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Application of momentum flux method for the design of an α-shaped flame incinerator fueled with two-component solid waste

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ABSTRACT

Kitchen waste and tree branches are two of the most common solid waste materials suitable for on-site disposal. Quantification of combustion characteristics of these waste materials is vital for designing an appropriate incinerator. In this paper, the combustion characteristics of a mixture of kitchen waste and tree branches have been analyzed. As the theoretical basis for the design of incinerator arches is severely limited in the published literature, a novel momentum flux methodology for designing α-shaped flame arches has been developed for the disposal and combustion of two-component solid waste. For this purpose, orthogonal experimental design methodology has been employed for eight different operating conditions of the incinerator. The theoretical results have been verified by cold-state experiments, resulting in the development of a novel small-scale, α-shaped flame incinerator fueled with kitchen waste and tree branches. Cold-state experimental results show that the optimum dimensionless structural parameters of the furnace arches are H_1/L of 0.3, H/L of 0.5 and h/L of 0.15, with the front arch angle of 45° and the rear arch angle of 12°. For full-scale validity and commercial viability of the novel incinerator, hot-state tests have been conducted in this study.

1. Introduction

The present study focuses on the combustion characteristics of kitchen waste and tree branches, with a view to design a novel incinerator for their disposal. The combustion characteristics of kitchen waste and tree branches dictate the air distribution mode and the furnace arch structure of the incinerator and thus, are closely related to the design of the incinerator. Accurate estimation of the combustion characteristics of kitchen waste and tree branches is essential for efficient design of waste incinerators.

1.1. Combustion characteristics of kitchen waste

Domestic waste can be divided into four main categories i.e. recycling waste, kitchen waste, hazardous waste and other waste [1]. Because of their decay and odor transmission characteristics, kitchen waste is a pollutant and the main source of foul odor [2]. Especially in south China, the high temperature and humidity accelerate the decay of food waste, which is even more pronounced during transportation, generating toxic pollutants to the environment [3]. Thus, there are centralized collection and local disposal mechanisms in-place for kitchen waste, having significant impact on ecological environment protection and sustainable economic development [4]. As the main components of kitchen waste are protein, animal fat, food fiber, starch and other organic substances, its calorific value is relatively high [5], which makes it suitable for resource utilization through incineration [6].

Several studies have been conducted to understand and quantify the combustion characteristics of kitchen waste. Saito et al. [7] conducted a detailed study on the combustion characteristics of balsa wood with high moisture content. It was found that the ignition started before the water was completely removed. The simultaneous vaporization of remaining water and devolatilization of volatile matter occurred during volatile matter combustion. The combustion rate of volatile matter was drastically reduced in proportion to the water content. It was found that moisture content remarkably affected the volatile matter combustion with a flame. Liu et al. [8] investigated the effects of microwave drying on the combustion characteristics of dried rice and vegetable leaves,

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Nomenclature

Aar	Ash Content (%)
Mar	Moisture Content (%)
Var	Volatile Content (%)
FCar	Fixed Carbon Content (%)
$Q_{net.v.ar}$	Low Heat Value of Coal (kJ/kg)
Car	Carbon Content (%)
Har	Hydrogen Content (%)
Sar	Sulfur Content (%)
Oar	Oxygen Content (%)
Nar	Nitrogen Content (%)
Clar	Chlorine Content (%)
DT	Differential Thermal
TGA	Thermogravimetric Analysis

Subscripts

y	average
A	Area (m^2)
E	Activation Energy (kJ/mol)
I	Momentum Flow Rate (kg m/s^3)
ω	Mass Fraction
α	Weight Loss (%)
B	Fuel Consumption (kg/s)
Q	Volumetric Flow Rate (m^3/s)
ρ	Density (kg/m^3)
K	Distribution factor of gas flow
v	Velocity (m/s)
α	Conversion (%)
g	Gravitational Acceleration (m/s^2)
o	initial

indicating that both are favorable fuels, with higher comprehensive combustion characteristics than other biomass types such as straw, sawdust etc. Zhou et al. [9] studied the combustion characteristics and kinetics of waste meat (WM), waste steamed bread (WSB), waste rice (WR) and waste vegetables (WV) using the non-isothermal thermogravimetric analysis (TGA). The order of ignition point was WV < WM < WR < WSB < coal. This clearly shows that the ignition characteristic of kitchen waste is much better than that of coal and thus, is suitable for incineration. Ming et al. [10] studied the thermal decomposition behavior, volatile release characteristics, and the pyrolytic product composition and distribution of two typical food waste components i.e. pork and rice, using TGA. According to the pyrolysis experiments, two different pyrolysis stages occurred both in pork and rice i.e. i) volatilization of moisture and ii) the main pyrolysis reaction. The activation energy values of pork were observed to be lower than those of rice. Liu et al. [11] used TGA to study the combustion characteristics of kitchen waste under different oxygen volume concentrations. It has been found that when the heating rate is 30 °C/min, the activation energy is 70.9 kJ/mol, which is lower than that of coal. It can thus be concluded that kitchen food waste has excellent combustion characteristics and is appropriate to be used for incineration.

1.2. Combustion characteristics of tree branches

A large amount of tree branches, which is a key component of garden waste, is discarded in China [12]. Tree branches are suitable for centralized on-site disposal [13], and because their calorific values are relatively high [14], it is more appropriate to use incineration method to dispose them and recover the heat value contained in them for power generation [12]. Xu et al. [15] investigated the combustion of sassafras wood (Sassafras Tzumu Hemsl) based on TGA under different heating conditions. Thermodynamic parameters, including Gibbs free energy, enthalpy, and entropy, were determined more precisely by activated complex theory. The combustion indices were found to be increasing notably at higher heating rates, indicating a more concentrated combustion zone and superior combustibility characteristics. Cai et al. [16] experimentally quantified the pyrolysis behavior of waste tea, indicating that maximum weight loss of waste tea occurs at the main stage of devolatilization, between 187 °C and 536.5 °C. A total of 33 organic compounds were identified. Kaa et al. [17] used asymptotic solution to conduct mathematical modeling of a multi-region premixed combustion of moist moso bamboo particles under adiabatic condition. The experimental validation using temperatures of homogeneous flame and heterogeneous reaction fronts confirm that the prediction accuracy is promising. The results show that increasing bamboo particle diameter leads to lower burning velocity, lower flame temperatures, and prolonged reaction fronts. Jianfei et al. [18] analyzed characteristics of lignin residues with different washing processes. The results show that washing processes change fuel properties of lignin samples. The ash content decreases and the volatile content increases during the washing process. Moreno et al. [19] studied the combustion processes of wood waste. The decomposition of the three main components of the wood (and also the combustion of the char) was obtained.

