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Study of the combustion in a rotary kiln of model household waste from the city of Abomey-Calavi in Benin

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Abstract

Africa's major cities and capitals have experienced rapid population growth over the past four decades. This often exponential population growth poses major challenges for public authorities in the area of sanitation and the collection and treatment of household waste. In Abomey-Calavi, the household solid waste management system is reduced to pre-collection, with no collection or disposal activities operational. It is therefore essential to set up an action plan to analyze the problem and its characteristics, to determine the recovery methods, to test the different solutions proposed and to optimize the most viable systems. The present study, based on a characterization of household waste in the city of Abomey-Calavi, has shown that the combustible fraction of household waste can be represented by the combustible mixture of Wood (88%), Cardboard (7%) and Plastic (5%). A feasibility study on the burning of household waste in the city of Abomey-Calavi was then carried out. A rotary kiln was used to dry the model waste. To take into account the humidity of Benin, the tests were also carried out on the fuel mixture with defined proportions of water. In each case, the temperature and pollutant profiles were analyzed.

Keywords: Combustion, Model Waste, Rotary Kiln, Pollutants, Temperature.

Introduction

In Abomey-Calavi, the household solid waste management system is reduced to the pre-collection which is the only link running, no collection action or disposal being operational.

Waste management in the municipality does not answer any planning. It is the spontaneous work of the actors who act each according to its immediate interests. It is therefore a risky and dichotomous management that is observed. Household subscribers pre-collection must coexist with wild dumps. These wild dumps are also used or created by the pre-collection structures that have no official discharge. As a result, waste out of the houses, do not come out of the neighborhoods and so continues, pollution of the immediate environment of the population.

To allow optimal management of such waste, a comprehensive policy should be implemented, but it cannot rest on tangible and demonstrated elements. It is therefore vital to put in place an action plan to analyze the problem and its characteristics, determine recovery methods, test various proposed solutions and optimize the most viable systems.

The results of Topanou characterization campaigns (humidity, pH, C / N, Organic Matter content, fermentable content) have shown that HSW of the city of Abomey are more favorable to the biological treatment (composting, biogas)[1,2]. Taking into account the experience of Hêvié and Tohouè treatment centers in Cotonou and Porto Novo towns respectively, it is clear that the production of compost remains only possible with the design of an integrated system. In addition to biological treatment from Household Solids Wastes (HSW) of Abomey-Calavi city, it would be important to conduct tests of thermochemical processes (combustion, pyrolysis, gasification) to study the conditions of their use and their adaptation for the city.

Incineration is a process of recovery and reduction of waste (about 90% in volume and 75% in mass) and allows the complete destruction of bacteria[3-6]. It allows the production of slag which can be used under certain conditions in the construction of infrastructures. The waste incineration process is often done in specifically adapted furnaces at temperatures up to 850°C. Incineration produces heat that can be used for electricity production and steam. It also produces gaseous effluents, clinkers in the order of 30% and 3 to 4% of ashes[7,8].

But to ensure the best conditions for incineration, the waste must have certain properties such as a water content of less than 50%, an inert content (glass, sand, shells, etc.) of less than 50%, a combustible content of more than 25% and a sufficiently high calorific value[9].

This is illustrated by the triangular diagram. It is in this context that is inscribed this study which proposes from the typological characterization to study the feasibility of combustion and incineration tests of the household waste of Abomey-Calavi.

Starting with the characterization made by Topanou[1,2], we will bring out the essential characteristics of domestic refuse of the said city. Then it will be developed a replicable model waste on which the combustion tests will performed in laboratory.

Methodology

The Rotary Kiln of LPCE (Laboratory for Environmental Physic and Chemistry).

Description of thermal Rotary Furnace: A waste treatment system by rotary heat furnace consists of a furnace which are added related equipment for receiving, handling of waste and the handling of waste residues. Such an assembly is often provided with an energy recovery system where the size of the plant is sufficient. The prototype that is used in this work is the co-flow type in which the fuel (extra fuel), air and fuel (waste) are introduced on the same side. The kiln incineration capacity is 60 to 80kg of solid waste per hour). It was manufactured by the Italian company EQUADOR and includes four main components: the combustion chamber, post combustion chamber, the chimney and the control box as shown in the Figure-1.

Temperatures recording and pollutants analysis: Temperatures (T_1, T_2, T_3 and T_4) were captured in the furnace by four (04) K-type thermocouples arranged in the furnace along a steel tube (respectively 10, 60, 110 and 155cm of the primary burner, Figure-1). These thermocouples are extended to the data recorder Testo 176T4 by energy loss compensating cable.

T_1 represents the temperature at the inlet of the combustion chamber (primary burner), T_2 the average temperature in the combustion chamber, T_3 the temperature between the two combustion chambers, T_4 the flue gas temperature.

