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Effect of nozzle diameter variation on flame height and combustion residue in a household-scale incinerator burner

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Abstract

Household waste is one of the main components of household waste in Indonesia, and its growth year-on-year requires solutions for efficient processing in the future through approaches of reduction, reuse and recycling. A possible solution is to reduce waste at household level and is the use of micro-scale incinerators. The efficiency of these systems, however, is very dependent on the combustion properties of the burner. The purpose of this study is to develop a household incineration system and to investigate the variation of nozzle size (2, 3 and 4 mm) on the flame height and combustion residue. 500g of plastic waste and dry leaves were used for each experiment. The results reveal that the nozzle of 2 mm is the most optimized nozzle which achieved mass reduction of 99.46% for plastic waste and 99.64% for dry leaves with a maximum flame height of 27 cm for both the plastic waste and dry leaves. The results show that nozzle diameters have a significant impact on the fuel–air mixing and the velocity of the resulting flow, which results in more complete combustion as evidenced by the level of flame height and the amount of residue. The study suggests that for household incinerator applications the nozzle should be no smaller than 2 mm, and diameters of less than 2 mm should be further investigated as there is a possibility of clogging and back-pressure.

Keywords: Incinerator; nozzle diameter; flame height; combustion residue; efficient combustion

1. Introduction

Domestic and industrial waste generation have increased tremendously in metropolitan areas due to rapid urbanization and increasing industrial activities [1,2]. The wastes comprise organic materials, inorganic materials as well as hazardous and toxic substances (HTS) [3]. If not managed correctly, waste buildup will result in lower quality of the environment and health problems through emission of harmful gases (CO, CO_2, NO_x, SO_2), contamination of soil and water bodies [4,5]. The types of waste that pose special problems are polypropylene (PP) plastics, and dry organic waste like fallen leaves, because they degrade naturally at a very slow pace and are continuously increasing in production volume [6-8].

Incineration is one of the most efficient thermal waste treatment technologies that can reduce the waste volume to 5-15% of its original mass, and has the potential to generate energy [9-12]. In comparison with the traditional methods like landfill disposal or composting [13,14] incineration has an advantage of shorter processing time and elimination of pathogens and organic parts. The performance of an incinerator, however, is very sensitive to combustion control. The failure of a combustion chamber to properly configure the burner can cause incomplete combustion, higher pollutant emissions and higher ash content of the combustion residues, thus worsening the environmental effects [12,15].

Burner design (including the nozzle diameter) is one of the main parameters that affects combustion quality in household-scale incinerators. The nozzle diameter has an effect on fuel-flow velocity, fuel-air atomization and the mixing ratio of fuel and secondary air. Fluid-dynamics theory predicts that fuel-oxidizer interaction and, consequently, more complete combustion will be achieved by decreasing the nozzle cross-section, which increases the flow velocity and turbulence. Nozzle diameter variation has been found to have a major impact on the stability of the flame, on the temperature of the combustion chamber and on the efficiency of mass reduction, as previously reported [16,17]. However, there are not many experimental studies addressing the optimization of nozzle diameter in household incinerators that deal with different type solid waste.

However, a recent study by Roring (2025) [18] suggested that a 3 mm nozzle is the optimum design for a burner fueled by waste cooking oil for which no validation has been performed for household-scale incinerators, using other waste characteristics. Thus, this research is to examine the influence of the nozzle diameter variation (2mm, 3 mm and 4 mm) for flame height and combustion residues mass in household waste (PP plastic and dry leaves) processing. Flame height is a visual measurement of combustion stability and intensity, and residue-mass reduction is a measure of the thermal efficiency of the system. The findings are anticipated to give technical suggestions to design effective and low emission burners for household scale incinerators applicable in decentralized waste management.

2. Method

The research process is shown in Figure *1*. The study started with a literature survey and data collection to provide the theoretical background of incinerator design and combustion characteristics. This was succeeded by the design stage, the preparation of the tool and materials and the manufacture of the incinerator unit. Burner functionality test was carried out after fabrication to ensure the proper functioning of the system. In case of a failure in the design process, it was returned for evaluation and refinement, while in the experimental phase if it succeeded, the study was carried on. The experiments consisted of combustion experiments of polypropylene plastic waste and dry leaves with nozzle diameters of 2 mm, 3 mm, and 4 mm. The resulting flame-height data and combustion-residue mass from each treatment were then analyzed to determine the relationship between nozzle-diameter variation and combustion performance. The results of these findings were used to draw conclusions and finalize the study.