1.3. Combustion characteristics of mixed waste

Yuan et al. [20] investigated the fuel properties of compost of food waste and sawdust samples subjected to torrefaction at five different temperatures and a residence time of 30 min. It has been found that torrefaction has great impact on proximate and ultimate analyses, chlorine contents, energy and mass yields, grindability and combustion characteristics, indicating that grindability and combustion properties of the compost of food waste and sawdust (CFS) improve by torrefaction. Chen et al. [21] investigated co-pyrolysis characteristics of kitchen waste with tire waste. TGA results indicate that co-pyrolysis displays positive synergy in pyrolysis kinetics, especially at a ratio of 5:5, whose apparent activation energy declined by 16.78% (using Ozawa-Flynn wall method) and 17.54% (using Kissinger-Akahira-Sunose method). In brief, co-pyrolysis of kitchen and tire wastes could be a potential way for improving quality of pyrolysis oil. Liu et al. [22] investigated the combustion characteristics of Mixed Municipal Solid Waste (MMSW) composed of food bag, disposable chopstick and cotton cloth. Using TGA results, it has been reported that the activation energy of mixed solid waste is lower than for a single component solid waste. Liang et al. [23] investigated co-combustion characteristics of bamboo and wood. Compared with untreated biomass, torrefied biomass has been found to have a higher initial and burnout temperature. Results also indicate that torrefaction is helpful to promote co-combustion of bamboo and masson pine wastes. Mi et al. [24] investigated pyrolysis and combustion characteristics of bamboo and masson pine through TGA. Torrefied biomass had a higher pyrolysis and combustion temperature due to moisture, volatile removal and thermal decomposition of hemicelluloses. Torrefaction also increases high heating value, ash content and C/H and C/O ratio of biomass. In addition to TGA, micro combustion calorimeter measurements [25] is also an excellent method used to evaluate the combustion characteristics of mixed waste. However, there was a ready-made TGA equipment for analyzing combustion characteristics in factory. In order to improve efficiency and shorten the time in experiment, TGA equipment has been used in this paper. It is essential to understand and quantify the combustion characteristics of a mixture of kitchen waste and tree branches, with the aim to provide theoretical basis for design of corresponding incinerator.

1.4. Incinerator design for combustion of solid waste

The design of the grate incinerator primarily depends on the design of its flame arch/es. Choi et al. [26] modified the configuration of the secondary air nozzles of a commercial wood-waste grate incinerator based on the jet penetration factor and momentum flux, for reducing CO emissions. The Computational Fluid Dynamics (CFD) based analyses show that the retrofit made the flow in the secondary chamber more uniform, leading to a reduction in CO emissions. Zadravec et al. [27] investigated how different fuel-bed models, or grate inlet profiles, affect the combustion of freeboard in industrial grate boilers. It has been observed that the fuel-bed model (or grate inlet conditions), accounting for the realistic lengthwise biomass conversion pattern, can be used reliably for numerical simulation-based grate boiler optimization. Moreover, the impacts of different fuel-bed models and different profiles of the grate inlet conditions are virtually restricted only to the vicinity of the fuel-bed (or in the primary combustion chamber). Alobaid et al. [28] developed a dynamic process simulation model of a 60 MW municipal solid waste incinerator. The study describes in detail the flue gas path with its vertical and horizontal passes, including grate, primary and secondary combustion zones, as well as the auxiliary burners. Liu et al. [29] carried out experimental investigations on the uniformity of air flow in Circulating Fluidized Bed (CFB) boilers. Using novel air caps, with outlet ports having an angle of 60°, the flow inhomogeneity is reduced by 66%, increasing the thermal efficiency of the boiler by 5.4%. Waste incineration methods include fixed bed and fluidized bed. Asfar et al. [30,31] proposed circulating fluidized bed incineration technology. Circulating fluidized bed is a good waste incineration equipment with high efficiency. Because of its high cost, it is suitable for large-scale waste treatment plants, but this paper studies the small waste incineration equipment. Considering that the cost should not be too high, the grate incineration equipment is adopted.

1.5. Research rationale and significance

Based on the literature review carried out in the previous sections, it can be seen that detailed and systematic investigations need to be carried out in order to better understand the combustion characteristics of kitchen waste materials and tree branches, along with a mixture of both. It has also been noticed that TGA is the preferred choice for scientific investigations on the combustion characteristics of solid waste materials. Therefore, TGA is adopted in this study. The literature review also points out to the excessive use of numerical methods for the design of incinerators. There is a lack of strict theoretical guidelines for this. The main component of waste incinerator is furnace chamber, and the key features of the furnace chamber are its arches. In the present study, using the principles of combustion and aerodynamics, a momentum flux-based methodology has been developed for the design of arches. Therefore, α-shaped flame arches, suitable for the combustion of two-component waste composed of kitchen waste and tree branches, have been designed, providing a theoretical basis for the design of waste incinerators. Empirical formulation has been carried out using cold and hot-state tests that can guide the engineering design of the incinerators.

2. Combustion characterization of kitchen waste and tree branches

In this section of the study, a comprehensive methodology for the characterization of combustion for kitchen waste and tree branches is presented. In this section, thermogravimetric (TG) and Differential Thermal (DT) curves of the waste materials are obtained, and the corresponding combustion characteristic parameters are evaluated, which aid in the design of waste incinerator.

2.1. Experimental investigations on the combustion characteristics of single component kitchen waste and tree branches

The mixture of high moisture kitchen waste and tree branches is conventionally fed into the waste storage equipment before incineration, where it stays for 7–10 days for drying. Due to long drying time, the moisture content in the waste is fully removed, significantly improving its flammability. In the present study, the waste mixture has been dried using an electrical oven in order to shorten the drying duration. Temperature of the electrical oven is set to 105 °C and the sample is baked until sample weight is stable (~2 h). The waste mixture is then grounded into powder form and weighted separately (as single component wastes). These are then mixed evenly according to the proportion of two-component waste. The specific process of fuel processing is shown in Fig. 1. The combustion characteristics of fully dried mixture of kitchen waste and tree branches have been obtained using thermal-analysis instrument. Table 1 summarizes the industrial analysis results where it can be clearly seen that the moisture content of waste materials is very low and the calorific value is relatively high, which indicates that the incineration method is suitable for the disposal of kitchen waste and tree branches. It is noteworthy that because the internal water content of tree branches is higher than that of kitchen waste, the moisture content is slightly higher after full drying.

The TG (Thermogravimetric) and the DT (Differential Thermal) curves of kitchen waste and tree branches, drawn using LINSEIS TGA PT1600, are shown in Fig. 2. The TG analyzer used in the present study is efficient and quick in evaluating combustion characteristics of solid waste materials and was readily available to us in the factory. It can be seen that the combustion process of both the waste materials consists of two stages. Stage 1 is the Volatilization stage in which weight loss of protein, sugar and carbohydrate (for kitchen waste), and pyrolysis of cellulose and hemicellulose (for tree branches) occurs. During stage 1, for kitchen waste, the temperature remains between 40 °C and 430 °C and the weight loss is 85%, while for the tree branches, the temperature range is 160 °C–380 °C with 90% of weight loss. The rate of weight loss reaches 96%/°C at 350 °C for kitchen waste and 66%/°C at 310 °C for tree branches during this stage.

Stage 2 is the Decomposition of fixed carbon. During this stage, for kitchen waste, the temperature remains between 440 °C and 520 °C with 15% weight loss, while for tree branches, the

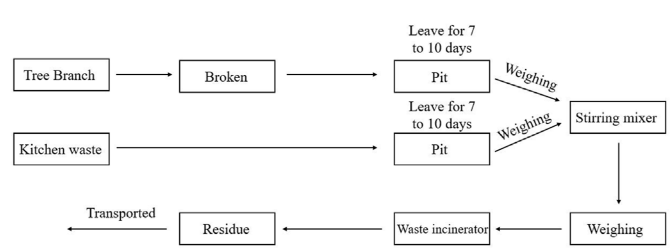

Fig. 1. Schematic of fuel processing.

Table 1
Industrial analysis of kitchen waste (%).

