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WASTE RECOVERY USING A HEAT-RECOVERY INCINERATOR

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ABSTRACT

The heterogeneity of waste, its considerable volumes, the lack of means and operating budgets, causing it to pile up on garbage bins, are among the problems faced by urban households and municipalities when it comes to waste management. Sorting at source and raising awareness among the population are proving to be effective solutions, but unequal levels of education are a major handicap to their implementation. The aim of this research project is to treat the daily waste of a modest Madagascan family, reducing its volume by 90% and recovering most of the energy from this reduction to meet part of its energy needs. In this way, a mini incinerator was created. The results of this research confirmed that incineration without waste sorting can be an effective solution for eradicating municipalities' concerns about urban waste management. The mini incinerator can reduce household waste by up to 91.02% in 1h30mn. Over 15 trials, the average weight of ash obtained during an incineration cycle was 3.952Kg for 44Kg of raw waste incinerated. Steam is emitted into the heat exchanger one hour after the start of the process, with a maximum temperature of 655°C. In short, incineration without sorting is the ideal technology not only for eliminating nuisance and pollution, but also for creating a healthier, better environment for mankind. Looking ahead, the installation of a heating system based on the recovery of the vapors obtained is the outcome of a new technology that every household can benefit from.

KEYWORDS:

Household waste, treatment, incineration, prototype incinerator, volume reduction, energy.

1- INTRODUCTION

Urban waste management is a major issue for all countries and a major challenge for municipalities. The increase in the world's population and its concentration in cities, as well as the development of industrial equipment and consumer goods, generate astronomical quantities of waste. Municipal solid waste poses serious environmental, health and economic problems worldwide **[1]**. Indeed, the industrial era has generated an ever-increasing amount of waste, presenting new problems: its considerable volume, the non-biodegradability and toxicity of some of it, its lifespan, and its negative impact on the environment **[2]**. However, once waste is produced, it cannot be ignored and will require safe disposal or alternative treatments **[3]**. The complex and heterogeneous composition of household waste makes it difficult to treat and manage. In the case of Madagascar, this situation is due to the absence of a national legal framework (policy and strategy) for waste management, for which landfill disposal was initially the most practical solution, moving over time from uncontrolled to controlled landfills **[4] [5]**. The latter receive waste of all kinds in bulk, and thus end up being a threat to the environment themselves **[4]**. Good urban waste management means recovering or recycling the majority of it in economically viable conditions. This management must have three main objectives: public health, urban aesthetics and sustainable environmental protection.

It is within this framework that the theme of this research project has been chosen: waste recovery through the use of a mini incinerator with heat recovery.

The aim of this research project is to identify appropriate technologies for reducing a large proportion of the waste generated in developing countries such as Madagascar. Among the technologies inventoried, incineration appears to be the best placed to reduce the volume of waste to be incinerated to around 90%, and to recover most of the energy contained in it. However, a number of questions remain:

- Is incineration really the right technology for treating and recovering household urban waste for energy purposes, and is it adaptable to the context of large cities in developing countries?
- Is this technology capable of reducing the daily volume of household waste in municipalities and recovering most of the energy produced?
- Is incineration the ideal way of eliminating source separation and nuisance, and reducing the pollution generated by the piling up of municipal household waste?

- Doesn't adapting incineration technology to households have an impact on their living conditions, on municipal budgets and on the environment in general?

The present document attempts to shed light on these questions by describing the various materials used and the methodology adopted to carry out this work; the results of the work carried out on the incineration of the urban household waste of a modest Madagascan family; and the discussion of the various results obtained. A conclusion concludes this work.

2- MATERIAL AND METHODS

To carry out this work, various materials used in the construction of a mini incinerator are provided, as well as study and laboratory equipment with various materials used in the laboratory experiments.

4.1 Equipment and materials

Materials were chosen and purchased according to the following criteria:

- Affordable price (low cost);
- Best quality;
- High-temperature and smoke-resistant;
- Non-corrosive at high temperatures;
- Easy to work with.

• Materials used to build the body of the incinerator

Several materials were used to build the body of the mini incinerator, including:

- Flat black plate

This is the main material used to cover the body of the incinerator. The quantity of flat black plate required for the construction is 30 Kg, equivalent to 2m/1m. (Figure 1)

- Galvanized sheet metal

Galvanized sheet metal is used to manufacture the 20 cm diameter, 90 cm high hollow round tube chimney. A 6 m bar is required for the mini incinerator. (Figure 2)

- Galvanized tube

This is used to manufacture the water pipe inside the exchanger and the steam outlet from the outside (Figure 3: Galvanized tube).

- Perforated plate with round hole

Perforated sheet metal, 3mm thick, is used to manufacture the two grates: one for sieving ash from incinerated waste and the other for depositing activated carbons for the treatment of fumes released during combustion (Figure 4).

- Angle iron

20 mm-thick angle iron is used to support the incinerator (Figure 5).