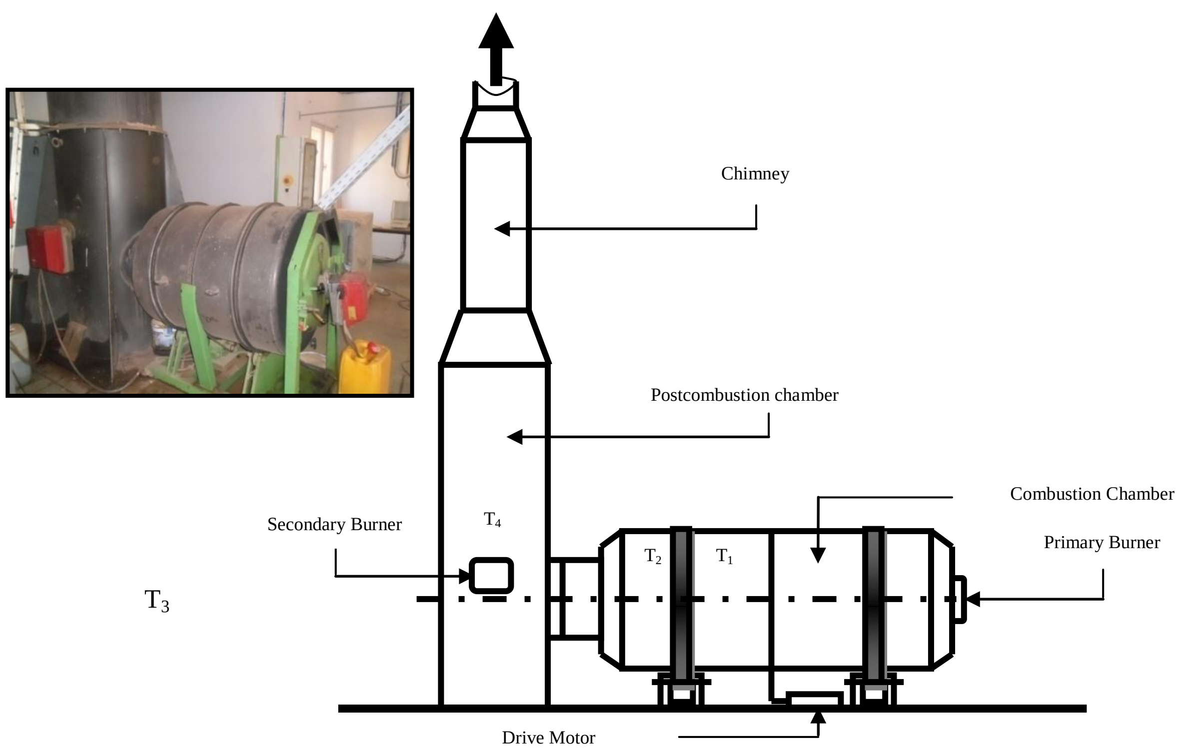

Figure-1: Rotary Kiln device.

Figure-2: Testo 176T4 with interface USB, SD card and thermocouples probe.

The data recorder Testo 176T4 has four thermocouples probe for connection, USB interface and SD card for fast transfer to PC acquisition. Reading and recording data are from Testo Comfort Software installed on the PC acquisition (Figure-2).

Measuring System of Gaseous Emissions: The exhaust emissions are analyzed by a gas analyzer manufactured by Testo with the reference "Testo 350". The gas analyzer can measure continuously the concentrations of O_2, CO_2, CO, NO, NO_2, SO_2 and many others parameters.

Testo 350 is a professional portable analyzer of the gases emitted by the combustion device. The equipment consists of the control unit (control unit for measurement value display and control of the analyzer housing) and the analyzer housing (measuring device). The connection between the control unit and the analyzer box is via plug contacts with a cable data bus.

Data acquisition is done by a computer connected to the control unit via an USB cable. The collection is given by the interface software installed on the computer: easy Emission that controls the acquisition system from the PC (Figure-3).

Figure-3: Data Acquisition via PC.

Sampling of the fuel (Model Waste): The first step consists on the sampling of the fuel. The fuel blend is composed of *x%* of Wood, *y%* of Cardboard and *z%* of Plastic.

The wood is as a mixture of sawdust and wood chips. The cardboard and the Plastic are first cut into squares. This size distribution ensures the homogeneity of the fuel.

The mass of each sample to test is m kg of fuel mixture, or *X g* of wood, *Yg* of cardboard and *Z g* of plastic bags. The samples are weighed with a CAMRY balance and OHAUS balance with low sensitivity.

The fuel mixture combustion: The fuel mixture was placed in the furnace combustion chamber. The oven door is closed. The control panel turns the oven and burners on. The burners are started from the reset buttons. The gas analyzer gives the composition of the flue gases. The data analyzed gas and the oven temperature values are transmitted to the acquisition PC for processing. At the end of combustion, ash and bottom ash are collected, cooled, weighed and then evacuated after taking a sample for analysis. This mass is used to determine the rate τ of mass reduction after incineration:

$$\tau = 100\frac{m - m_r}{m}$$

With m the mass of fuel mixture, m_r the mass of incineration residues.

