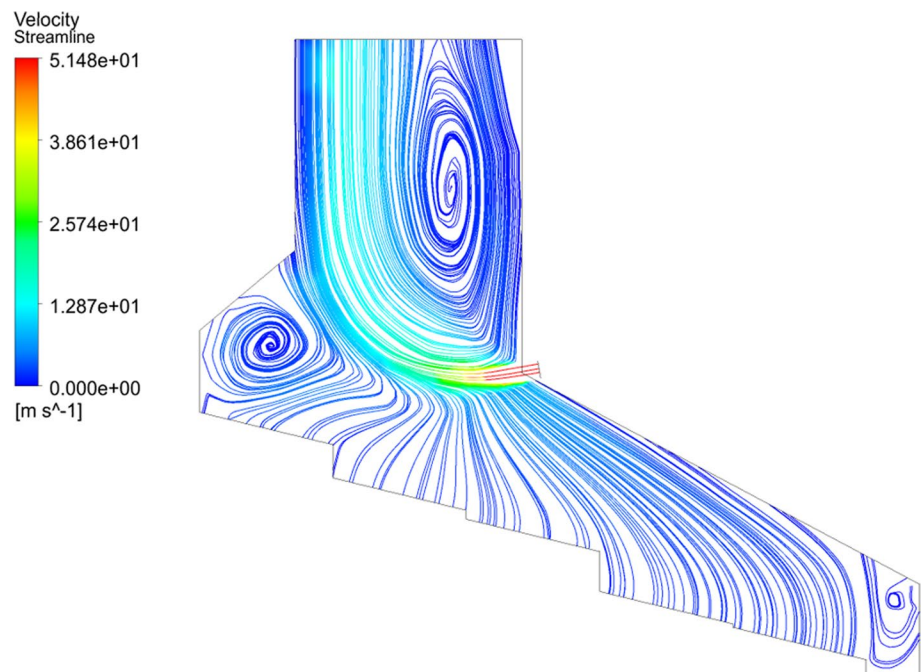
Flue Gas Route in the Novel Flame Incinerator

The flue gas flow velocity has been numerically calculated and the streamlines are plotted in Fig. 6. It can be clearly seen that with the incorporation of the design modifications to the flame incinerator, the secondary air supply disrupts the conventional L-shaped route of the flue gas by injecting high momentum fresh air. This leads to the formation of two flue gas flow recirculation zones, one below the front arch and the other one above the secondary air nozzles' outlets. Tracking the new path of the flue gas from the inlets, it travels under the rear arch, reaching the throat area, and then being forced to go under the front arch. This is envisaged to enhance combustion of the municipal waste fuel in this

Table 4 Momentum flux parameters of the novel waste incinerator

I_{1y}	I_{2y}	I_{3y}	I_{4y}	I_y
7.24	41.31	12.66	−21.55	39.66
I_{1x}	I_{2x}	I_{3x}	I_{4x}	I_x
8.62	0	−23.82	−246.31	−261.51
$\gamma = -\arctan(I_y/I_x) = 8.62^\circ$				