• Thermal insulation materials for the prototype

To insulate the prototype from the various external parameters with a view to conserving heat and minimizing heat loss, various materials were mixed in, such as:

- Clay: grayish in color with a total mass of 15 Kg (Figure 6);

- Grog: 5 Kg (Figure 7);
- Lateritic soil: reddish in color with a total mass of 1kg (Figure 8);
- Jirama tap water: 5 liters

- Laboratory equipment for various prototype tests

The prototype mini-incinerator was tested using a range of laboratory equipment and apparatus. These included:

- Electronic balance: for various weighing operations (ash, start-up combustion) (Figure 9);
- Roberval balance: for weighing raw materials (Figure 10);
- 1000 ml volumetric flask: for measuring water poured in during heat transfer tests (Figure 11);
- Thermocouple with probe: to monitor the temperature inside the incinerator body (Figure 12);
- Thermal protection glove: to protect against flames;
- Pharmaceutical glove: for mixing raw materials;
- Mask: for protection against the smoke generated during experimentation (Figure 13).

4.2 Methods

A mini incinerator prototype is designed to offer the following thermal characteristics: improved combustion through good thermal insulation, generating a temperature sufficient to reduce waste to ash, improved flue gas extraction and good heat conservation. These thermal specificities of the prototype will not be obtained without going through the three stages mentioned above.

- Stages in the manufacture of the prototype incinerator

The manufacture of the prototype must pass through the following three main stages: study, design and realization. Of these three stages, design is the most important.

- Design of the incinerator prototype drawing

The prototype design was created using ArchiCAD and Blender software. This step was essential to facilitate assembly. The 3D drawing (Figure 15) illustrates the final image of the mini-incinerator at the end of construction, while the 2D drawings (Figure 14) show the cross-sectional diagram and plan view with their respective dimensions.

- The heat exchanger

Viewed from the operating base, to take advantage of the heat energy generated by incinerating household waste, a heat exchanger has been integrated.

Our incineration prototype uses a **tube bundle and calender heat exchanger** (Figure 16).

The device consists of a bundle of tubes, arranged inside an envelope known as a calender. Around the tubes. Baffles are usually added to the calender, acting as turbulence promoters and improving transfer outside the tubes **[6]**.

Distribution boxes are fitted at each end of the bundle to ensure fluid circulation inside the bundle in one or more passes. The calender is also fitted with inlet and outlet manifolds for the second fluid (which circulates outside the tubes) following the path imposed by the baffles **[6]**.

- Making the prototype

Building the prototype took 62 days and was divided into five different stages:

❖ First stage (10 days): dimensioning, grinding and welding of materials for the prototype's main fireplace (Figure 17);

❖ Second stage (12 days) :

- Fabrication of the heat exchanger: assembly of 7 galvanized tubes placed horizontally on 2 flat black plate walls by welding placed above the hearth (Figure *18*);
- Drilling two holes for the exchanger's water inlet and steam outlet (Figure 19);

❖ Third stage (9 days):

- Welding of the perforated sheet support with an angle iron (Ash screener) (Figure 20);
- Installation of the smoke purification chamber without welding: support for activated carbons made of perforated sheet metal;
- Installation of the galvanized sheet metal chimney (Figure 21).

❖ Fourth stage (duration: 16 days): it includes the following activities:

- Preparing the clay, grog and water mixture;
- The aging process, which consists of placing the paste in the shade for five days (Figure 22);
- Reinforcing the interior of the main hearth with the aged clay to give the kiln its ability to retain very high temperatures;
- The finishing work, which consists of lining and filing the aged paste inside the hearth with a trowel and sponge (Figure 23);
- Drying the hearth for 10 days in the shade (Figure 24).

❖ Fifth stage (15 days) consists respectively of:

- Weighing of the entire main hearth lined with the clay and grog mixture, using a Roberval balance to monitor the drying progress of the mixture. Weighing was carried out every 2 days for a period of eight days (Figure 25);
- Around the eighth day of weighing, the parts inside the main hearth that have been lined with mixture (clay + grog) will be relined with lateritic soil (lining) to ensure that these mixtures are watertight with the metal parts of the main hearth;
- After 15 days of drying, we began the various incineration tests.

Drying allows the shaping water to be slowly removed without deforming our prototype, reducing the weight of the clay inside the main hearth. It's a delicate operation, as we need to avoid cracking and warping: the aim is to stop drying below the stress limit that the clay can withstand (plasticity limit). This limit varies according to the structure of the clay, its fineness, and cohesion and shaping method.

- Experimental studies
  - ❖ Raw materials

Household waste is waste that comes mainly from the home, containing "a bit of everything"; that is:

- Green waste: dead leaves, grass clippings, wilted flowers, moss, manure, dried ferns, straw, hay ;
- Food waste: eggshells, peelings, fruit and vegetables, even damaged ones;
- Household waste: hair, nails, feathers, cardboard, newspaper, tissues, cotton, damaged fabric, plastic bags, plastic bottles.

These raw materials are those of a retailer's household with a household size of **8**, including **5 adults and 3 children**.

❖ Experimental tests with the prototype

Before each incineration trial, the preparation phase must be completed:

- Weighing household waste and firewood on the Roberval scale;
- Weigh the wood branches to be used as a fire starter using the electronic scale;
- Mix dry and wet household waste by hand (pharmaceutical glove mandatory) (Figure 26). Install the thermocouple probe at the prototype's hot spot (Figure 27) ; Add water to the heat exchanger (Figure 28).