Results and Discussions

The Modeled Waste of Abomey-Calavi Town: Regarding the heterogeneous nature of the waste in its raw state, laboratory studies are very expensive and quite difficult to carry out, in addition they are not reproducible. The waste characterization methods used in the countries with experiments aim at identifying the main components of the waste and their essential properties. The methods used to achieve this are based on statistical techniques. These statistical studies show that wastes of heterogeneous nature are made up of main components of cellulosic, lignocellulosic and plastic types. These main and dominant components determine the properties of the waste. It is then possible to concept a model that will have the same properties as the raw waste. This allows reproducing the experimental conditions for research purposes.

Typological characterization of HSW of Abomey-Calavi town: Domestic wastes have a variable structure depending on the time and place of the production. In the case of a locality or a region, finding a representative mixture of the waste requires characterization operations according to the different periodicity of the year (rainy or dry), in order to obtain a statistically valid model.

Table-1: Typological Characterization of waste[1,6,15].

	Town of Abomey-Calavi		
Waste type	Dry Period	Rainy Period	Medium
Biodegradable	48,64	53,50	51,07
Sand	34,50	19,64	27,07
Cardboard Paper	1,14	1,76	1,45
Plastics	2,69	2,75	2,72
Glass	1,50	1,45	1,47
Metals	1,04	1,44	1,24
Textiles	2,28	2,79	2,54
Others	8,23	16,67	12,45

The latest waste characterization campaigns of the city of said area were made in bibliography[2]. The results are summarized in Table-1.

Triangular diagram of Household Solid Waste of Abomey-Calavi: Table-2 contains the thermochemical processing parameters of HSW of Abomey-Calavi city for both characterization campaigns made by Topanou[1,2]. These are the combustible fraction, inert rates and moisture (or water content). These parameters were determined by considering the fuel elements and inert elements in the balance sheet categories.

Table-2: Combustion parameters of HSW.

	Dry Season		Rainy Season	
Categories (%)	Without fines	With fines	Without fines	With fines
Combustible fraction	26,08	17,08	23,61	18,97
Inert rate	5,13	14,12	7,59	12,23
Water content (average)	68,80			

Figure-4 below illustrates the location of the points corresponding to these values in the combustion diagram of HSW. It is clear from this graph that no representative points of the composition of household waste in the dry season as in the rainy season is part of the combustion zone, so the waste of Abomey-Calavi do not meet the conditions for their thermochemical degradation.

Then it is important to test not only the dry waste but also the wet waste to determine the optimal incineration conditions of HSW in the city of Abomey-Calavi.

Model Waste: The heterogeneity of the waste does not allow them laboratory study, it is necessary to establish a model combustible mixture to as close as possible the composition of household waste, as defined by ADEME[9].

The composition of the representative samples of domestic refuse reflects the household waste fuel for thermochemical conversion. Thus, according to the experiences of experienced countries in the field of waste management and the literature, Organic and Biodegradable Materials are treated chemically as wood; cardboard, paper, textiles and sanitary textiles as cardboard; plastics and special waste as plastics; On this basis, the representative fuel mix of the city's waste consists of wood, cardboard and plastic in the proportions of 88%, 7% and 5% respectively as shown in Table-3.

Table-4 summarizes the compositions of the experimental mixtures used by some authors compared that of the present study.

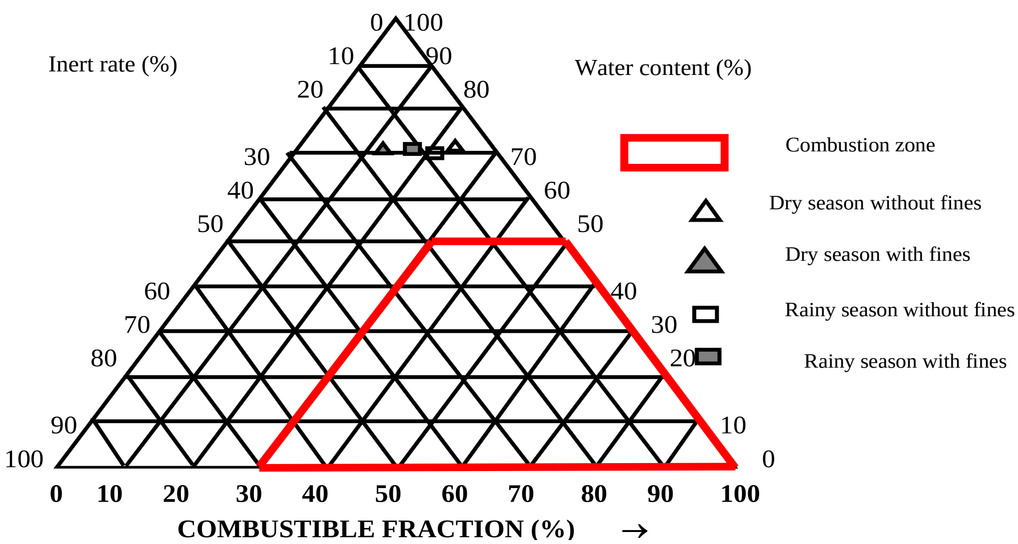

Figure-4: Combustion diagram of HSW of Abomey-Calavi town.