Components	Mar	Aar	Var	FCar	Low calorific value (LHV, MJ/kg)
Kitchen Waste	3.30	11.11	68.08	11.51	13.62
Tree Branches	6.17	1.18	73.22	19.43	18.396

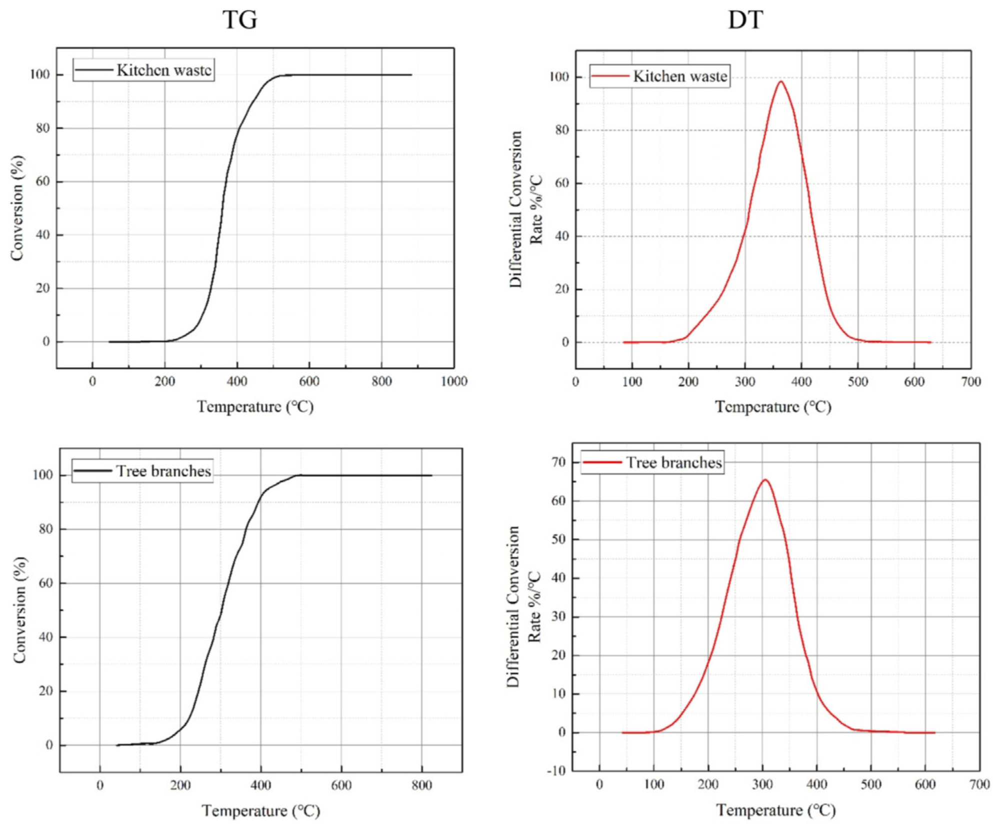

Fig. 2. Thermogravimetric and Differential Thermal curves of kitchen waste and tree branches.

temperature remains between 380 °C and 500 °C with 10% weight loss. Thus, the weight loss is significantly lower in stage 2 compared to stage 1. For both the waste materials, it can be noticed that the combustion is primarily volatile (accounting for more than 85% for kitchen waste and 90% for tree branches). Based on these results, the values of activation energy and frequency factor can be obtained. The detailed calculation process for activation energy and frequency factor can be found in the literature [32–34]. The results obtained indicate that Activation Energy (E) and Frequency Factor (k_0) values for kitchen waste are 58.82 kJ/mol and 4.51×10^4 s^{-1}, and for tree branches are 62.7 kJ/mol and 1.51×10^3 s^{-1} respectively.

2.2. Combustion characteristics of a mixture of kitchen waste and tree branches

Apart from the quantifying the combustion characteristics of single component solid wastes i.e. kitchen waste and tree branches, it is important to understand and analyze the combustion characteristics of mixture of these two waste materials (two-component solid waste). The process adopted here for analyzing the combustion characteristics of the mixture waste is the same as in previous section (for single component wastes. The Thermogravimetric (TG) and Differential Thermal (DT) curves of the mixed waste materials are shown in Fig. 3. It can be noticed that the main component is still the volatile matter. Weight loss is 90% in the Volatilization stage, which is between 150 °C and 420 °C. Temperature corresponding to the highest conversion rate is around 310 °C, indicating that the combustion characteristics of mixed waste (kitchen waste and tree branch) are biased towards low-fire point waste components. The activation energy (E) and frequency factor (k_0) of the mixture solid waste have been computed to be 54 kJ/mol and 9980 s^{-1} respectively (see Fig. 4).

3. Design of a novel α-shaped flame incinerator for the combustion of two component solid waste

After quantifying the combustion characteristics of kitchen waste, tree branches and a mixture of both, this section presents the details regarding the design and testing of a novel incinerator in order to burn the said waste materials. The two most common types of solid waste incinerators are L-shaped and α-shaped flame reciprocating grate incinerators, shown in 4. It can be seen that the structures of the two waste incinerators are significantly different, as well as the combustion characteristics of the fuels to be burned. Waste incinerator with L-shaped flame is used for burning scorn stalk, while kitchen waste and tree branch are more suitable for burning in α-shaped flame/arc waste incinerator as the moisture content of these waste materials is high. Therefore, α-shaped flame/arc waste incinerator produces significant backflow of high-temperature flue gas under front arch, which has a preheating effect on the waste just entering the furnace and is conducive to the ignition and combustion of the waste. Hence, in this paper, the

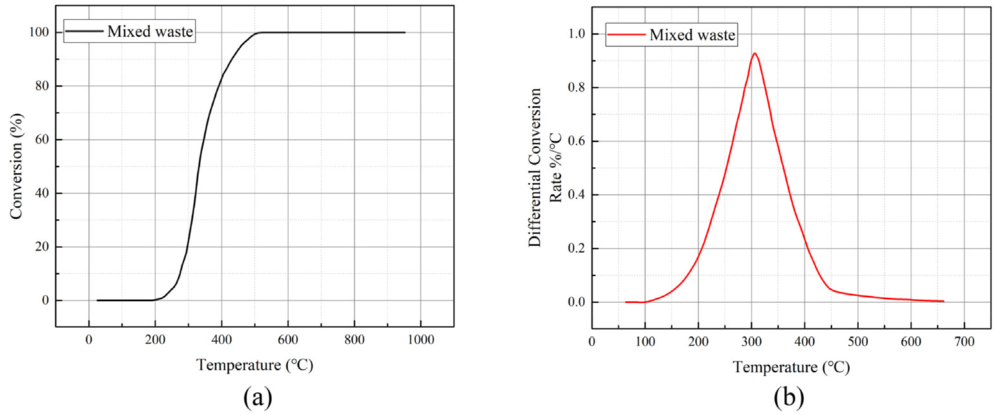

Fig. 3. Combustion curves for the mixture of kitchen waste and tree branches experiments (a) TG curves (b) DT curves.

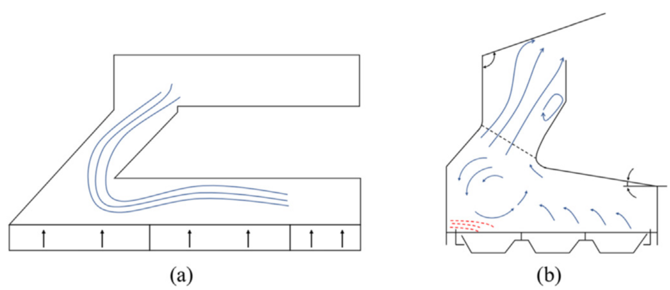

Fig. 4. Solid waste grate incinerators (a) L-shaped flame (b) α-shaped flame.

incinerator under consideration is an α-flame shaped reciprocating horizontal grate incinerator, which is commonly used in China for municipal waste disposal.