❖ Incineration tests proper

After the preparatory phase and prior to the incineration tests, the following steps must be taken respectively:

- Loading waste into the main furnace (Figure 29);
- Starting the fire with firewood in the combustion chamber (Figure 30);
- At the end of incineration, recover and weigh the ash in the combustion chamber (Figure 31).

❖ Summary of experimental trials

During the course of this research work, fifteen (15) experimental trials were carried out to determine, respectively: temperature variation, household waste burning time, steam outlet time and ash residue. This summary table (Table 1) summarizes the quantities of household waste processed, the start-up combustion, the quantity of firewood used and the quantity of water poured into the heat exchanger for each experimental test carried out.

It should be noted that:

- Firstly, the additive used was 26g of firewood for all trials except trial 2, where 50g of briquette fuel was used with 26g of additive to check the combustion rate compared with the first trial;

- Secondly, the household chosen is a merchant with a household size of 8, including 5 adults and 3 children. It produces an average of 3 kg of household waste made up of cardboard, paper and plastic bags;

- Thirdly, for test n°4, the household produced only 0.5 kg of waste instead of 1.5 or 2 kg compared with the other tests. These are all fruit and vegetable wastes.

It is necessary to carry out measurements: weights and capacities before starting the experimental trials with the prototype, to ensure the homogeneity of the results.

Taking measurements

All experimental parameters were measured using suitable equipment:

- The temperature in the furnace was measured with a thermocouple. Measurements were taken from room temperature to burning temperature.

- A stopwatch was used to determine the duration of each process.

- At the end of each test, the ash residue in the combustion chamber was weighed using an electronic balance. This measurement is essential to determine the prototype's performance and efficiency.

3- RESULTS

5.1 General temperature curve during the incineration process

The incineration process is divided into four distinct phases:

- 1st phase: starting the fire

At the start of the process, this first phase corresponds to the lighting of the fire, i.e. the start of waste combustion, but each time these four phases, i.e. an incineration cycle, are completed, this first phase corresponds to the loading of the incinerator with waste.

- 2nd phase: waste drying

Once combustion begins, the waste gradually catches fire. This second phase corresponds to a rise in combustion temperature equivalent to the drying of the waste.

- 3rd phase: gasification

During this third phase, all the waste has already been burned and transformed into gas. This is confirmed by the maximum temperature and the transformation of the waste into charcoal.

- 4th phase: decline

An abrupt drop in temperature corresponds to the exhaustion of waste in the main furnace. Carbonized waste is transformed into ash. This is the end of the first cycle.

The graph in Figure 32 shows the shape of the incineration cycle succession curve for the various experimental tests carried out, according to the temperature recorded at each phase and the corresponding time.

The curve comprises two incineration cycles, each consisting of four phases: fire start-up, drying or combustion start-up, gasification and decay.

The first incineration cycle began at 09:40 and ended at 10:20. The second cycle, on the other hand, started at 10.20 a.m. and ended at 11.30 a.m., until all the waste had been turned to ash.

In addition, the results of this research work have been classified into groups, with each group comprising five experimental trials. Fifteen incineration trials were carried out with the mini incinerator and are divided into the following three groups:

- First group: comprising trials n°1, n°2, n°3, n°4 and n°5;
- Second group: comprising tests n°6, n°7, n°8, n°9 and n°10;
- Third group: comprising tests n°11, n°12, n°13, n°14 and n°15;

In order to follow and understand the temperature evolution curve of the fifteen experimental tests carried out, we present in Table 2 the correspondence of the number of each test according to the group considered (1st, 2nd or 3rd) and in Table 3 the correspondence between test group and maximum temperature reached.

Table 3 shows that the maximum temperature reached for the first test in group 1 is 246°C. This temperature rises to 480°C in group 2 and 520°C in group 3, showing that the prototype's waste incineration performance has improved once it has been run through its paces.

5.2 Reducing the daily volume of household waste

Table 4 summarizes the quantities of waste generated per day by the household and the ash obtained after incineration. These results are illustrated in Figure 33.

This table shows that for the 15 experimental trials, the household in question produced 44 kg of waste in 15 days, and after incineration, this 44 kg was reduced to 3.951 kg of ash, i.e. a weight reduction of 91.02%.

5.3 Duration and temperature of steam output in the exchanger for each test

The duration of steam emission into the exchanger is one hour after the start of the process. The maximum temperature reached is 655°C. Table 5 and the graph in Figure 34 show the volume of water poured into the exchanger, as well as the duration and temperature of steam discharge from the exchanger.

No water was poured into the exchanger during tests n°3, n°4, n°5, n°6, n°7, in order to test the efficiency of mini-incinerator operation without energy recovery, but simply to process them. They tested the efficiency of the incineration machine without using the heat exchanger, i.e. treatment (reduction to ash) without energy recovery from household waste.

4- DISCUSSION

- Is incineration without waste sorting more advantageous than incineration with waste sorting?