Table-3: Percentage Composition of Model Waste.

Percentage Composition	Wood	Cardboard	Plastics	Total
Mass	51,07	3,98	2,72	57,77
Proportion (%)	88,40	6,89	4,71	100,00
Proportion used (%)	88	7	5	100

Analysis of this Table-4 shows that the waste models elaborated for France and for the city of Ouagadougou in Burkina Faso have a lower amount of wood than the present study. By against, these models have higher waste cardboard and plastics quantities than the present study. These differences are explained by the fact that the wastes from the city of Abomey-Calavi have a very high proportion of fermentable materials. In addition, these wastes do not contain certain types such as special waste, unclassified fuel and composites that are considered in proportion to cardboard and plastic.

The plastic residues considered in the composition of the combustible mixture in this study are only Polyethylene (PE). Indeed, the other types of plastics are recycled and valorized in all the departments of Benin, and more particularly in the locality considered in this study.

Elemental composition of Model Waste: As Rogaume T.[12,20] and Nzhiou[11], retaining wood composition for this study is that of Baumont[17]. The elemental composition of these three main components is given in Table-5.

The various constituents of the waste model as wood, cardboard and plastic are essentially constituted of carbon atoms and hydrogen. The elemental composition of waste model is deduced from those fuels constituting the fuel mixture and proportions of them (88% for wood, cardboard 7% and 5% for plastic).

Based on Table 5 and the respective proportions of the constituents of the fuel mixture in Abomey-Calavi, the elemental composition of the fuel mixture is as follows: 52,0% Carbon, 6,0% Hydrogen, 0,2% Nitrogen, 40,0% Oxygen, 0,1% Sulphur, 0,1% Chlorine and 1,6% Ash.

Analysis of these results shows that the waste model of the city of Abomey-Calavi is mostly composed of Carbon, Hydrogen and Oxygen.

However, there is the presence of traces of chlorine atoms which are linked to the manufacturing process of the plastic bags and in particular to the fact that additives are added. Indeed, during his various research works, Ouiminga[18] carried out elementary analyses on plastic bags. The results showed that the plastic bags contained 300ppm of chlorine. These results were compared with the elemental analysis of pure polyethylene which did not contain chlorine. It can also be seen that this composition is very close to that of wood.

Approached empirical formula and Calorific Value (PCI) of Abomey-Calavi's Model Waste.

Table-6 provides a summary of the numbers of moles of atoms for each element present in the fuel mixture of the city of Abomey-Calavi and Calorific Value of each component. Indeed, Cl mainly from admixtures plastic bag has been neglected. Calorific Values of various fuels were determined by calorimetric bomb of LERMAB.

From Table-6, the approximate empirical formula of the fuel mixture of Abomey-Calaviis: $C_{4,295}H_{6,043}O_{2,527}N_{0,014}S_{0,02}$. This empirical formula is very similar to that found by Nzhiou[8] for the case of the city of Ouagadougou those the model for waste consists of 53% wood, 25% cardboard and 22% plastic (with 19% of PET and 2% Polyamide 6-6). In fact, the Household Waste of Ouagadougou contains others types of waste such as specials, composites, unclassed unburnables which are assimilated to plastics and papers. Passing unit mole of carbon atom, the approximate empirical formula become $CH_{1,4}O_{0,6}N_{0,003}S_{0,0004}$. This formula is very close to that of wood $CH_{1,395}$ $O_{0,645}$ $N_{0,002}$ proposed by Strehler[19]. This formula confirms once again that the waste model of the city of Abomey-Calavi is very close to the wood.

Combustion of Wood and Model Waste (MW): The model waste (88% of wood, cardboard 7% and 5% plastic) is mostly made of wood and its elemental composition very close to that of wood (Table-5) , it seemed interesting to compare the results obtained for tests performed on our model with those performed with wood.

Profiles of temperatures: Profiles of temperatures of combustion tests of wood and Model waste are given in Figure-5.

Table-4: Composition of different experimental mixtures[10-15].

Composition	Ouagadougou		France		Present Study
-	N'Zhiou[8,11,16,]	Salou[13]	Rogaume[20]	Barhe[11]	-
Wood (%)	53	54	41	43	88
Cardboard (%)	25	24	37	32	7
Plastics (%)	22	22	22	25	5

Table-5: Elemental analysis of dry matter[12,19,20].

Type of fuel	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Sulfur (%)	Chlorine (%)	Ash (%)
Wood	50,9	5,76	0,2	42,1	0,04	0	1
Cardboard	43,73	5,7	0,09	44,93	0,21	0	5,34
Plastics	73,8	11,5	0,2	4,8	0,2	2,8	6,7

Table-6: Moles numbers of Atoms and Calorific values of each type of fuel.