Fig. 6 Flue gas velocity streamlines in the novel flame incinerator



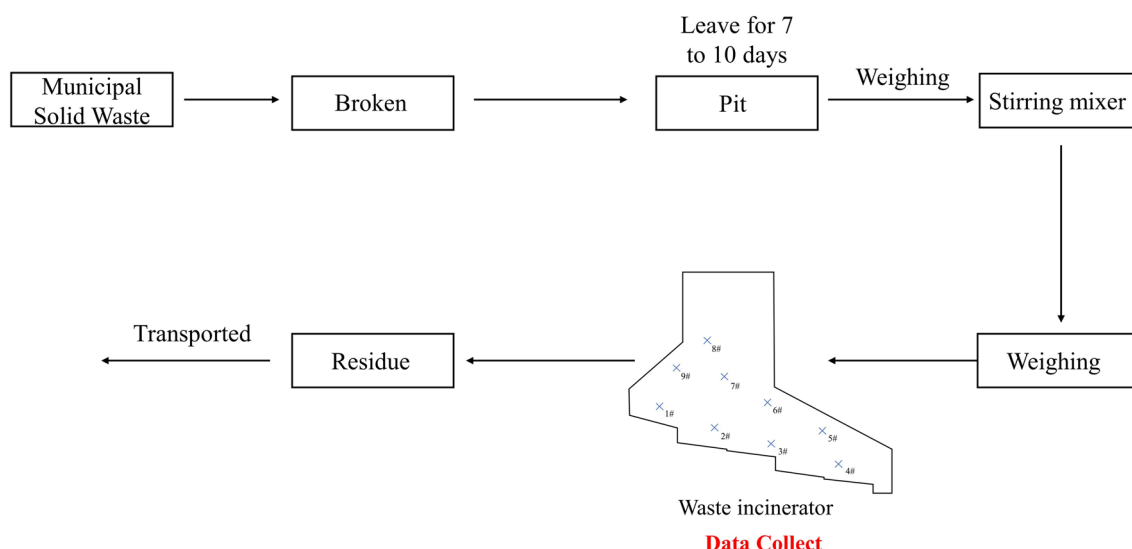


Fig. 7 Hot-state test flowchart of novel α -shaped flue gas route incinerator

Table 5 Industrial analysis of samples

M (%)	V (%)	FC (%)	A (%)
47.20	27.07	4.36	21.37

region, further increasing flue gas temperature (which is presented in the next section). The flue gas then rises through the rear arch outlet, to the outlet of the flame incinerator, thus following an α -shaped path in the incinerator.

Hot-State Testing of Novel α -Shaped Flame Incinerator

The cold-state testing has been carried out numerically, where the focus was mainly on the qualitative results. In order to validate the cold-state test results, real-world full-scale hot-state testing has been carried out on the 750 tonnes/day flame incinerator. The flowchart demonstrating the different steps involved in hot-state testing is shown in Fig. 7, which has been covered extensively in the literature [26, 27, 33].

Data analysis of the municipal solid waste entering the incineration plant is summarized in Tables 5 and 6. Due to being placed in the garbage pit for about a week before combustion, the moisture content decreased from 47.2% to 30%, and the mass of the municipal domestic waste increased by 32%. $((1-30\%) \div (1-47.2\%) = 1.32)$. The calorific value of

the waste before entering the furnace becomes 6730 kJ/kg ($1610 \text{ kcal/kg} \times 1.32 = 8888.68$ (2123 kcal/kg)).

The incinerator being tested is located in Guangzhou (Guangdong, China). In order to ascertain the superiority of the thermal/combustion characteristics of the novel α -shaped flue gas route flame incinerator, a comparative analysis has been carried out on the local flue gas temperature (Q_V) with an existing similar scale (700 tonnes/day) horizontal grate incinerator, whose hot-state test results have been reported by Liu et. al. [33]. For effective comparison purposes, the methodology adopted by Liu et. al. [33] has been repeated for the novel α -shaped route incinerator. This means that the same data measuring locations have been chosen, as shown in Fig. 8a. The hot-state test results have been plotted in Fig. 8b.

As described in the cold-state test section, the flue gas is forced downwards under the front arch for enhanced combustion, which then rises towards the outlet of the incinerator. Thus, the temperature in the α -loop i.e. measuring locations 6, 7, 9, 2 and 8, are expected to be significantly higher than the rest of the measuring locations. This can be clearly seen in Fig. 8b. Thus, it can be concluded with confidence that the methodology developed in the present study, based on momentum flux method, results in α -shaped flue gas route inside the flame incinerator for enhanced combustion. Comparative analysis between the novel α -shaped flue gas route flame incinerator with the hot-state test results of a horizontal grate incinerator demonstrates the superiority of

Table 6 Element analysis of samples

[M](%)	[C](%)	[H](%)	[O](%)	[N](%)	[S](%)	LHV/kJ.kg ⁻¹
47.20	20.41	2.92	7.95	0.37	0.02	6730