This research work is specific to each household, with a view to lightening the management of their respective waste, not only in terms of dumping their waste in the bins, but also in terms of the time it takes to travel to and from the bins. What's more, waste sorting is an additional activity in the household, and one that takes up a lot of household time, which is why we opted for this incineration technology. There is no financial or personnel burden to adopt it. Any waste can be treated and recycled at the same time. In short, experimental trials have shown a reduction in the volume of waste ashes of the order of waste recovery in the designed areas, then loading the waste into the mini incinerator, and immediately burning the whole thing until energy recovery without even wasting time.

Incineration with sorting, on the other hand, is considered the best technology for reducing household waste, but the problem lies in the financial and human resources required. This situation has created a crisis at municipal level for the management of their respective waste and has led to the piling up of household waste in garbage bins, generating nuisance, human pollution and environmental pollution in general. Waste is a valuable energy resource. Energy recovery from waste can solve two problems at once: treating non- recyclable and non-reusable waste; and generating a significant amount of energy which can be included in the energy production mix in order to satisfy the consumers' needs and also substitute landfills in the years to come **[7]**. What's more, sorting this waste takes time and slows down the volume of waste to be processed and managed daily at the incinerator. This situation does not facilitate the total elimination of the waste produced each day, but rather complicates the task, since there is always untreated waste, and this always comes back to the initial problem: the piling up of waste in bins.

In short, the process of reducing waste through this technology is interesting because :

- On average, it takes only 1h 30 min;
- The mini incinerator is highly efficient once the insulation (clay) has dried out, and the maximum temperature reached averages 650°C. The prototype retains heat well.

- Is bulk incineration of urban household waste the ideal solution for dealing with the pollution and various nuisances produced by piling up waste in municipal bins?

Based on the results of this research work, bulk incineration technology (without sorting) is seen as the ideal solution not only for households but also for municipalities, since for households, this technology facilitates their daily lives: reduced waste, a healthy environment, no clutter in the home, no more time for throwing waste into the bins, and more time for other household or income-generating activities. As far as municipalities are concerned, the environment becomes healthy: there's no more waste piling up in the bins, nuisance and pollution are gone, and budget constraints are no longer a problem, as the technology doesn't require staff for sorting and collection. At that time, environmental quality will gradually improve along with the growth of the economy **[8]**.

In short, it's the most appropriate solution not only for households, but also for communities, since according to experimental tests, the prototype treats both wet and dry waste at the same time. It also reduces the harmfulness of hazardous waste.

- What are the various impacts of this unsorted incineration technology on the household, the community and the nation as a whole?

Once households and municipalities have adopted this unsorted incineration technology, it will have a number of impacts. These impacts are direct for households and municipalities, and indirect for the nation. At household level, the adoption of this unsorted incineration technology improves living conditions in the home by reducing domestic energy consumption for home heating, and also by cutting fuel consumption for cooking. At community level, the recovered energy can be used to meet energy needs and increase the electrification rate in rural areas, and over time for local development. Adopting this technology will reduce dependence on fossil fuel sources.

5- CONCLUSION

It is clear that the initial objective has been achieved: incineration is the appropriate technology for reducing by 90% the amount of household waste produced each day by a modest Madagascan household, and for recovering most of the energy obtained... This technology is suitable and adaptable to large cities in developing countries. It requires neither sorting nor human resources. It can treat and recover any type of waste, wet or dry. It's also a technology that's easy to adapt, as it doesn't require any particular skills or knowledge to use.

The methodology adopted is both qualitative and quantitative. Its eventual realization requires the following activities to be carried out in chronological order: bibliographical research and webography on waste treatment and recovery technology, in particular incineration, study, design and manufacture of the mini incinerator, vacuum testing of the mini incinerator, insulation with clay to reduce energy loss, drying the prototype, adjusting and readjusting the mini-incinerator, collecting samples of the waste to be incinerated, carrying out various incineration tests in the laboratory, processing and analyzing the data collected, and writing the present research paper.

The results of this research work are convincing, among other things:

- Data on the performance and efficiency of the prototype mini-incinerator are available,
- The mini incinerator can reduce the quantity of household waste by up to 91.02% for an average incineration time of 1h 30 min;
- In 15 experimental trials, the average weight of ash obtained during an incineration cycle was 3.952 kg for 44 kg of raw waste;
- Incineration is the ideal technology for eliminating nuisance, pollution and, by extension, a better, healthier environment for human beings.
- Steam is emitted into the heat exchanger one hour after the start of the process. The maximum temperature reached is 655°C.

Much remains to be done, including optimizing the various parameters required to manage the process, insulating the mini incinerator and designing the prototype. This work will continue with the next project, which will involve energy recovery through thermal conversion into electrical energy.