Type of fuel	C%	H%	N%	O%	S%	PCI (kJ/kg)
Wood	3,7327	5,0688	0,0126	2,3155	0,0011	18899
Cardboard	0,2551	0,3990	0,0005	0,1966	0,0005	15642
Plastics	0,3075	0,5750	0,0007	0,0150	0,0003	45948
Model Waste	4,2953	6,0428	0,0137	2,5271	0,0019	19999

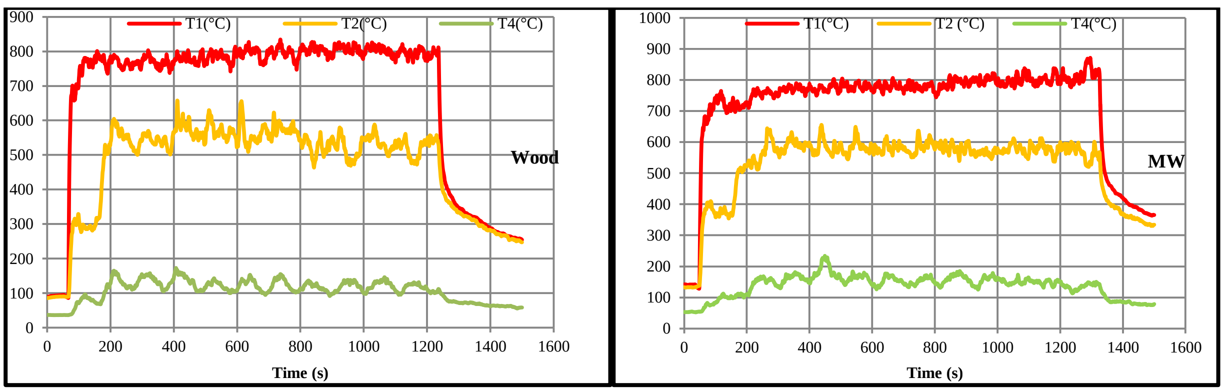

Figure-5: Profiles of combustion temperatures of wood and Model Waste.

These results show that the combustion of cellulosics and plastics solids materials can be divided into three major steps as already shown by Ouiminga and Rogaume[20-22] :

Drying and devolatilization: in the first combustion stage, the drying of the fuel takes place, followed immediately by the thermal degradation during which volatile compounds are produced. In this section, fuel degradation depends primarily on the energy (heat) brought to the solid and thus the combustion temperature. This combustion phase is illustrated by a sharp rise in temperature;

Oxidation of the volatiles in the gas combustion zone. This step is often called homogeneous combustion. Following the growth of the combustion, there is oxidation of volatile gases (flame zone), to achieve an established combustion phase. Temperatures are then stationary.

Combustion of char: It is the stage of oxidation of char which take place heterogeneous reactions. Temperatures are decreasing.

In other hand, Temperature T_2 (inside the combustion chamber) observed for the model waste combustion are slightly higher than those observed for the combustion of wood (steady state). This can be explained by the presence of plastic bags in the model waste whose calorific value is higher than that of wood and cardboard (PCI model > PCI wood). Indeed, during his work on burning plastic bags and millet stalks, Ouiminga[20,23,24] demonstrated the important influence of the proportion of plastic bags which increases with temperature.

Analysis of pollutants emissions: Figure-6 and 7 give CO and CO_2 concentrations versus combustion time t. The analysis of the graphs shows that during the first five minutes, the CO emissions during combustion of the two types of fuels give the largest CO values and begin to stabilize with a lower average value. This is explained by the significant presence of oxygen in the fuel. Indeed, the higher is the temperature, the higher the probability of breaking the C = O bonds and release oxygen in the fuel is high, which may result in the oxidation of hydrocarbons to CO.

Moreover, it is showed that CO_2become essentially from oxydation of CO[23-28], that explain that at the end of combustion (decreasing temperatures), it has increasing of CO emissions and the end of CO_2 emissions because the combustion temperature is not enough sufficient to cause the CO oxidation. At the stationary step of combustion, the CO and CO_2 emissions are relatively stables for both fuels.

Analysis of the graphs of Figure-7 which gives NO emissions plots of wood and MW, shows that during the stationary state, NO emissions are also stables for both types of fuels as it is showed by the graphs. The highest temperatures being below 1200°C, the produced NO is mainly become from fuel in combustion.

The results of wood and DM combustion are much closed and offer similaries tendencies. This can be explained by the fact that these two types of fuels have closed elemental compositions, empirical formulas and calorific values.

The Table-7 summarizes the average values of pollutants emissions for wood and model wastes of Abomey-Calavi town.