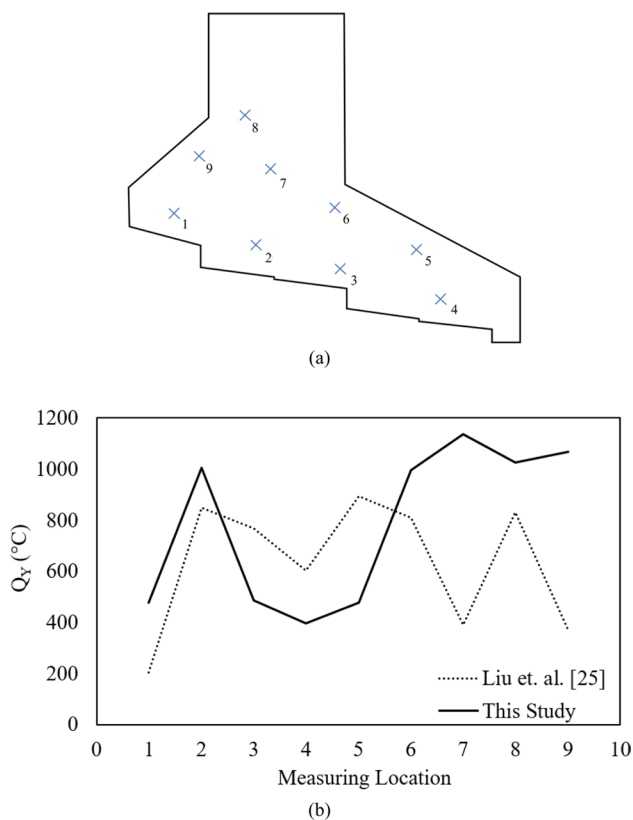


Fig. 8 Hot-state test results of novel α -shaped flue gas route 750 tones/day flame incinerator **a** Measuring locations **b** Variations in average flue gas temperature

the developed incinerator design. It is also noteworthy that the flue gas route reported by Liu et. al. [32] is α -shaped, but a careful examination of the local thermal characteristics, especially at location 7, indicate that it is, at best, partial α -route instead of a complete α -route. The reason for this is that Liu et. al. [33] modified the design of the arches but did not add secondary air supply into the incinerator design. Both these design modifications have been carried out in the present study, resulting in the formation of complete α -shaped flue gas route, higher temperature and enhanced combustion characteristics of the incinerator.

Local thermal quantitative analysis of the novel α -shaped flue gas route flame incinerator indicate that municipal waste fuel is not fully ignited at measuring location 1, and the temperature here should be around 200 °C, as observed in case of Liu. et. al. [33]. The reason that temperature at location 1 is 477 °C is due to the α -shaped flue gas route, resulting in higher temperature flue gas, which passes through the area under the front arch. The increase in temperature here is of considerable benefit to the smooth ignition of municipal waste fuel with low calorific value. The reason for higher temperature at measuring location 2 is that the waste fuel here has caught fire and burns completely.

Moreover, high temperature flue gas flows through this area, resulting in a sharp rise in temperature. Lower temperatures at measuring locations 3, 4, 5 are due to the fact that it is in the burn-out area of the incinerator and the waste fuel does not release significant heat. Temperatures at measuring locations 6, 7, 8 and 9 are very high because these locations are in strong combustion area and the fuel releases a considerable amount of heat.

It needs to be pointed out here that since the combustion-supporting air is hot (at 260 °C), although the fuel calorific value is low, the overall incinerator temperature is not low. It is not difficult to see from the results above that the temperature values in the annular area under the front arch and the uncovered area are higher than those in other areas, which means that an ideal α -shaped flue gas route is formed, which is consistent with the cold-state results. Thus, the novel α -shaped flue gas route flame incinerator is both effective and efficient in combusting municipal waste materials which have high water content and in which the combustion is relatively difficult to penetrate, especially in case of sewage sludge.

Significance of Novel α -Shaped Flame Incinerator

In the developed novel α -shaped flame Incinerator, the high speed (and high momentum) secondary air flow prolong the generation process of flue gas and fly ash, and change the position of the combustion center. When the secondary air arrangement is appropriate, a secondary air curtain can be formed in the furnace to lock in fly ash particles in the flue gas, which not only changes the ignition conditions of the fuel, but also further reduces the incomplete combustion losses in the furnace and improves the combustion efficiency of waste. In order to fully utilize the mixing effects of secondary air, it is essential that secondary air have a certain initial velocity (or penetration depth). However, when the incinerator is operating in a hot state, the temperature inside the furnace is very high. At this point, the viscosity of the flue gas increases considerably, making it difficult for the secondary air to penetrate. Therefore, the calculated penetration depth of the secondary air according to the traditional free jet attenuation formula does not match the actual situation, resulting in the secondary air not achieving the expected outcomes. The penetration depth of secondary air in the hot state is not only related to the speed but also the density and flow volume of the secondary air i.e. momentum flow rate of the secondary air. Higher the secondary air flow rate, greater the penetration. Moreover, it is also related to the ratio of the momentum flow rate of the secondary air to that of the rising flue gas on the grate surface. When this ratio increases, the mixing effects are enhanced. Reasonable

values of these two physical quantities can achieve the optimal secondary air flow effects however, the optimal value of these two physical quantities is a relatively complex problem. Therefore, one of the purposes of this study is to derive equations formulas based on the momentum design method, and use the calculation results to change the flow conditions and path of the airflow in the furnace. This results in changing the traditional L-shaped flow path to an α -shaped flow path, forcing the high-temperature airflow to form a large reflux under the front of the furnace, facilitating the ignition and combustion of low calorific value fuels.