This section is divided into three sub-sections i.e. the design considerations for the incinerator, design development based on flue gas momentum flux and finally the extensive testing that will be carried out to analyze incinerator's performance.

3.1. Design considerations for the incinerator

The sketch of an α-shaped flame reciprocating horizontal grate incinerator is shown in Fig. 5(a). The name α-shape basically represents the structure of its flame, resulting from a large range of backflow in the front of the furnace chamber, prolonging the residence time of high-temperature flue gas and facilitating the ignition and burnout of waste materials. The formation of α-shaped flame depends on the selection of arches' structural parameters. At present, selection of arches' structural parameters is primarily based on design experience, lacking theoretical guidance. In the present study, it is envisaged that a novel incinerator will be developed, based on flue gas momentum flux, which can provide a theoretical basis for the design of the furnace chamber, but before that, the design criteria for a conventional α-shaped incinerator needs to be identified. The main structural parameters of the furnace chamber are shown in Fig. 5(b), where L is the length of grate and b is its width. As the size of the incinerator is small, the length of grate is 2000 mm. The key design aspects of this incinerator are:

1. *Projection length of rear arch:* should be long enough, ensuring stable combustion of waste fuel. According to design experience, the projection length of rear arch on the grate considered here is 0.7 L.
2. *Projection length of front arch:* significantly affects the radiant area of the front arch. Because of the limited volume of waste incinerator, sufficient throat area must be maintained for smooth outflow of flue gas. Therefore, the projection length of front arch on the grate considered here is 0.16 L.
3. *Angle of front arch (α):* not only affects the area covered by the front arch, but also affects the geometrical dimensions of the throat. In order to ensure smooth outflow of high-temperature flue gas, α of 45° and 60° have been chosen (based on the experience) for further analyses [35].
4. *Height of front wall (H_1):* has considerable effects on the radiant area of the front arch and helps determine whether there is

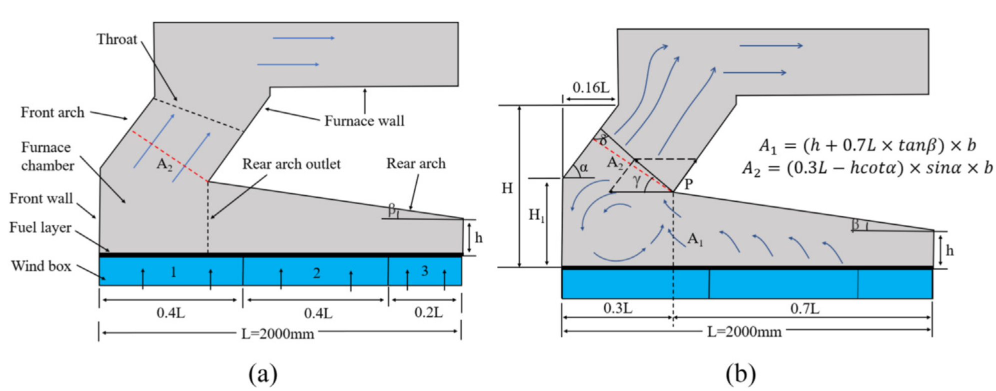

Fig. 5. Structural parameters of the furnace chamber.

enough space below the front arch that can cause high-temperature flue gas to flow back and form an α-shaped flame, while avoiding gas blockage. In the present study, H_1 of 300 mm and 600 mm have been considered (based on the experience) for experiments.

5. *Height of rear arch (h):* determines whether the incinerator has enough space for slag discharge. For the experiments, h values of 200 mm and 300 mm have been considered, based on the experience.
6. *Combustion air supply mode:* Appropriate furnace arch structure, combined with corresponding combustion air supply mode, plays an important role in the design of waste incinerators. As shown in Fig. 5(a), three wind boxes are installed (numbered 1, 2 and 3 respectively) below the grate to provide multi-stage combustion air [36]. It is not necessary to supply a large amount of air in the ignition and burnout stages, because fuel is preheated by the high temperature flame radiation in the furnace, and the fixed carbon content in kitchen waste or tree branches is relatively small according to the TGA curve (Fig. 3). It is necessary to supply a large air volume (70–80% of total) in volatilization stage because weight loss is 90% according to the TGA curve (Fig. 3). Therefore, the proportion of combustion-supporting air supplied by the three wind boxes is selected as 15%, 70%, 15% and 5%, 80%, 15% respectively.
7. *Thickness of the fuel layer:* The amount of waste material entering the incinerator varies with the thickness of the fuel layer on the grate. Therefore, the combustion chamber of the incinerator with reciprocating horizontal grate should be designed to have a wide range of load adjustment. Due to the high moisture content and low calorific value of waste, in order to maintain the stability of combustion, the fuel layer needs a certain thickness. It is noteworthy that the thickness of the fuel layer should not be very high, which can potentially affect the supply of combustion-supporting air. Thus, the thicknesses of the waste layer specified in the present study are 375 mm and 500 mm respectively.
8. *Angle of rear arch (β):* ensures high velocity ejection of high-temperature flue gas from the rear arch into the domain under the front arch, forming the ideal α-shaped flame. In this study, β values of 6° and 12° have been considered for experiments [35].

The composition of the waste fuels (kitchen waste, tree branches and mixture of both) has been summarized in Table 2. The subscript ar denotes the application base and $Q_{net.\ v.ar}$ means low calorific value of fuel, where the mixing ratio is 5:1 as mentioned earlier.

3.2. Design development of a novel α-shaped flame incinerator

Theoretical design of an α-shaped flame reciprocating horizontal grate incinerator has been developed here, based on momentum flux method, which is derived from the principles of hydrodynamics and combustion aerodynamics. The gas flow in the furnace is relatively complex, especially in the rear arch outlet (A_1), the plane passing through point P as well as perpendicular to the front arch (A_2) and the furnace chamber area under the front arch, as shown in Fig. 5(b). The flow at the rear arch outlet A_1 comprises of updraft and backflow of air. The outlet velocity of the flue gas from the rear arch at point P is calculated using the average velocity at rear arch's outlet section A_1 ($v_1 = Q_1/A_1$). Similarly, the flue gas flow velocity direction from the front arch at point P is parallel to the front arch, with an average flow velocity of $v_2 = Q_2/A_2$. The point P is the intersection between the momentum flow rate of the fluid in the rear arch (I_1) and the momentum flow rate of the updraft in the front arch (I_2). It is assumed that the distribution of the main updraft along the width of the grate (normal to Fig. 5) is uniform and thus, can be considered as a one-dimensional flow field. It should be noted that the directions of I_1 and I_2 are parallel to the rear and front arches respectively.