6- ACKNOWLEDGEMENTS

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8- TABLES

Table 1: Summary of the fifteen experimental trials

Tests	Quantities of household waste (kg)	Start-up combustion (Kitaykely) (g) Appoint : 26	Quantities of firewood used (kg)	Volume of water poured into exchanger (l)
N°1	3	26	1,5	1
N°2	3	Appoint + Briquette=76	1,5	1
N° 3	3,5	26	1,5	
N°4	1,5	26	0,5	
N°5	3	26	1	
N°6	3	26	2	
N°7	3	26	1,5	
N°8	3	26	2	2
N°9	3	26	1,5	2
N°10	3	26	2	2
N°11	3	26	1,5	2
N°12	3	26	1,5	2
N°13	3	26	2	2
N°14	3	26	1,5	2
N°15	3	26	1,5	2

Table 2: Correspondence of each Group 1 trial with Groups 2 and 3

	Correspondence	
Group 1	Group 2	Group 3
Test 1	Test 6	Test 11
Test 2	Test 7	Test 12
Test 3	Test 9	Test 14
Test 4	Test 8	Test 13
Test 5	Test 10	Test 15

Table 3: Correspondence between test group and maximum temperature reached

		CORRESPONDANCE			
GROUP 1		GROUP 2		GROUP 3	
Tests n°	temp max (°C)	Tests n°	temp max (°C)	Tests n°	temp max (°C)
Test 1	246,5	Test 6	480	Test 11	520
Test 2	207	Test 7	616	Test 12	320
Test 3	333	Test 9	530	Test 14	453
Test 4	225	Test 8	655	Test 13	453
Test 5	409	Test 10	440	Test 15	555

Table 4: Reduction in daily household waste volume

Tests	Gross waste weight (kg)	Weight of ash (kg)	Percentage of ash (%)	Percentage ash reduction (%)
n°1	3	0,156	5,2	94,8
n°2	3	0,312	10,4	89,6
n°3	3,5	0,352	10,06	89,94
n°4	1,5	0,123	8,20	91,80
n°5	3	0,328	10,93	89,07
n°6	3	0,257	8,57	91,43
n°7	3	0,396	13,20	86,80
n°8	3	0,31	10,33	89,67
n°9	3	0,248	8,27	91,73
n°10	3	0,292	9,73	90,27
n°11	3	0,19	6,33	93,67
n°12	3	0,275	9,17	90,83
n°13	3	0,235	7,83	92,17
n°14	3	0,248	8,27	91,73
n°15	3	0,229	7,63	92,37

Total	44	3,951	8,98	91,02

Table 5: volume of water poured into the exchanger and time and temperature of steam outlet from the exchanger.

Test number	Volume of water poured into exchanger (l)	Length of incineration process (mn)	Moment (h : mn)	Steam outlet temperature (°C)
n°1	1	88	11h 40	232,5
n°2	1	115	11h 07	131
			11h 30	145
n°8	2	90	10 h 20	235
			10 h 25	218
			10 h 30	560
			10 h 33	165
			10 h 35	450
			10 h 37	650
			11 h 00	350
n°9	2	130	10 h25	528
			11h 35	450
n°10	2	110	10 h25	520
			10 h45	180
n°11	2	110	11h05	311
			11h 10	300
n°12	2	110	10h 54	6,5
			11h10	453
n°13	2	110	11h00	553
			11h05	490
n°14	2	110	11h15	534
n°15	2	110	11h35	410