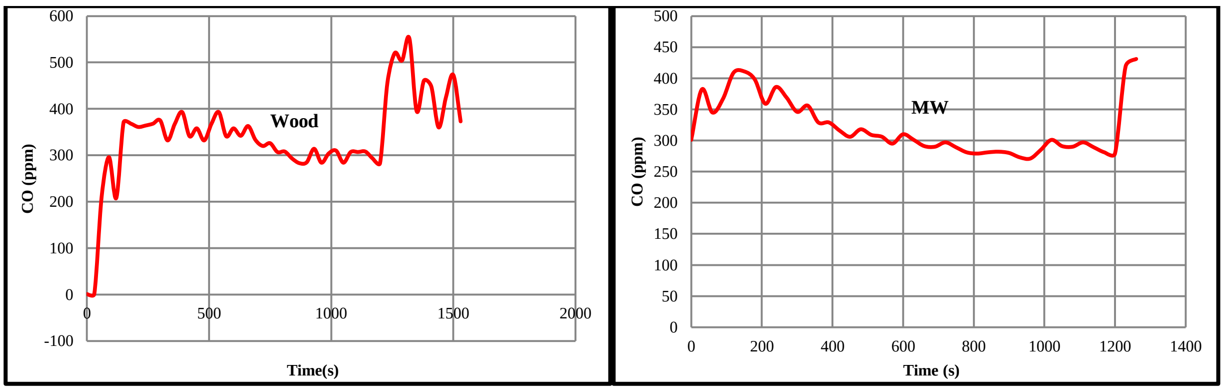

Figure-6: Emissions of CO (ppm).

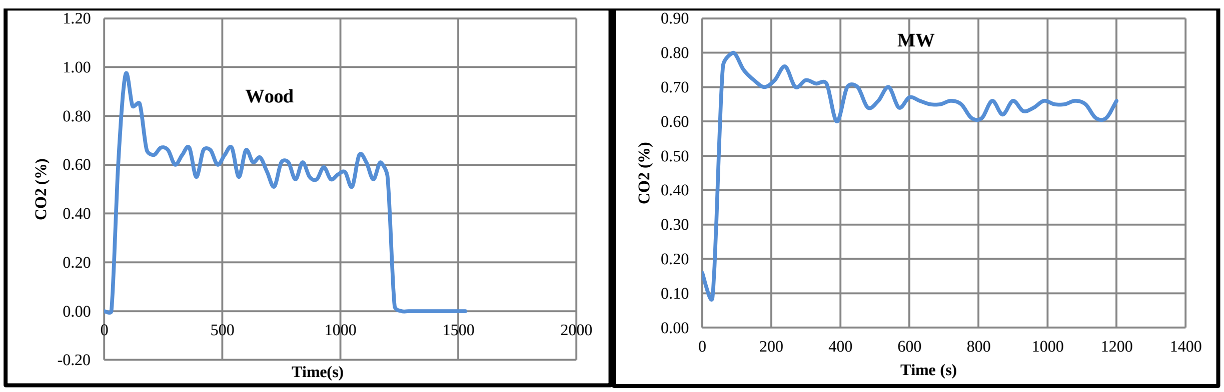

Figure-7: Emissions of CO_2 (%).

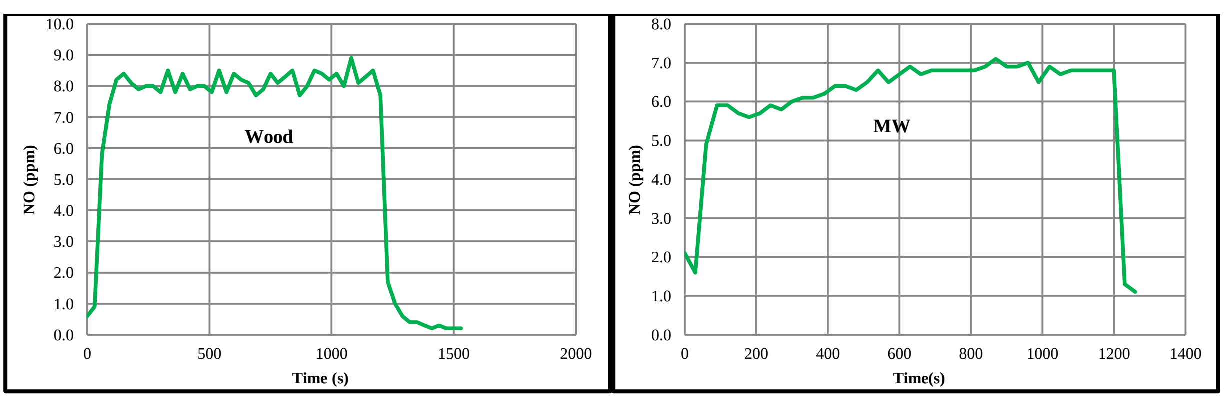

Figure-8: Emissions de NO (ppm).

Table-7: Pollutants emissions of various fuels.

Combustibles	CO (ppm)	NO (ppm)
Vacuum (extra fuel)	37	4
Wood	325	8
MW	316	6

Mass reduction rate after incineration: The mass average of residues obtained after incineration is 0,96kg, this value corresponds to mass reduction rate $\tau = 24\%$. This result confirms those found by many others authors according to mass reduction rate of incineration in literature[3].

Combustion of Wet Model Waste: Benin was a coastal country located in the tropical region, with humidity around 80%, household wastes include a significant amount of water. It then seemed necessary to experiment the model waste with defined amounts of water in order to perceive the effect of moisture on combustion.