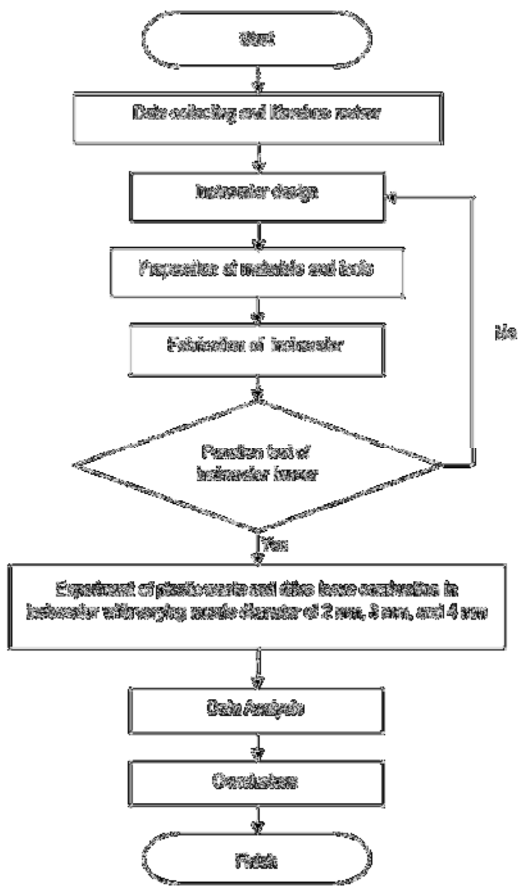

Figure 1**.** Research flowchart.

This study employed an experimental approach consisting of prototype fabrication and performance testing of a household-scale incinerator. The incinerator unit was designed using a structure of seven main units: the exhaust chimney, waste inlet door, primary combustion chamber, outer casing, residue collection container, combustion chamber support frame and the burner system. During incineration, the combustion chamber needs to endure thermal loads, and a steel drum with a diameter of 300 mm, a height of 600 mm, and a wall thickness of 3 mm was used. The supporting structure was made of 30 mm × 30 mm angle iron and the top cover of the burner was made of 2mm thick steel plate. The water reservoir was a second use R22 refrigerant cylinder (diameter 250 mm, thickness 1.0 mm), that was connected to a 15 mm × 15 mm × 280 mm square steel pipe. The base for the flame projecting was made of 40 mm × 40 mm × 240 mm square-steel profile. To guarantee mechanical integrity and sufficient amount of thermal insulation during the operation of all components they were assembled as shown in Figure *2*.

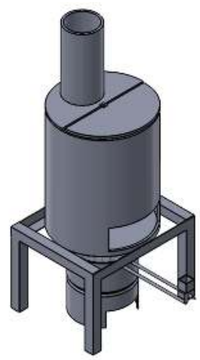

Figure 2**.** Design of household-scale incinerator.

The variable in this study is the nozzle-orifice diameter that was changed in this study at 2 mm, 3 mm and 4 mm as presented in Figure *3*. The three were made by center drilling the M10 × 1.25 mm bolts to the required diameter. To ensure flame stability and operational safety, a burner functionality test was performed before collection of the main experimental data; uncontrolled incineration could lead to higher emissions of particulates and gaseous products. Controlled waste samples were combusted with each nozzle configuration to perform the performance testing. These variables were measured:

1. Final residue mass: Mass of the residue after combustion and cooling, measured by a precision digital balance;
2. The time required to bring the combustion chamber to 400 °C (measured by a calibrated type-K thermocouple), is called the thermal response time;
3. The height of flame above the burner outlet (measured vertically with a standard measuring scale from the burner outlet to the flame tip).

To reduce random error each treatment was replicated three times and all data were recorded quantitatively to observe the relationship between nozzle-diameter variation, combustion efficiency, and flame characteristic. Combustion efficiency is one of the most important plant performance parameters of an incineration system and it was calculated according to the following equation:

$$\eta = \frac{m_{initial} - m_{residue}}{m_{initial}} \times 100\% \tag{1}$$

(a) (b) (c)

Figure 3**.** Nozzle design of household-scale incinerator with varying diameter of (a) 2 mm, (b) 3 mm, and (c) 4 mm.