Estimates show that the conventional incinerator generates 1.8 tons of steam for every 1 ton of municipal waste material. Integration of secondary air supply increases the steam generation to 1.9 tons. Thus, the combustion efficiency of the incinerator increases by approximately $(1.9 - 1.8) \div 1.8 = 5.56\%$. According to the elemental analysis of municipal domestic waste, the carbon content is about 20.41%, which in-turn means that the carbon content of 1 ton of waste is about $1000 \times 20.41\% = 204.1$ kg. Based on the molar mass ratio of CO_2 to carbon ($44 \div 12 = 3.67$), it can be calculated that the CO_2 content produced by 1 ton of waste is about $204.1 \times 3.67 = 749.05$ kg, while CO_2 emissions reduce by approximately $1364.14 \times 5.56\% = 41.95$ kg. At present, there is one 750 ton/day waste incineration mechanical grate furnace in the power plant. According to the annual operational time of 360 days, the annual waste disposal volume is about $750 \times 360 = 270,000$ tons/year, with a reduction in CO_2 emission of approximately $270,000 \times 41.95 = 11,326.5$ tons/year.

Contribution to the Field

In order to improve the combustion efficiency of solid waste with poor combustion performance and reduce pollutant emissions, a design method for waste incinerators, based on momentum flux theory, has been developed. Using this method, the conventional L-shaped flue gas route within the incinerators is transformed into an α -shaped route. This is achieved through the integration of secondary air supply, resulting in significantly improvement in the combustion efficiency of the waste incinerator and reduction in the emission of pollutants. Moreover, this study presents a novel design formula suitable for engineering calculations, which can easily improve the design of the secondary air supply to the waste incinerator without changing the furnace arches structure, and do not require the use of expensive numerical simulations. Thus, the developed methodology is a low-cost solution which can be easily implemented in large scale applications as well. The theoretical design methodology developed in this study provides important reference for the design of other types of waste incinerators.

Limitations of the Novel Incinerator

The novel α -shaped flame incinerator developed in this study is suitable primarily for solid waste materials which exhibit high ignition temperatures and low calorific values (ranging from 1500 to 2500 kcal/kg). The novel incinerator can fully burn such solid waste materials, maximizing their internal energy utilization, leading to improvement in waste incineration treatment efficiency. In general, the water content of sludge produced by sewage treatment plants is about 80%. After being treated by mechanical filtration, thermal drying and other methods, the water content decreases to about 25%, while wet sludge changes to dry sludge. The α -shaped waste incinerator developed in this study can also be fueled with waste mixture composed of municipal waste and some dry sludge. Considering the low calorific value of dry sludge, excessive mixing ratio will cause the temperature in the incinerator to drop, which will degrade combustion and thus, is not conducive to waste incineration. Therefore, the mixing ratio of sludge is about 15% maximum.

Conclusions

This study involves extensive research on incinerators fueled by municipal domestic waste and has found that an effective way to improve the combustion efficiency of waste is to transform the structure leading to the formation of an α -shaped flue gas route in the incinerator. Unlike traditional methods, based on the momentum flow rate method, the momentum vector synthesis theory is utilized to design and modify the secondary air supply which replaces the L-shaped flue gas route with an α -shaped path with enhanced combustion characteristics. The corresponding design model has been developed and verified through numerical simulations and hot testing of the incinerator, where the cold state numerical predictions confirm the formation of an α -shaped flue gas route, significantly increasing the residence time of the flue gas in the furnace arches area and ensure fuel burnout. Due to the α -shaped flow of flue gas, larger unburned fuel particles in the flue gas are redirected back onto the fuel layer by centrifugal force for further enhancing the combustion efficiency. Hot state experimental results on a full-scale incinerator indicate that the flue gas temperature in the throat area of the incinerator is significantly higher, leading to complete combustion of municipal solid waste, which significantly reduces carbon monoxide and dust emissions from the incinerator.