9- FIGURES

Figure 1: Flat black plate

Figure 2: Galvanized sheet metal

Figure 3: Galvanized tube

Figure 4: Perforated sheet with round hole

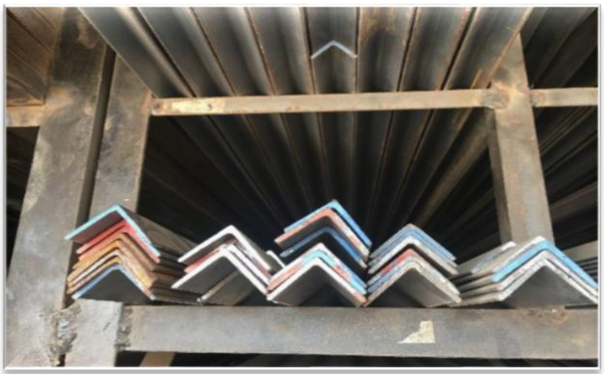

Figure 5: Angle iron

Figure 6: Clay

Figure 7: Grog

Figure 8: Laterite soil

Figure 9: Electronic balance

Figure 10: Roberval balance

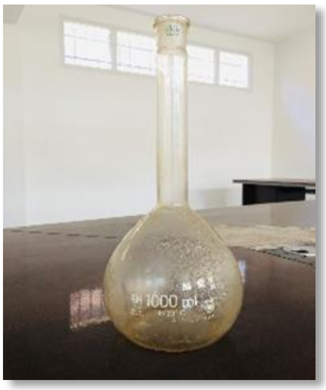

Figure 11: Volumetric flask

Figure 12: Thermocouple

Figure 13: Thermal protection glove/ Pharmaceutical and Mask

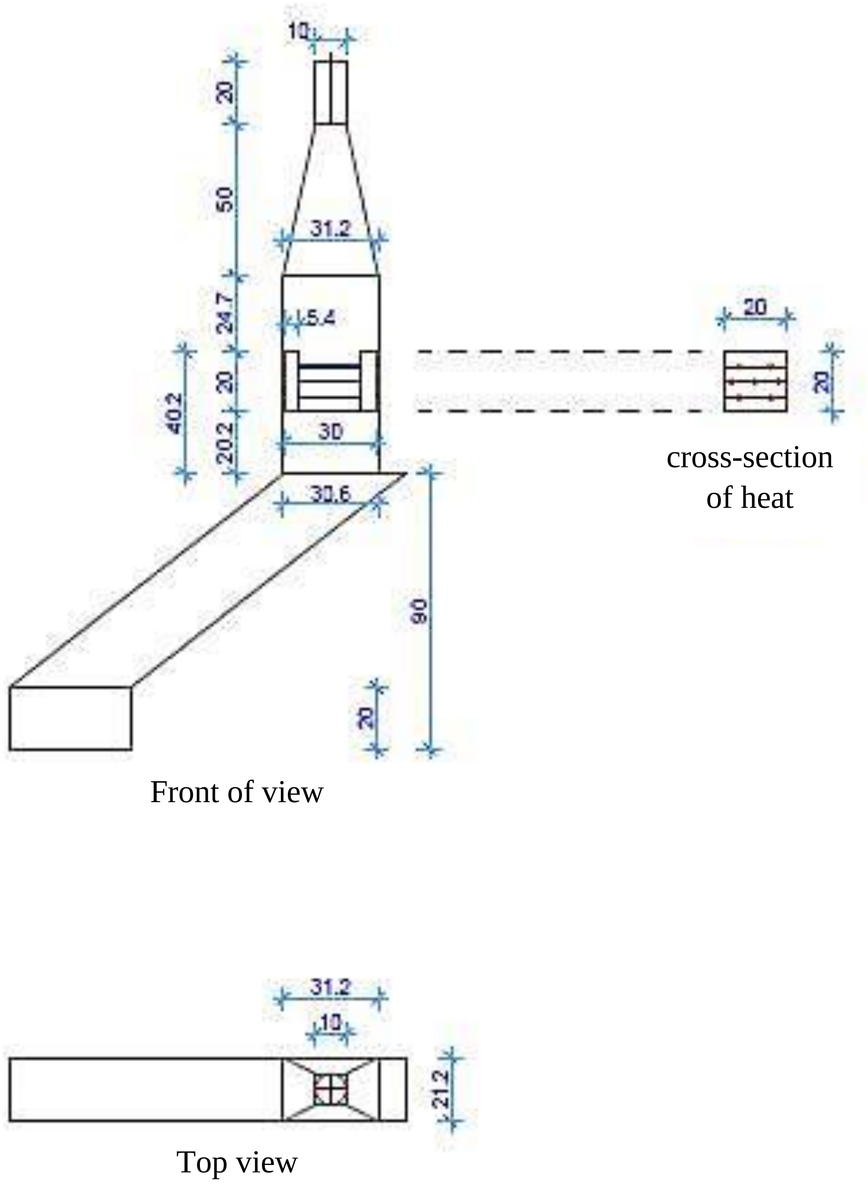

Figure 14: 2D representation of the mini incinerator

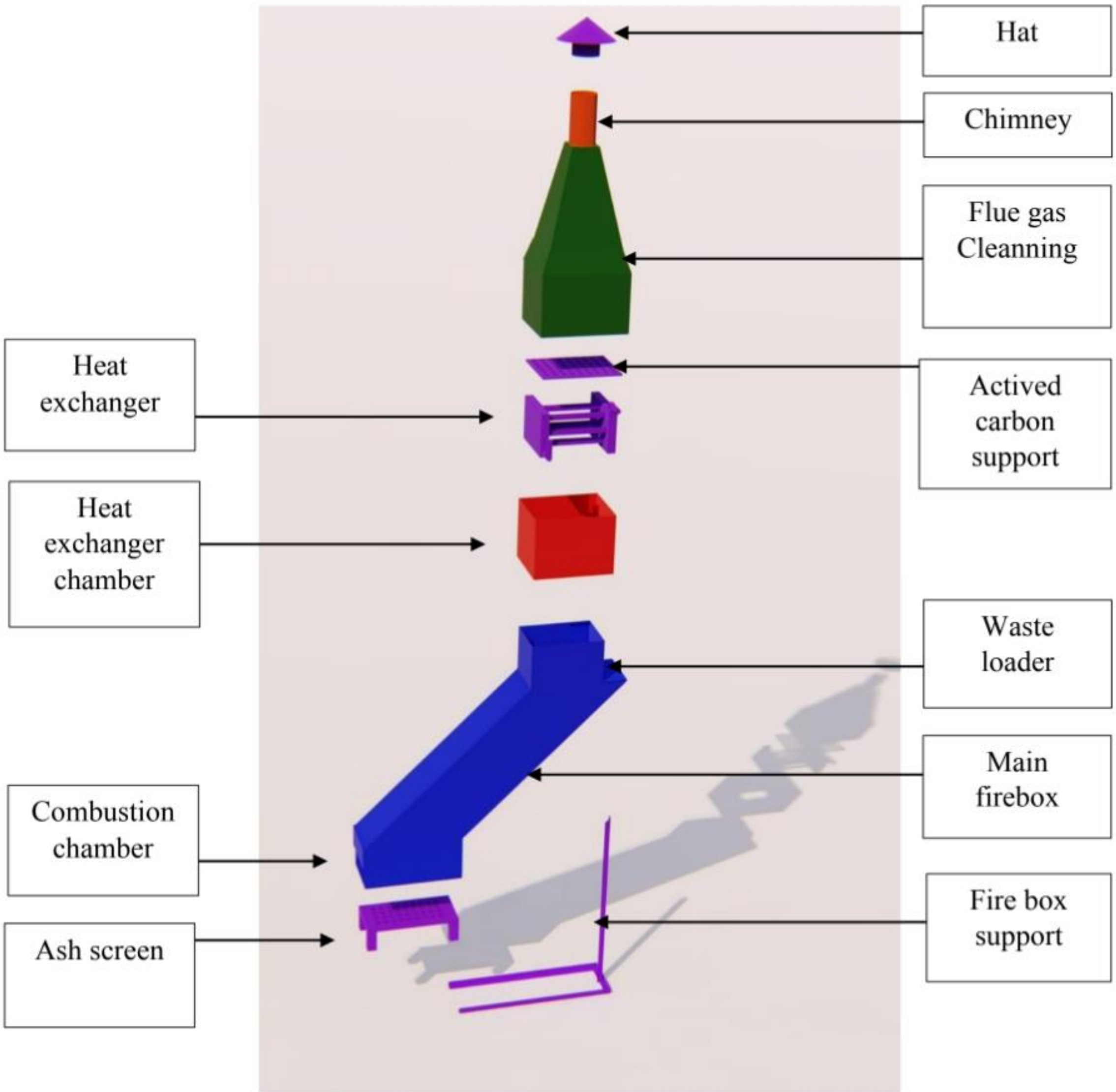

Figure 15: 3D representation of mini incinerator

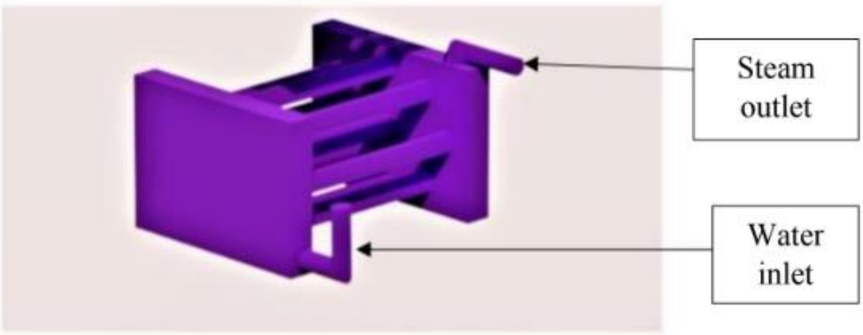