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3. Results and Discussions

The incineration process is started by filling the fuel reservoir with used lubricating oil, and a small quantity of gasoline is added to the fuel as "starter fluid" as a starting aid. This burner system, with the specified nozzle diameter variation is then placed over the fuel reservoir and the heating process is started. The used oil is vaporized in this step and then blended with air to create a combustible fuel–air mixture. The amount of time it takes for the burner to reach maximum flame is dependent on the nozzle diameter, and is one of the system's performance parameters.

When the burner is at a stable operating point, the main combustion chamber is mounted on the supporting frame and the waste sample is loaded via the loading door provided. The combustion time was fixed at 5 minutes for all tests to assure data consistency and thus allow for valid comparisons between nozzle variations. In order to assess the effect of all three nozzle diameters (2 mm, 3 mm, 4 mm) upon the flame height, time to attain operating temperature and residual mass, this operational procedure was applied to all three. The entire process is shown in Figure *4*.

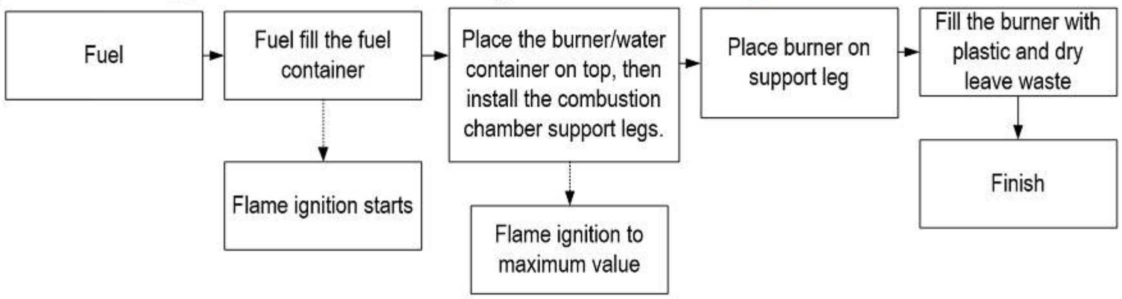

Figure 4**.** Operational diagram of household-scale incinerator.

3.1. Time to reach operational temperature of 400°C

The time taken for the burner to operate at the desired temperature of 400 °C was measured when the combustion chamber was not placed above the burner. The temperature was measured with a thermocouple on the burner tip, at the point of the emission of the flame. The results were obtained in three replications for each nozzle diameter to obtain reproducible data. The results of this test are listed in Table 1 and displayed in Figure *5* as a graph.

Table 1**.** Time to reach operational temperature of 400°C with varying nozzle diameter of household-scale incinerator.

Nozzle diameter (mm)	Experiment 1 (minutes)	Experiment 2 (minutes)	Experiment 3 (minutes)	Average (minutes)
2	17	18	17	17.3
3	19	22	23	21.3
4	26	25	27	26.0

The test results indicate a negative relationship between nozzle diameter and the time for the burner to reach the operating temperature of 400 °C. The 2 mm nozzle reached the desired temperature the quickest, at an average of 17.3 minutes, compared to 21.3 minutes for the 3 mm nozzle and 26.0 minutes for the 4 mm nozzle. The fluid continuity principle ($Q = A \cdot v$) can be used to explain this phenomenon: When the nozzle cross sectional area decreases, fuel velocity increases, which improves fuel atomization and optimum fuel, i.e. air mixing. This, in turn, creates a higher turbulence and heat release for a more homogeneous mixture and thus increases the rate of transfer of thermal energy to the walls of the burner to help it attain stable operating conditions more quickly. The results have been verified and show that hydrodynamically smaller diameter nozzles are more successful in improving the thermal response of the incinerator, while maintaining the initial stability of the flame.

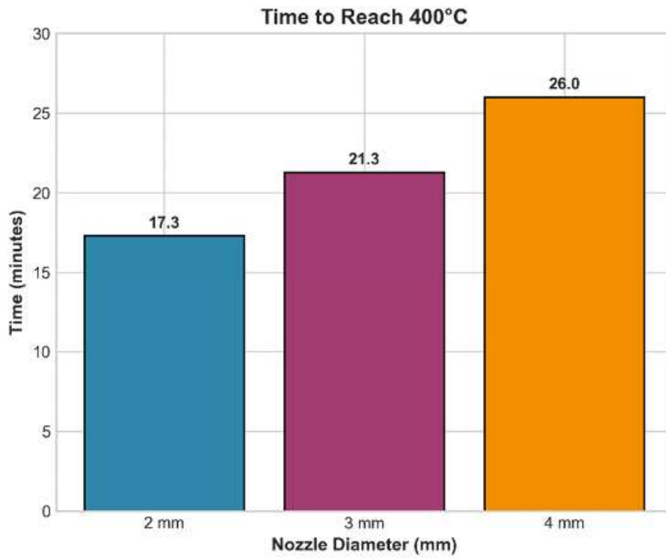

Figure 5. Time to reach operational temperature of 400 °C with varying nozzle diameter of household-scale incinerator.