It is evident from Fig. 5(b) that the direction of flue gas flow in the front arch region comprises of two components i.e. horizontal (from the rear arch) and vertical (towards the throat), giving rise to the backflow. This mixed flow velocity behavior must be accounted for in the design of the incinerator. Thus, the modified volumetric flow rates (Q; m^3/s) of the flue gas at sections A_1 and A_2 (m^2) can be defined as [37]:

$$Q_1 = (1-2K)(V_y \times B_j) \tag{1}$$

$$Q_2 = 2K(V_y \times B_j) \tag{2}$$

where K is the distribution factor of gas flow (K = 0.3), Vy is the volume of flue gas per kilogram of waste combustion (m^3/kg) and B_j is the fuel consumption (kg/s). The flue gas velocity at the rear arch outlet (v_1; m/s) needs to be compensated for increase in the flue gas temperature, and thus, can be computed as:

$$v_1 = \frac{Q_1}{A_1} = \frac{(1-2K)(V_y \times B_j)}{b \times (h + 0.7L \times \tan g\ \beta)} \times \frac{273 + T_y}{273} \tag{3}$$

w here b is the width (m) of the grate, h is height (m) of rear arch and T_y is average temperature (K) of the flue gas. For the momentum flow rate of the flue gas from the rear arch I_1 (N):

$$I_1 = \int_{A_1} (\rho v)\ v\ dA = \rho_y\ v_1\ Q_1 \tag{4}$$

Here:

$$\rho_y = \rho_0 \times \frac{273}{273 + T_y} \tag{5}$$

where ρ_y is actual density of flue gas (kg/m^3) and ρ_o is its density under NTP conditions. For temperature-compensated upward flue gas velocity under front arch (v_2):

$$v_2 = \frac{Q_2}{A_2} = \frac{(2K)(V_y \times B_j)}{b \times (0.3L - h \cot \alpha) \sin \alpha} \times \frac{273 + T_y}{273} \tag{6}$$

For momentum flow rate (kg m/s^3) of upward flue gas under front arch:

$$I_2 = \int_{A_2} (\rho v)\ v\ dA = \rho_y\ v_2\ Q_2 \tag{7}$$

Here, I_2 is divided into two parts:

Table 2
Compositions of waste fuels.

Parameters	Kitchen waste	Tree branches	Mixed waste
$Q_{net.v.ar}$ (kJ/kg)	4120	7535	4689.17
C_{ar} (%)	12.35	20.60	13.73
H_{ar} (%)	1.95	3.20	2.16
S_{ar} (%)	0.34	0.60	0.38
O_{ar} (%)	9.45	14.60	10.31
N_{ar} (%)	0.42	0.50	0.43
Cl_{ar} (%)	0.2	0.34	0.22
A_{ar} (%)	26.09	22.76	25.54
M_{ar} (%)	49.2	37.40	47.23

$$I_{2x} = I_2 \cos\alpha \tag{8}$$

And:

$$I_{2y} = I_2 \sin\alpha \tag{9}$$

where I_{2x} is the horizontal component and I_{2y} is the vertical component of I_2. Momentum flow rate in horizontal (X) direction is $I_x = I_1 - I_{2x}$ and in vertical (Y) direction is $I_y = I_{2y}$. Thus, total momentum flow rate (I) can be computed as:

$$I = \sqrt{I_x^2 + I_y^2} \tag{10}$$

And the momentum direction angle (γ) can be defined as:

$$\gamma = \tan^{-1} \frac{I_y}{I_x} \tag{11}$$

According to Ref. [35], in order to form an ideal α-shaped flame, $\delta > 110°$, as shown in Fig. 5(b). It should be noted that $\alpha + \gamma + \delta = 180°$.

3.3. Experimental modelling of the novel α-shaped flame incinerator

In order to carry out extensive testing of the novel α-shaped flame incinerator, its design conditions need to be identified. Table 3 summarizes the values of different parameters used during the experiments for the incinerator. These values have been obtained through the principle of orthogonal experiments [38]. Orthogonal experiments are an effective alternative to full factorial design of experiments [39,40], keeping the cost of experimentation in check. The eight-factor (design parameters), two-level (values) based experimental methodology has been adopted in the present study.

Before moving on to the experimental testing of the incinerator, the design conditions provided in Table 3 have been used to compute the values of different parameters of the incinerator, using the theoretical method presented in section 3.2. These results have been summarized in Table 4. It can be noticed that out of the total 8 operating conditions considered (in Table 3), the first 6 meet the condition for the formation of α-shaped flame, as the value of $\delta > 110°$ for these conditions. Moreover, based on previous design experience (non-theoretical), it is known that the height of the front wall (H_1) and the inclination angle of the rear arch (β) should be as large as possible. The higher H_1 value can ensure the transfer of sufficient radiant heat to the new fuel layer, and a larger β angle is conducive to the smooth flow of flue gas out of the rear arch area, preventing gas blockage. Based on the operating conditions in Table 3 and the corresponding results in Table 4, the conditions that meet these criteria are 3 and 4.

Table 4
Theoretical results for the α-shaped flame incinerator.

Name	Con 1	Con 2	Con 3	Con 4	Con 5	Con 6	Con 7	Con 8
Q_1 (m^3/h)	1620	1757	2160	2342	1757	1620	2342	2160
Q_2 (m^3/h)	102	34	136	45	34	102	45	136
A_1 (m^2)	0.06	0.07	0.16	0.17	0.06	0.07	0.16	0.17
A_2 (m^2)	0.15	0.15	0.15	0.15	0.18	0.18	0.18	0.18
ω_1 (m/s)	8.04	6.97	3.75	3.74	8.72	6.43	4.06	3.45
ω_2 (m/s)	0.19	0.06	0.26	0.09	0.05	0.16	0.07	0.21
I_1 (N)	16,804	15,812	10,440	11,292	19,765	13,443	12,279	9601
I_2 (N)	25.5	2.8	45.2	5.0	2.3	20.8	4.1	36.9
I_x (N)	16,786	15,810	10,180	11,042	19,764	13,433	12,009	9373
I_y (N)	18	2	2202	2351	2	18	2556	2028
α (°)	45	45	45	45	60	60	60	60
δ (°)	134	134	122	122	120	120	108	108

3.3.1. Cold-state experimental setup

After identifying the suitable operating conditions for the α-shaped flame incinerator (conditions 3 and 4), cold-state experiments (isothermal) have been performed under both these conditions in order to find out the optimal conditions for the incineration process. The main purpose of conducting cold-state experiments is to quantify the flow field of flue gas in the furnace as it is very difficult to do this in hot-state experiments. The cold-state experimental setup developed for this purpose is shown in Fig. 6. The cold-state experimental setup is made of perspex and stainless steel, with a grate area of 2.0 m × 0.35 m = 0.7 m^2. The resistance between the grate and the fuel bed is simulated using steel meshes, as in Refs. [41,42]. A positive pressure allows cold air to enter the wind boxes in the test model. At the beginning, cold air enters wind boxes, below the grate, through the flow control valve, and then enters the furnace chamber. The 9 specific location where the data has been recorded are numbered in Fig. 6 as N0, N1, N2, …etc. Hot wire anemometers are used to obtain the flow velocity data at each measuring point; the least count of anemometers is 0.01 m/s. The

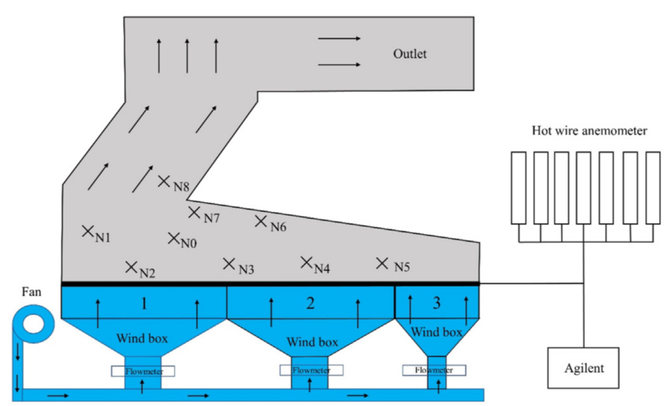

Fig. 6. Cold test setup.

Table 3
Design of experiments for the incinerator.