Figure 16: 3D representation of heat exchanger

Figure 17: Main hearth

Figure 18: Welded heat exchanger assembly

Figure 19: Drilling and leak testing the heat exchanger

Figure 20: Ash screen

Figure 21: Chimney and smoke treatment chamber assembly

Figure 22: Clay + grog preparation and aging process

Figure 23: Tapissage and filing work

Figure 24: Kiln interior drying

Figure 25: Weighing the main hearth

Figure 26: Mixing household waste


Figure 27: Thermocouple installation


Figure 28: Adding water


Figure 29: Loading household waste


Figure 30: Lighting the fire

Figure 31: Weighing ash

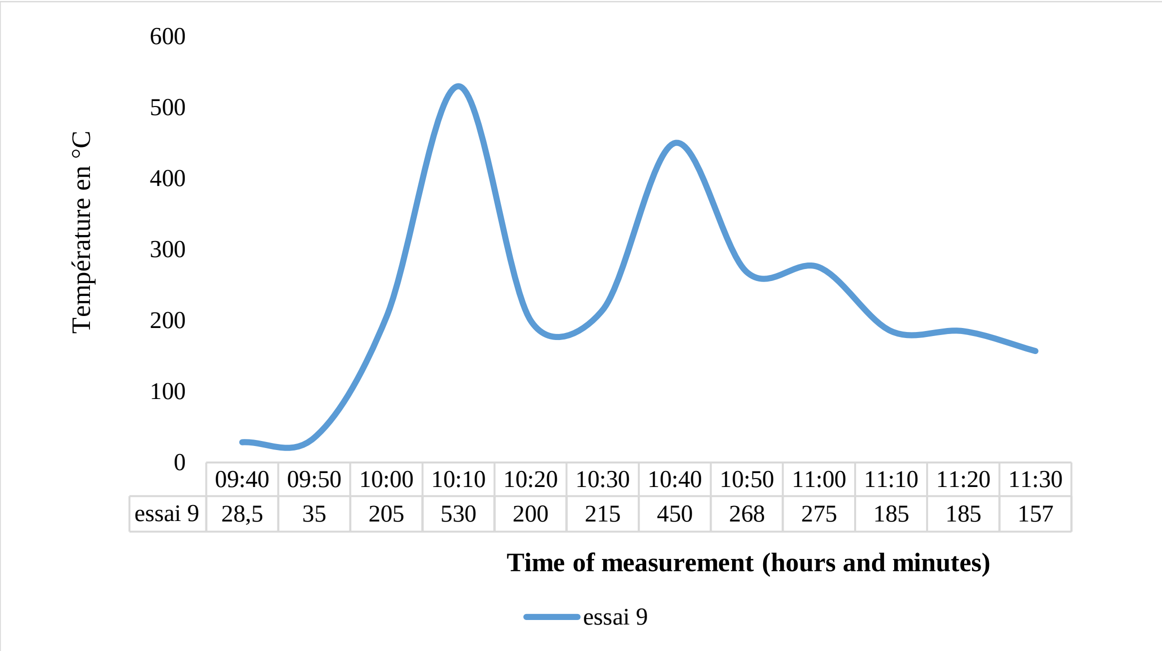

Figure 32: General curve (test no. 9)