Besides the time to reach the operating temperature, the uniformity of the operating temperature is a most important parameter for the burner performance. After 400 °C, the 2 mm nozzle showed a lower temperature fluctuation (3.2 °C) than the 3 mm (5.8 °C) and 4 mm (7.1 °C) nozzles (calculated as the difference between the first, second and third test repetition). The resulting stability is closely related to the atomization quality: The smaller the nozzle, the finer the fuel droplets, which helps to achieve more uniform evaporation and to deliver continuous and stable heat release without sudden jumps or decreases. These are very desirable conditions during the initial phase of incineration where the combustion chamber quickly can reach a complete combustion regime with carefully controlled oxygen supply, leading to reduce by product generation (e.g. carbon monoxide (CO) and unburned particulates). In general, the use of a nozzle with a diameter of 2 mm is able to reduce the time to reach the incineration temperature and also provide more stable and environmentally friendly incineration thermal behavior.

3.2. Flame Height

After the burner had warmed up and was burning at a steady rate, we measured the flame height. We did this with a set square, from where the flame comes out of the burner to the very top of the flame. Table *2* has all the flame heights we found for each of the different burner nozzles, and Figure *6* is a graph of the information. The measurements showed that as the nozzle opening got bigger, the flame got shorter. The 2 mm nozzle made the highest flame, reaching 27 cm. This was a good deal higher than the flames from the 3 mm nozzle (20 cm) and the 4 mm nozzle (16 cm). Because the smaller opening in the 2 mm nozzle makes the fuel shoot out faster, the spray has more energy, and the flame is longer, brighter and burns more steadily. Bigger nozzles, with their slower fuel exit speeds, give shorter flames and the fuel is not spread as well. This backs up the idea that smaller nozzles are better at using the fuel to create the highest flame, and so the hottest burn, in home incinerators. However, making the nozzle opening smaller does increase the pressure inside the burner. This is something to be aware of, because too much back pressure is not good. It can be dangerous, or at the very least, make the burning uneven. So, while the 2 mm nozzle makes a much better flame, one need to be careful about its limits and the possibility of pressure building up.

Table 2. Flame height with varying nozzle diameter of household-scale incinerator.

Nozzle diameter (mm)	Flame height (cm)
2	27
3	20

Nozzle diameter (mm)	Flame height (cm)
4	16

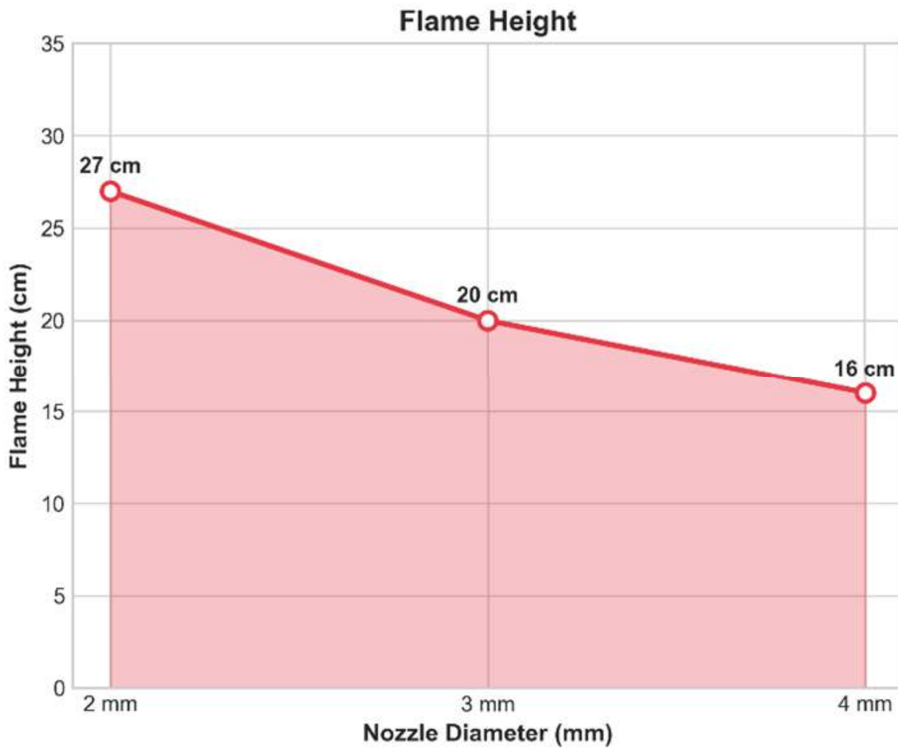

Figure 6. Flame height with varying nozzle diameter of household-scale incinerator.