Con	α (°)	β (°)	H_1 (mm)	h (mm)	Air supply mode	Thickness of Waste layer (mm)	Chain Speed (m/h)	Flue Gas Volume (m^3/h)
1	45	6	300	200	5%, 80%, 15%	375	1.5	913
2	45	6	300	300	15%, 70%, 15%	375	2	913
3	45	12	600	200	5%, 80%, 15%	500	2	1217
4	45	12	600	300	15%, 70%, 15%	500	1.5	1217
5	60	6	600	200	15%, 70%, 15%	375	1.5	913
6	60	6	600	300	5%, 80%, 15%	375	2	913
7	60	12	300	200	15%, 70%, 15%	500	2	1217
8	60	12	300	300	5%, 80%, 15%	500	1.5	1217

temperature and pressure of the cold air are maintained at 20 °C and 1500 Pa,g respectively.

3.3.2. Hot-state experimental setup

In order to further ascertain the effectiveness of the novel α-shaped flame incinerator developed in this study, hot-state experiment has been carried out to measure the temperature distribution in the furnace chamber of the incinerator. Fig. 7 depicts the sketch of the hot-state experimental setup developed for this purpose. The hot-state experimental setup is a small-scale layer-burning grate incinerator whose daily disposal of corn stalk is about 10 tons. The length and width of the grate is 2.0 m and 0.35 m respectively (same as for cold-state setup). Hot test has been conducted on the optimal operating conditions identified through cold testing. Temperature readings have been obtained, using thermocouples, at the same points as in case of cold tests (see Fig. 6), where the least count of thermocouples used is 0.1 K. The thermocouples are connected to the DAQ Agilent 34970 A, recording data every 5 min. It is noteworthy that the mixed waste, comprising of kitchen waste and tree branches, has been used in hot-state experiment.

4. Results and discussions

This section presented the results obtained from i) cold-state experiments on conditions 3 and 4 and ii) hot-state experiment on the optimal operating condition based on the results of cold-state experiments.

4.1. Cold test results

Cold-state experiments should be carried out in a self-modeled region, which means that the Reynolds number of the flue gas (Re_{out}) should be higher than critical Reynolds number (Re_{cr}), where $Re_{cr} = 1.5 \times 10^4$. This further implies that the cold testing results are independent of the size of the model [43]. The equivalent diameter of the rear arch's outlet is chosen as the characteristic length for the calculation of the Reynolds number [35]. Thus, Re_{out} for operating condition 3 has been found to be 4.0×10^4, while for operating condition 4 Re_{out} is 4.43×10^4. As both Re_{out} values are > Re_{cr}, cold-state testing has been carried out within the range of the self-modeled zone.

Fig. 8 depicts the velocity vectors of the flue gas within the furnace chamber, at the 9 data measurement points discussed earlier. Analyzing the flow velocity data is critical for understanding the aerodynamic behavior of the flue gas within the furnace chamber (especially under the front and rear arches), and for developing better strategies for supply of combustion-supporting air, through the performance analysis of the arches. In Fig. 8, for both the operating conditions considered, the formation of α-shaped flow field is evident under the front arch. The flow velocity at N1, N2 and N0 for operating condition 3 is 0.77 m/s, 0.25 m/s and 0.58 m/s respectively. For operating condition 4, it can be seen that the flow velocity is significantly higher than for operating condition at the same measurement points; higher by 14.3%, 84% and 63.8% respectively. Thus, the strength/formation of the α-shaped flow field under the front arch is more pronounced under operating condition 4, which is more conducive for solid waste combustion. For measurement points N3, N4 and N5, the flue gas velocity is higher for operating condition 3 compared to 4 (by 10%, 26.6% and 10% respectively). Same is the case for points N6, N7 and N8. The flue gas velocity in operating condition 4 is higher only in the α-shaped flame region compared to operating condition 3 (which is

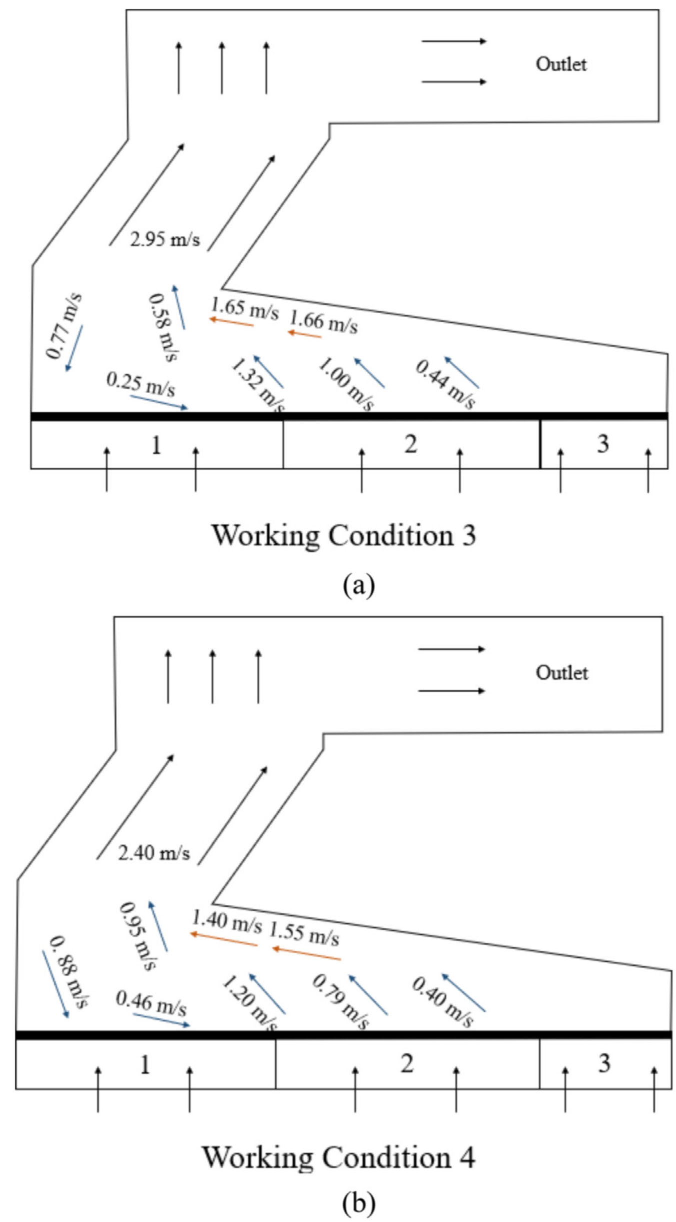

Fig. 8. Velocity vectors obtained from cold-state testing of the α-shaped flame incinerator for (a) condition 3 (b) condition 4.

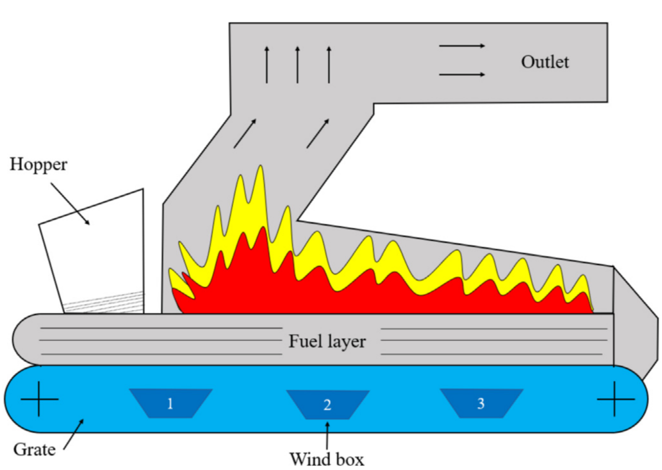

Fig. 7. Sketch of the hot-state experimental setup.

beneficial for drying of high moisture content waste fuel), but elsewhere, it is lower. Therefore, operating condition 4 is more favorable for two-component solid waste combustion.