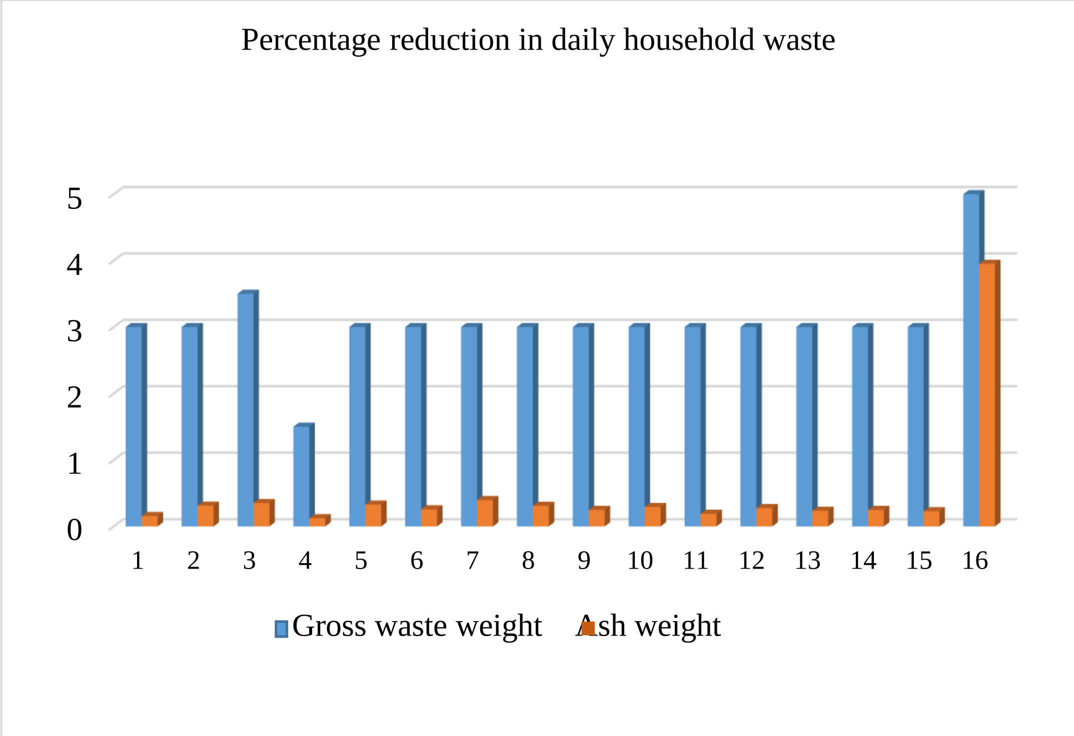

Figure 33: Quantity of daily waste and ash obtained

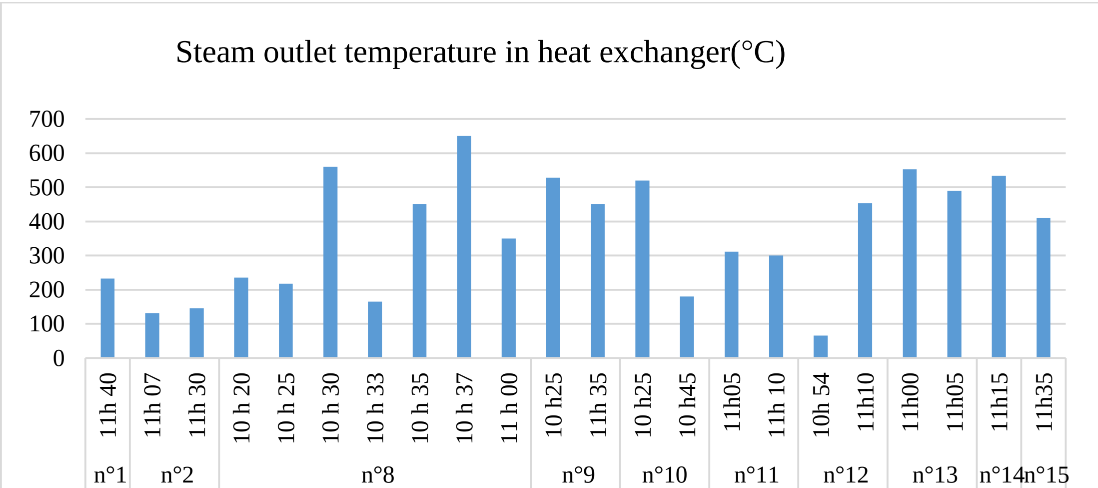

Figure 34: Steam outlet temperature from heat exchanger