3.3. Residue from Combustion

Combustion tests were performed after the burner achieved its working temperature of 400 °C. A mixture of plastic wastes (bottles and plastic bags) and dry leaves with an initial mass of 500 g was used for each test, and all experiments lasted the same amount time (5 min). Overall, the combustion duration was standardized in order to compare nozzle variations accordingly. This represents the mass of residue after combustion and complete cooling of the system. Table 3 summarizes the findings of the residue-mass measurements, and Figure 7 presents plots for both waste types with various nozzle diameters.

Table 3. Residue mass resulted from the combustion with varying nozzle diameter of household-scale incinerator.

Nozzle diameter (mm)	Types of waste	Initial mass (gr)	Residue (gr)	Mass reduction (%)
2	Plastic	500	2.7	99.46
2	Dry leave	500	1.8	99.64
3	Plastic	500	3.4	99.32
3	Dry leave	500	2.5	99.50
4	Plastic	500	5.2	98.96
4	Dry leave	500	3.1	99.38

The test results show that 2 mm nozzle had the highest mass reduction efficiency of 99.46% and 99.64% for plastic and dry leaves, respectively. Combustion efficiency was found to decrease with increasing nozzle size. The smallest mass-reduction value was measured for 98.96% (plastic) and 99.38% (dry leaves) for the 4 mm nozzle. The percentage-reduction trends are illustrated in Figure *8*. The efficiency of these differences relates directly with the quality of atomization and fuel, i.e. air mixing. Smaller nozzles produce smaller fuel droplets that lead to more even combustion chamber heat distribution and a more complete combustion of the fuel. However, its effectiveness on atomization will decrease with larger nozzles because there will be less complete combustion and more leftover mass. For the dry-leaf waste, the mass-reduction values were also regularly a little higher when compared to plastic in all the nozzle variations. This behavior is attributed to the intrinsic properties of dry leaves, low moisture content and a cellulose based structure which oxidizes more readily. In comparison, the polymer products of plastics have a higher activation energy for the process of thermal decomposition, and are therefore harder to completely burnt.

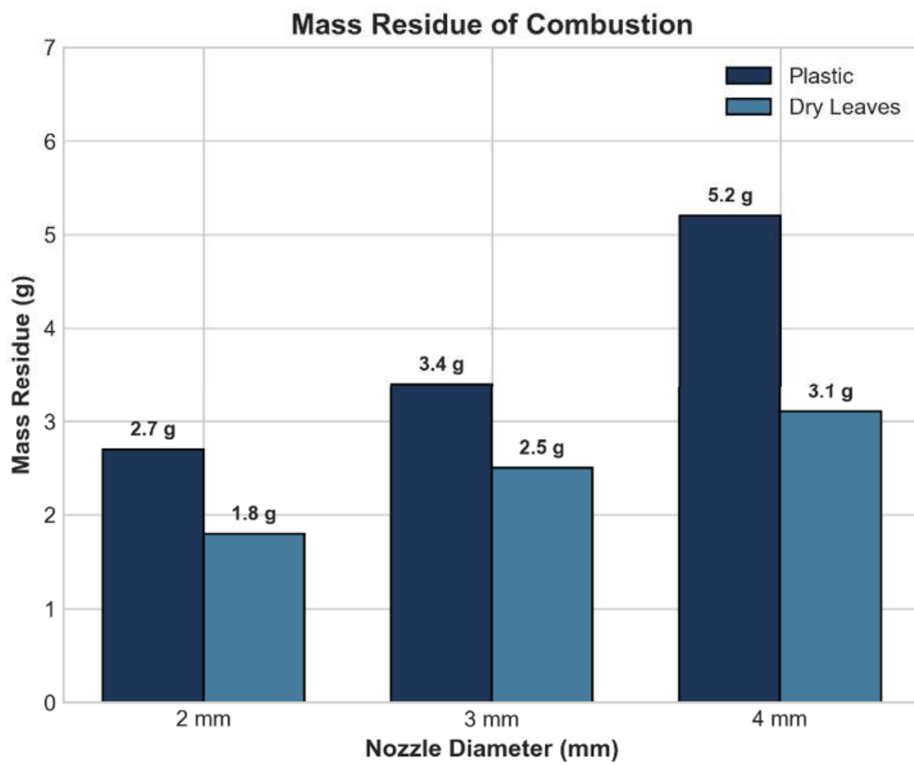

Figure 7**.** Mass reduction, i.e. residue, generated from the household-scale incinerator with varying nozzle diameter.