4.2. Hot test results

For hot-state experiment, operation condition 4, identified as optimal through cold-state testing, has been used. Hot-state testing has been carried out in order to get flue gas temperature values at measuring points N0–N8. As the primary focus of the present study is the combustion of two-component solid waste, hot testing is essential for the practical validation and commercial viability of the novel α-shaped flame incinerator developed. This part mainly studies temperature distribution of the incinerator combustion chamber. Temperature distribution is shown in Fig. 9. It can be seen that the highest temperature is recorded at location N6, which is located under the rear arch, in the intense combustion region of the furnace chamber. Minimum temperature has been recorded at N2, which is expected as this location is the drying areas and very close to new fuel surface. The general trend of temperature distribution, along the length of the grate, is from low (N5) to high (N3) and then to low (N2). It is also noteworthy that temperature of flue gas is 893 °C at N6, reducing to 810 °C at N7 before increasing to 832 °C at N8. The reason for temperature drop at N7 is that it is located below the rear arch (at its exit), where the low-temperature flue gas from the region under the front arch and the high-temperature flue gas from the area under the rear arch are mixed together. The reason for N8 to have lower temperature than N6 is that N8 lies just below the front arch, where the flue gas is used to dry the waste first, and then it is mixed with high-temperature flue gas from the intense combustion zone. Therefore, the temperature at N8 is lower than at N6.

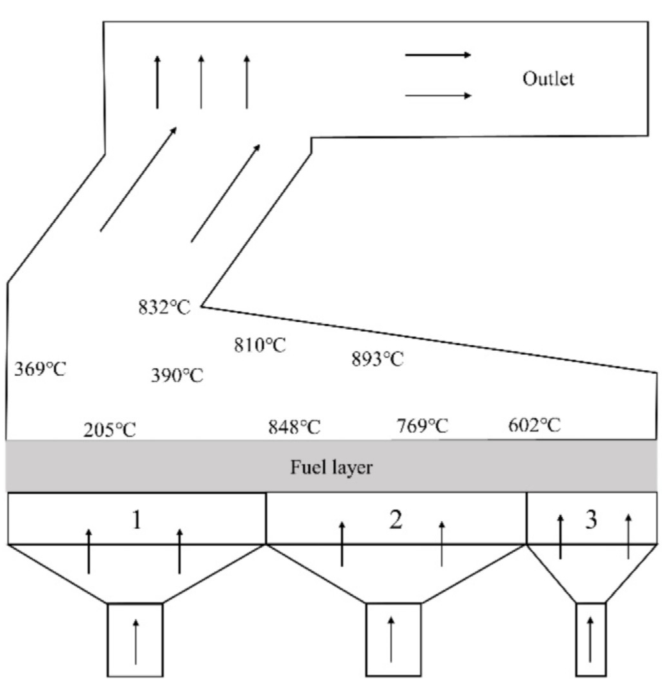

Fig. 9. Variations in flue gas temperature within the combustion chamber of the α-shaped flame incinerator.

The hot-state testing for operating condition 4 provides desired results for effective combustion of two-component solid waste. The temperature in the strong combustion region (N3, N4, N6 and N7) is highest within the chamber (800–900 °C), which is advantageous for stable combustion of mixture of kitchen waste and tree branches. The temperature in the burnout area (N5) reaches 600 °C, which is adequate for burnout of mixed waste. In the drying area (N0–N2), the temperature range is 200–400 °C, which is ideal temperature for α-shaped flame. Thus, the novel α-shaped flame reciprocating horizontal grate incinerator developed in the present study burns two-component solid waste materials effectively.

In order to further verify the waste treatment by the incinerator, the disposal rate of waste from the incinerator is calculated. Disposal rate of waste can be defined as:

$$\text{Disposal rate of waste} = \left|\frac{\text{Waste quality}_{\text{before incineration}} - \text{Waste quality}_{\text{after incineration}}}{\text{Waste quality}_{\text{before incineration}}}\right| \tag{12}$$

where the waste quality refers to the weight of waste, measured on a scale during the experiments. The hot-state experimental results show that the disposal rate of mixed waste (kitchen waste and tree branches), under operating condition 4, is about 75%, which clearly shows the effectiveness for mixed waste's volume reduction, verifying the rationality of the design of the incinerator.

5. Conclusions

Thermogravimetric and Differential Thermal curves of two-component kitchen waste have been obtained through TGA method. Based on the combustion characteristics of kitchen waste, tree branches and their mixture, a novel incinerator has been designed for stable and effective combustion of the solid waste. The incinerator has been designed based on the momentum flux of the flue gas in the furnace chamber. The designed incinerator has an α-shaped flame and a reciprocating horizontal grate. A practical range of operating conditions for the novel incinerator have been carried out using cold testing first, which has resulted in the identification of optimal operating conditions for the α-shaped flame incinerator. Hot testing has been carried out on these operating conditions.

Based on the results obtained in the present study, it can be concluded that the DT curve of the two-component solid waste depict a distinct peak, indicating that the combustion of waste depends primarily on the volatiles and thus, can be regarded as a gas phase combustion. The kinetic parameters such as activation energy and frequency factor of mixed waste are obtained, which informs the design of waste incinerator. The cold-state experimental results depict that effective aerodynamic performance of the flue gas can be achieved in the furnace chamber when the dimensionless parameters of the arches are $H_1/L = 0.3$, $H/L = 0.5$, $h/L = 0.15$, with the front arch angle of 45° and the rear arch angle of 12°. The optimum air supply ratio for controlling the airflow from the rear arch are 15%, 70% and 15% respectively for wind boxes 1, 2 and 3. The hot-state experimental results show that an α-shaped flame is formed under the front arch under the optimum operating conditions. The disposal rate of the mixed solid waste has been computed to be about 75%, demonstrating effective and stable combustion of the two-component solid waste in the novel α-shaped flame incinerator.