The α -shaped flue gas route incinerator developed in this study is more suitable for solid waste materials with high ignition point, poor combustion performance and excessive pollutant emissions. The novel waste incinerator has higher

incineration efficiency and lower pollutant emissions for such solid wastes. The limitation of the novel incinerator is that for solid waste with high calorific value and excellent combustion performance, it is unnecessary to use α -shaped waste incinerator because coking in furnace arch area may occur. Furthermore, the existing optimization of incinerator mainly focuses on improving the heat transfer efficiency by using various technical methods, such as increasing the radiant intensity of the flue gas in the furnace, reducing heat loss, adding waste heat recovery and utilization devices. Momentum flow rate based flame incinerator design methodology developed in this study takes into account the distribution of flue gas flow and the relationship between the secondary air supply and the geometric dimensions of the furnace arches, leading to significant improvement to existing incinerator designs.

Author Contributions XL: Conceptualization, Methodology, Validation, Writing—Original Draft, Supervision and Project administration. GZ: Conceptualization, Methodology, Validation, Formal analysis, Data Curation and Writing—Original Draft. TA: Methodology, Validation, Investigation and Writing—Review & Editing. RM: Investigation and Writing—Review & Editing.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data Availability The datasets generated during and/or analysed during the current study are not publicly available due to confidentiality but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ding, Y., Zhao, J., Liu, J.W., Zhou, J., Cheng, L., Zhao, J., Shao, Z., Iris, C., Pan, B., Li, X., Hu, Z.T.: A review of China's municipal solid waste (MSW) and comparison with international regions: management and technologies in treatment and resource utilization. *J. Clean. Prod.* **293**, 126144 (2021)
- NBSC (2021) China Statistical Year Book. National Bureau of Statistics of China. National Bureau of Statistics of China. <https://data.stats.gov.cn/easyquery.htm?cn=C01> (Accessed 6th Nov 2022)
- National Development and Reform Commission, Ministry of Housing and Municipal-Rural Development. The 14th Five Year Plan for the Development of Municipal Waste sorting and Treatment Facilities. https://www.gov.cn/zhengce/zhengceku/2021-05/14/content_5606349.htm (Accessed 6th May 2021)
- Yang, C., Yang, M., Yu, Q.: An analytical study on the resource recycling potentials of municipal and rural domestic waste in China. *Procedia Environ. Sci.* **16**, 25–33 (2012)
- Zhou, H., Wei, L., Wang, D., Zhang, W.: Environmental impacts and optimizing strategies of municipal sludge treatment and disposal routes in China based on life cycle analysis. *Environ. Int.* **166**, 107378 (2022)
- Wang, Z., Hong, C., Xing, Y., Li, Y., Feng, L., Jia, M.: Combustion behaviors and kinetics of sewage sludge blended with pulverized coal: with and without catalysts. *Waste Manage.* **74**, 288–296 (2018)
- Xiaoxin, Z., Jin, H., Ling, L., Sinan, Z.: Current status of technology and standards of domestic solid waste Incineration in China. In *IOP Conf. Series: Earth Environ. Sci.* **510**, 042035 (2020)
- Frey, H.H., Peters, B., Hunsinger, H., Vehlou, J.: Characterization of municipal solid waste combustion in a grate furnace. *Waste Manage.* **23**, 689–701 (2003)
- Luo, Z., Chen, W., Wang, Y., Cheng, Q., Yuan, X., Li, Z., Yang, J.: Numerical simulation of combustion and characteristics of fly ash and slag in a “V-type” waste incinerator. *Energies* **14**, 7518 (2021)
- Huai, X.L., Xu, W.L., Qu, Z.Y., Li, Z.G., Zhang, F.P., Xiang, G.M., Zhu, S.Y., Chen, G.: Numerical simulation of municipal solid waste combustion in a novel two-stage reciprocating incinerator. *Waste Manage.* **28**, 15–29 (2008)
- Department for Environment, Food and Rural Affairs (2022) UK statistics on waste. <https://www.gov.uk/government/statistics/uk-waste-data> (Accessed 5th December 2022)
- Yang, Y.B., Sharifi, V.N., Swithenbank, J.: Converting moving-grate incineration from combustion to gasification—Numerical simulation of the burning characteristics. *Waste Manage.* **27**, 645–655 (2007b)
- Yang, Y.B., Sharifi, V.N., Swithenbank, J.: Effect of air flow rate and fuel moisture on the burning behaviors of biomass and simulated municipal solid wastes in packed beds. *Fuel* **83**, 1553–1562 (2004)
- Yang, Y.B., Newman, R., Sharifi, V.N., Swithenbank, J., Ariss, J.: Mathematical modelling of straw combustion in a 38 MWe power plant furnace and effect of operating conditions. *Fuel* **86**, 129–142 (2007a)
- Swithenbank, J., Sharifi, V.N.: *Flame incinerator Grate Combustion Phenomena*. Renewable Energy Systems, Springer, New York (2013)
- Hu, Z., Jiang, E., Ma, X.: Numerical simulation on NO_x emissions in a municipal solid waste incinerator. *J. Clean. Prod.* **233**, 650–664 (2019)
- Yang, X., Liao, Y., Ma, X.: Effects of air supply optimization on NO_x reduction in a structurally modified municipal solid waste incinerator. *Appl. Therm. Eng.* **201**, 117706 (2022)
- Yan, M., Tian, X., Yu, C.: Influence of multi-temperature primary air on the characteristics of MSW combustion in a moving grate incinerator. *J. Environ. Chem. Eng.* **9**(6), 106690 (2021)
- Dan, Z., Che, Y., Wang, X.: Environmental, economic, and energy analysis of municipal solid waste incineration under anoxic environment in Tibet Plateau. *Environ. Res.* **216**, 114681 (2023)
- Jiang, M., Lai, A., Law, A.: Solid waste incineration modelling for advanced moving grate incinerators. *Sustainability* **12**(19), 8007 (2020)