Profiles of temperatures: Figure-9 shows the change in temperature T_2 during combustion of the Model waste with 20, 40, 50, 60 and 70% water. Table-9 presents the average values of temperatures and drying and temperature rise periods.

The analysis of the Figure-9 and the Table-9 shows that the average temperature T_{2m} of the combustion chamber decreases and the temperature stabilizing time increases when the amount of water increases in the fuel mixture. That is predictable. The following Figure-9 shows the evolution of the temperature T2m and stabilization time depending on the proportion of water. The average humidity of household waste in the city of Abomey is 68.85% ≈70%, according to the work of Topanou[1,2], the average temperature of the oven and the temperature rise time are respectively 399°C and 872s.

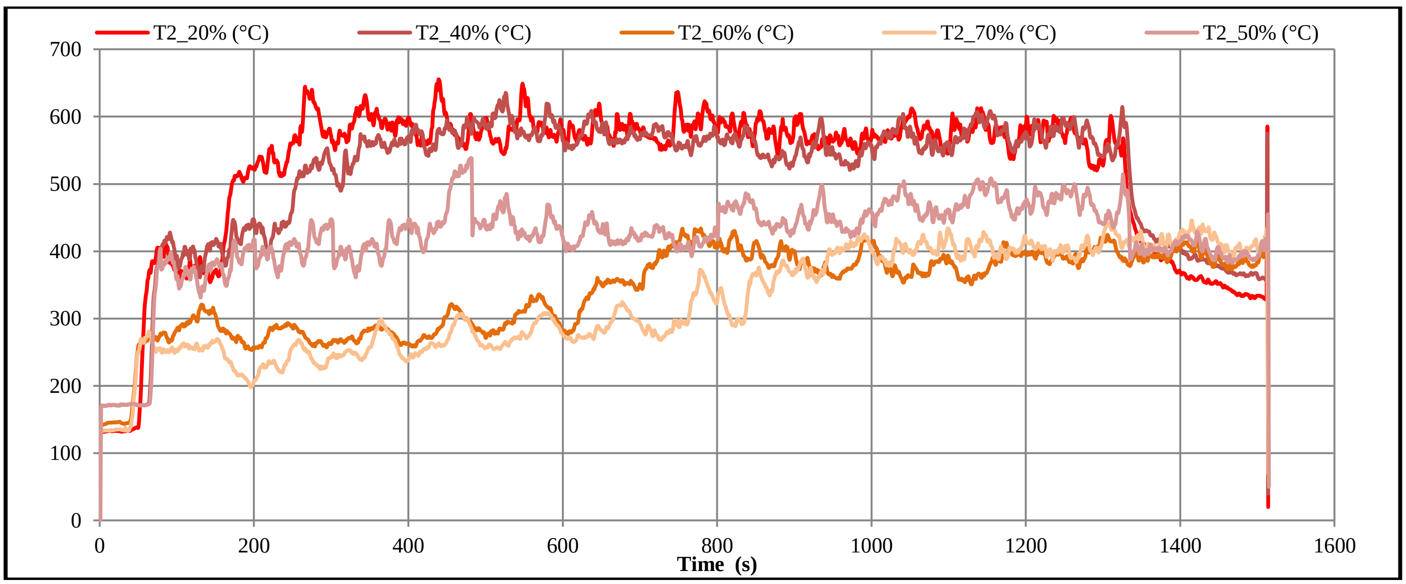

Figure-9: Profile of temperatures T_2 at 20, 40, 50, 60 and 70% water content.

Table-8: Average temperatures in steady state and drying and temperature rise time.

Water (%)	T_{1m}	T_{2m}	T_{Fm}	Drying and temperature rise time (s)
0	939	628	108	60
20	888	578	103	200
40	833	567	139	300
50	802	451	110	400
60	782	386	118	643
70	811	399	118	872

It is commonly accepted that moisture represents an obstacle for combustion or other thermo chemical treatment (combustion triangle) by lowering significantly the calorific value of the fuel. The results above (decrease in temperature and increase the drying time) readily confirmed by a progressive energy consumption.

It is therefore essential that a good strategy well thought out is in place in advance to obtain considerable decrease of humidity in household waste to an effective and sustainable management.

Emission of pollutants: Table-10 summarizes the sample mass and the measured amounts (average) of CO and NO during combustion of the wet waste.

The analysis of this Table shows that when the mass of fuel double, the amounts of CO and NO emitted tend to doubleas already shown some authors[13,29] to the waste with 0% of water.

The proportion of water does not appear to have a significant impact on emissions of CO and NO between 0 and 20%. From 20% water, CO emissions begin to increase significantly, from against the emissions of NO vary slightly. These results show that the combustion of a fuel with high humidity not only consumes a huge amount of energy, but also leads to a very important issue in CO. Moreover, these results confirm those of Barhe[11] whom showed in his work that the temperature also affects the emission of NO in the primary zone fuel during combustion of waste. Indeed, when the water content becomes very high, the amount of NO has a decreasing trend. The graphs of the evolution of CO and NO are given by the following Figure-11.