Credit author statement

Xiaozhou Liu: Conceptualization, Methodology, Validation, Writing – original draft, Supervision and Project administration. **Guangyu Zhu**: Conceptualization, Methodology, Validation, Formal analysis, Data curation and Writing - Original Draft. **Taimoor Asim**: Validation, Investigation and Writing - Review & Editing. **Rakesh Mishra**: Investigation and Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Peng H, Shen N, Ying H, Wang Q. Factor analysis and policy simulation of domestic waste classification behavior based on a multiagent study—taking Shanghai's garbage classification as an example. Environ Impact Assess Rev 2021;(89):106598.
[2] Wang H, Xu J, Sheng L. Study on the comprehensive utilization of city kitchen waste as a resource in China. Energy 2019;173:263–77.
[3] Li Y, Jin Y, Li J, Chen Y, Gong Y, Li Y, Zhang J. Current situation and development of kitchen waste treatment in China. Procedia Environmental Sciences 2016;31:40–9.
[4] Huang C, Liu S, Hsu N. Understanding global food surplus and food waste to tackle economic and environmental sustainability. Sustainability 2020;(12):2892.
[5] Ravindran R, Jaiswal A. Exploitation of food industry waste for high-value products. Trends Biotechnol 2015;34:58–69.
[6] Pham T, Kaushik R, Parshetti G, Mahmood R, Balasubramanian R. Food waste-to-energy conversion technologies: current status and future directions. Waste Manag 2015;38:399–408.
[7] Saito M, Amagai K, Ogiwara G, Arai M. Combustion characteristics of waste material containing high moisture. Fuel 2001;(80):1201–9.
[8] Liu H, Jiaqiang EMa X, Xie C. Influence of microwave drying on the combustion characteristics of food waste. Dry Technol 2016;(34):1397–405.
[9] Zhou D, Wei R, Long H, Li J, Qi L, Xu C. Combustion characteristics and kinetics of different food solid wastes treatment by blast furnace. Renew Energy 2020;145:530–41.
[10] Ming X, Xu F, Jiang Y, Zong P, Wang B, Li J, Qiao Y, Tian Y. Thermal degradation of food waste by TG-FTIR and Py-GC/MS: pyrolysis behaviors, products, kinetic and thermodynamic analysis. J Clean Prod 2020;244:118713.
[11] Liu L, Li H, Chen M, Wu H, Ou F. Study on combustion characteristics and kinetics of kitchen waste for degreased under different oxygen concentrations. Chinese Journal of Environmental Engineering 2015;9:929–33.
[12] Shi Y, Ge Y, Chang J, Shao H, Tang Y. Garden waste biomass for renewable and sustainable energy production in China: potential, challenges and development. Renew Sustain Energy Rev 2013;(22):432–7.
[13] Eades P, Kusch-Brandt S, Heaven S, Banks C. Estimating the generation of garden waste in England and the differences between rural and urban areas. Resources 2020;9:8.
[14] Ozcan H, Guvenc S, Guvenc L, Demir G. Municipal solid waste characterization according to different income levels: a case study. Sustainability 2016;(8):1044.
[15] Xu L, Li S, Sun W, Ma X, Cao S. Combustion behaviors and characteristic parameters determination of sassafras wood under different heating conditions. Energy 2020;(203):117831.
[16] Cai H, Liu J, Xie W, Kuo J, Buyukada M, Evrendilek F. Pyrolytic kinetics, reaction mechanisms and products of waste tea via TG-FTIR and Py-GC/MS. Energy Convers Manag 2019;184:436–47.
[17] Kaabinejadian A, Maghsoudi P, Homayounpour M, Sadeghi S, Bidabadi M, Xu F. Mathematical modeling of multi-region premixed combustion of moist bamboo particles. Renew Energy 2020;162:1618–28.
[18] Jianfei Y, Zixing F, Liangmeng N, Qi G, Zhijia L. Combustion characteristics of bamboo lignin from kraft pulping: influence of washing process. Renew Energy 2020;162:525–34.
[19] Moreno A, Font R, Conesa J. Combustion of furniture wood waste and solid wood: kinetic study and evolution of pollutants. Fuel 2017;(192):169–77.
[20] Yuan H, Yang Q, Wang Y, Gu J, He M, Sun F. Impact of torrefaction on the fuel properties and combustion characteristics of compost of food waste and sawdust. Energy Fuels 2018;32:3469–76.
[21] Chen J, Ma X, Yu Z, Deng T, Chen X, Chen L, Dai M. A study on catalytic co-pyrolysis of kitchen waste with tire waste over ZSM-5 using TG-FTIR and Py-GC/MS. Bioresour Technol 2019;(289):121585.
[22] Liu X, Asim T, Zhu G, Mishra R. Theoretical and experimental investigations on the combustion characteristics of three components mixed municipal solid waste. Fuel 2020;267:117183.
[23] Liang F, Wang R, Jiang C, Yang X, Zhang T, Hu W, Mi B, Liu Z. Investigating co-combustion characteristics of bamboo and wood. Bioresour Technol 2017;(243):556–65.
[24] Mi B, Liu Z, Hu W, Wei P, Jiang Z, Fei B. Investigating pyrolysis and combustion characteristics of torrefied bamboo, torrefied wood and their blends. Bioresour Technol 2016;(209):50–5.
[25] Lyon R, Walters R, Stoliarov S. Screening flame retardants for plastics using microscale combustion calorimetry. Polym Eng Sci 2007;47:1501–10.
[26] Choi C, Choi W, Choi J, Kim W, Shin D. Reducing CO emissions through a secondary air nozzle retrofit based on the jet penetration factor and the momentum flux ratio of a commercial wood waste incinerator. Appl Therm Eng 2017;118:101–12.
[27] Zadravec T, Yin C, Kokalj F, Sameca N, Rajh B. The impacts of different profiles of the grate inlet conditions on freeboard CFD in a waste wood-fired grate boiler. Appl Energy 2020;268:115055.
[28] Alobaid F, Al-Maliki W, Lanz T, Haaf M, Brachthauser A, Epple B, Zorbach I Dynamic simulation of a municipal solid waste incinerator; Energy (149) 230-249.
[29] 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 2021;221:119844.
[30] Asfar J, AlShwawra A, Shaban N, Alrbai M, Qawasmeh B, Sakhrieh A, Hamdan M, Odeh O. Thermodynamic analysis of a biomass-fired lab-scale power plant. Energy 2020;(194):116843.
[31] Asfar J, Hammad A, Sakhrieh A, Hamdan M. Two-dimensional numerical modeling of combustion of Jordanian oil shale. Energy Sources, Part A Recovery, Util Environ Eff 2016;38:1189–96.
[32] Yuan J, Li Y, Wang G, Zhang D, Shen Y, Ma R, Li D, Li S, Li G. Biodrying performance and combustion characteristics related to bulking agent amendments during kitchen waste biodrying. Bioresour Technol 2019;(284):56–64.
[33] Malika A, Jacques N, Jaafar E, Fatima B, Mohammed A. Pyrolysis investigation of food wastes by TG-MS-DSC technique. Biomass Conversion and Biorefinery 2016;(6):161–72.
[34] Soria-Verdugo A, Goos E, García-Hernando N. Effect of the number of TGA curves employed on the biomass pyrolysis kinetics results obtained using the Distributed Activation Energy Model. Fuel Process Technol 2015;134:360–71.
[35] Qian Z, Hao M, Li Z, Qian H. Reconstruction technology of high efficiency and energy saving α - flame arch of boiler. J Energy 1998:26–30.
[36] Li Z, Liu G, Chen Z, Zeng L, Zhu Q. Effect of angle of arch-supplied overfire air on flow, combustion characteristics and NOx emissions of a down-fired utility boiler. Energy 2013;59:377–86.
[37] Xu T. Boiler combustion equipment. Xi'an, China: Xi'an Jiaotong University Press; 1990.
[38] Wu H. Application of orthogonal experimental design for the automatic software testing. Appl Mech Mater 2013;(347–350):812–8.
[39] Jiaqiang E, Dandan H, Qiu A, Zhu H, Deng Y, Chen J, Zhao X, Zuo W, Wang H, Chen J, Peng Q. Orthogonal experimental design of liquid-cooling structure on the cooling effect of a liquid-cooled battery thermal management system. Appl Therm Eng 2018;132:508–20.
[40] Li Y. Experiment design and data processing. Beijing, China: Chemical Industry Press; 2017.
[41] Qian H, Miao Z. Numerical of air flow in arches of grate stokers. Energy Conservation 2007;26.
[42] Miu Z, Huang X, Yang D, Yu G, Huang J. Study on heat transfer and its effect on the fire bed burning in arch rear area of fire-bed furnace. Industrial Boiler 1996;(4):18–24.
[43] Schetz A, Fuhs A. Fundamentals of fluid Mechanics. John Wiley & Sons; 1999.