21. Lin, H., Ma, X.: Simulation of co-incineration of sewage sludge with municipal solid waste in a grate furnace incinerator. *Waste Manage.* **32**, 561–567 (2012)
22. Yang, Y.B., Yamauchi, H., Nasserzadeh, V., Swithenbank, J.: Effects of fuel devolatilisation on the combustion of wood chips and incineration of simulated municipal solid wastes in a packed bed. *Fuel* **82**, 2205–2221 (2003)
23. Shin, D., Ryu, C.K., Choi, S.: Computational fluid dynamics evaluation of good combustion performance in waste incinerators. *J. Air Waste Manage. Assoc.* **48**, 345–351 (1998)
24. Xu, J., Liao, Y., Yu, Z., Cai, Z., Ma, X., Dai, M., Fang, S.: Co-combustion of paper sludge in a 750 tonnes/day waste flame incinerator and effect of sludge water content: a simulation study. *Fuel* **217**, 617–625 (2018)
25. Nasserzadeh, V., Swithenbank, J., Schofield, C., Scott, D.W., Loader, A., Leonard, A.: Design optimization of coventry municipal solid waste incinerator. *J. Environ. Eng.* **120**, 1615–1629 (2009)
26. Liu, X., Asim, T., Zhu, G., Mishra, R.: Theoretical and experimental investigations on the combustion characteristics of three components mixed municipal solid waste. *Fuel* **267**, 117183 (2020)
27. Liu, X., Zhu, G., Asim, T., Zhang, Y., Mishra, R.: The innovative design of air caps for improving the thermal efficiency of CFB boilers. *Energy* **221**, 119844 (2021)
28. Qian Z, Hao M, Li Z, and Qian H.: Reconstruction technology of high efficiency and energy saving α -Flame arch of boiler. *J. Energy Saving* 26-30 (1998)
29. Siddiqui, M., Khalid, H., Badar, A., Saeed, M., Asim, T.: Parametric analysis using CFD to study the impact of geometric and numerical modeling on the performance of a small-scale horizontal axis wind turbine. *Energies Special Issue Adv Wind Turbine Technol* **15**, 505 (2022)
30. Craig, M., Asim, T.: Numerical investigations on the propagation of fire in a railway carriage. *Energies* **13**, 4999 (2020)
31. Singh, D., Charlton, M., Asim, T., Mishra, R., Townsend, A., Blunt, L.: Quantification of additive manufacturing induced variations in the global and local performance characteristics of a complex multi-stage control valve trim. *Petrol. Sci. Eng.* **190**, 107053 (2020b)
32. Singh, D., Aliyu, A., Charlton, M., Mishra, R., Asim, T., Oliveira, A.: Local multiphase flow characteristics of a severe-service control valve. *Petrol. Sci. Eng.* **195**, 107557 (2020a)
33. Liu, X., Zhu, G., Asim, T., Mishra, R.: Application of momentum flux method for the design of an α -shaped flame incinerator fueled with two-component solid waste. *Energy* **248**, 123647 (2022)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.