Table-9: Emission of CO and NO during combustion of wet waste.

Moisture (%)	Mass (kg)	CO (ppm)	NO (ppm)
0	4,00	316	6
0	2,00	132	3
20	2,00	132	4
40	2,00	236	4,5
50	2,00	314	3,5
60	2	393	3
70	2	386	2

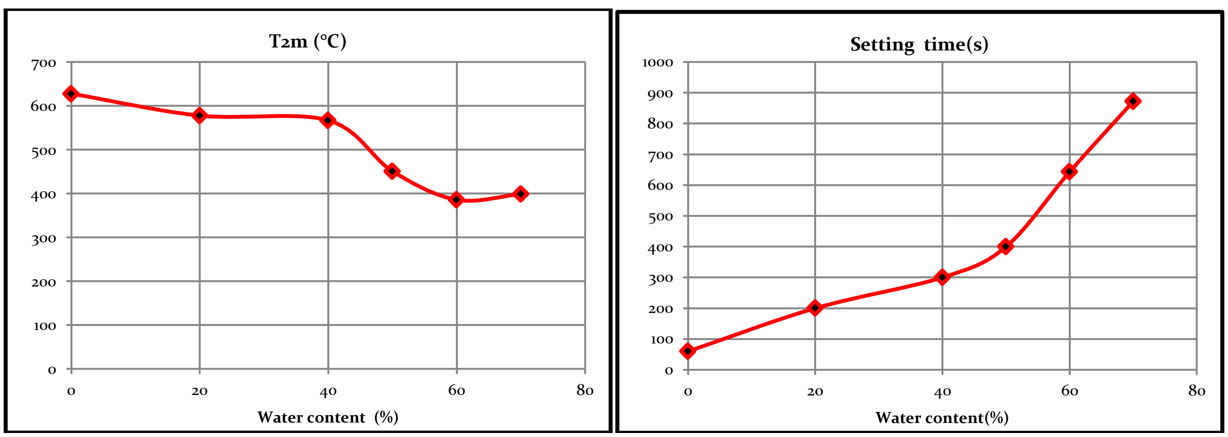

Figure-10: Average temperature T_{2m} and stabilization time versus the water proportion in Model waste.

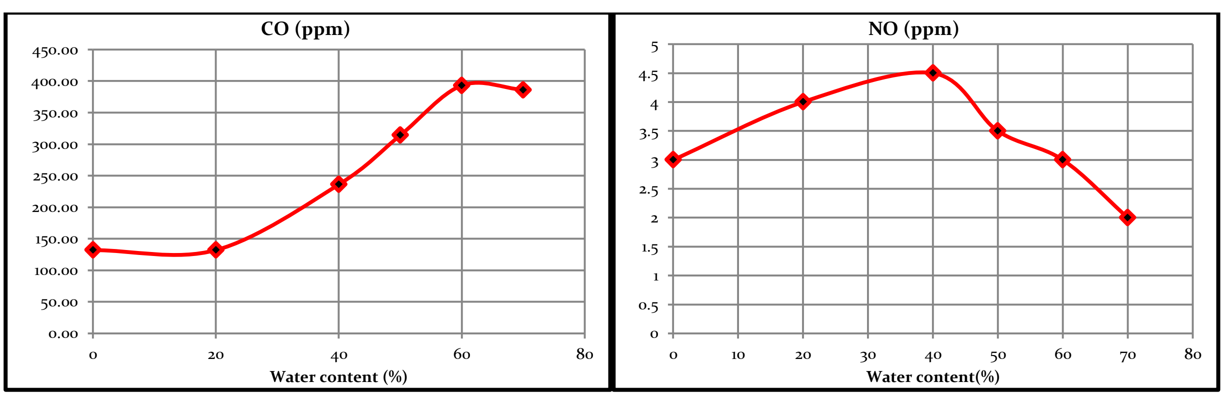

Figure-11: Emissions of CO and NO of Model Waste versus the water proportion.

Conclusion

The current waste management system in the city of Abomey-Calavi has negative impacts on the environment. The study of the characterization of household waste conducted through two campaigns helped to develop a model representative of their waste combustible fraction (88% wood, 7% Cardboard and 5% plastic). Combustion parameters of HSW do not meet the requirements to be incinerated. In fact, the moisture of the domestic waste of the locality is very high. Thus, tests were carried out not only on dry waste but also on the wet waste.

The results obtained in the dry waste are very satisfactory as being very close to those obtained on the wood.

Between 0 and 20% humidity, the results are close to those obtained in the dry waste. By against, over 20% of water content, the results are not satisfactory. Indeed, the average temperature of the combustion chamber is low, the stabilization time is increasing and the CO content increases dramatically.

Therefore, for better treatment of waste combustion (or others thermochemical treatment), a strategy must be put in place in advance to reduce humidity at least 20%.

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