Furthermore, the small quantity of residue left by the 2 mm nozzle reflects not only increased thermal efficiency, but also increased complete combustion, which is an important element in reducing the production of harmful by-products, like carbon monoxide. The larger nozzles (3-4 mm) on the other hand produced higher mass of unburned carbon fragments and partially disintegrated polymer chain which could cause secondary pollution if the ash is not properly controlled. Residual properties of plastic and dry leaf waste also show a main difference between the different waste types, and the necessity for residence time distributions and temperature gradients within the combustion chamber. Given the high temperature thresholds needed to break down the polymer chains, with cellulose-based waste rapidly pyrolysing at relatively low temperatures, the latter is the better method for recycling waste. The distributed heat from the 2 mm nozzle has an adequate effect on keeping these conditions and avoiding quenching effects in the ash matrix that can trap volatile organic compounds. Therefore, optimization of nozzle geometry is, more generally, an operational tool to manage ash quality, lower post-combustion handling costs and maintain a consistent thermal performance for decentralized waste management systems, especially in household incineration systems.

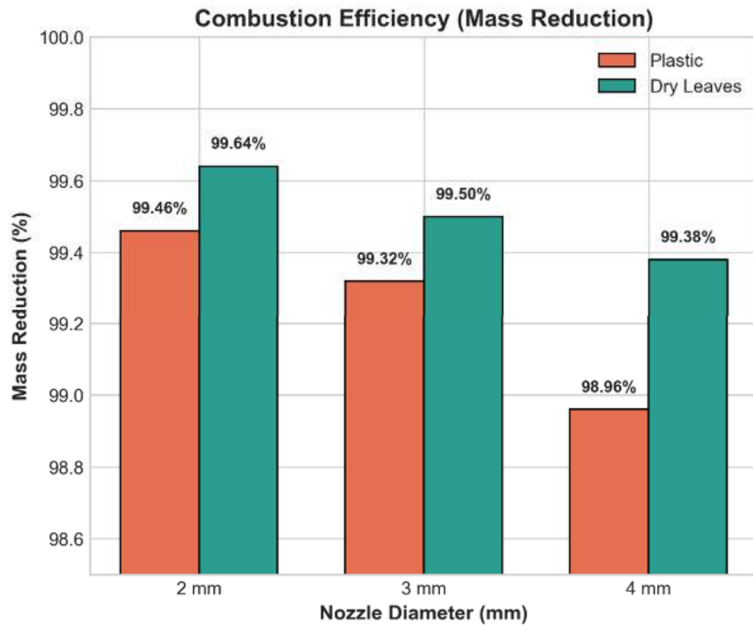

Figure 8. Percentage of mass reduction as the residue of combustion of household-scale incinerator with varying nozzle diameter.

4. Conclusions

According to the experimental results, the household scale incinerators can be affected significantly by the variation of the nozzle diameter especially in terms of the thermal performance and combustion efficiency. The nozzle with a diameter of 2 mm had the best overall performance, i.e. the shortest time to reach the target operating temperature of 400 °C was 17.3 minutes, the highest mass reduction efficiency was >99.4% (plastic and dry-leaf), and the highest and most stable flame was produced. This superior performance is achieved due to decreasing the size of the orifice leading to increase the velocity of fuel flow, which helps to improve fuel atomization leading to better fuel, which is the air mixing and heat transfer to the combustion chamber. On the other hand, the nozzle diameter was increased which caused less effective atomization and uneven mixing leading to slower heating rate, shorter flame height, and higher residual mass. Under these circumstances, incomplete combustion and low thermal efficiencies occur. From those results, a 2 mm nozzle was found to be the best configuration to use in household incinerator applications because of its advantageous thermal responsiveness, stability, and combustion efficiency. However continued research is needed to assess any possible risks of decreasing nozzle size below 2 mm, especially in terms of back-pressure effects.

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