Using Dulong and Vandralek Formulas to Estimate the Calorific Heating Value of a Household Waste Model

Jean Fidele NZIHOU[1*], Salou Hamidou[2], Medard Bouda[3] , Jean Koulidiati[4], B. Gerard Segda[4]

[1] Higher Teachers Training School / University of Koudougou, [2] Catholic University of West Africa /Academic at Bobo-Dioulasso, [3] Institut de Recherche en Mine et Environnement, Université de Québec en Abitibi-Témiscamingue. Québec [4] LPCE / University of Ouagadougou

(*) Corresponding author : jean_fidele@hotmail.com

Abstract— In this paper, Dulong, modified Dulong, Vandralek and direct formulas have been used to calculate the higher calorific value (HCV) and lower calorific value (LCV) of the waste model of the combustible fraction of the town of Ouagadougou. Different results from these formulas have been compared to experimental results obtained form measures made with a semi-industrial calorific heating value measurement apparatus. Comparison shows that the Dulong and Vandralek HCV formulas calculation gives us the lowest relative errors or differences in respect of the experimental LCV. On contrast, the direct LCV calculation formula give use the biggest relative error. This suggests that Dulong and Vandraleck formula could help quickly estimate the calorific value of a household waste combustible fraction model.

Keywords — Waste model, Combustible fraction, Calorific heating value, Elemental makeup, Dulong formula, Vandralek formula, Sensible heat.

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1 INTRODUCTION

In developing countries (DCs), the production of urban waste has increased in recent decades with the changing lifestyles and fast population growth in large cities. These wastes pose a very serious environmental problem. Mechanisms and management systems are almost nonexistent. And in some African capitals, less than 30 % of waste is disposed off. This situation is more aggravated by the attitude of the populations themselves, who do not have the reflex of "useful disposal" and continue to release more and more unsorted waste. Until year 2010, there were almost no national effective sanitation strategies for these cities because priorities are assigned to other development sectors such as the fight against desertification and concerns for food security. It was and is still usual to dispose of household waste by land filling outside urban areas.

Ouagadougou, the biggest city of Burkina Faso for example only got its first land filling facility on February 05, 2005. In year 2011, 300 000 tons of municipal waste were produced in the Burkina Faso's political capital, 243 000 tons were collected and processed, of which 6% was recycled in compost or pellets [1]. This means that more than

90% of municipal waste is stockpiled. The same is true in several sub-Saharan countries.

As a result, the town of Ouagadougou's first and single modern stockpiling facility will only last for 20 years. The lifespan of this facility seems short, because if used, a waste incineration facility could help reduce the volume of waste up to 90% and thus augment the lifespan of a stockpiling facility for the same built capacity.

In addition, at the landfill facility of Ouagadougou, the waste is exposed to air. This results in obvious visual pollution and odor pollution of surrounding areas. It is established that the landfill sites are sources of gas production resulting from chemical reactions and microbes acting upon the waste as the biodegradable materials begins to break down [2]. Due to the constant production of landfill gas, the increase in pressure within the landfill (under the wastes) causes the gas' release into the atmosphere. Such emissions lead to important environmental, hygiene and security problems in the landfill [3], [4]. According to [5], landfill gases have an influence on climate change. The major components are CO_2 and methane, both of which are greenhouse gas. Methane is considered over 20

times more detrimental to the atmosphere than Carbon Dioxide.

In several developed countries, incineration has become one of the two most used waste disposal method [6]. For example since June 1, 2005, untreated waste is no longer land filled in Germany [7], the same apply to England as of October 30, 2007 [8]. Waste incineration thus appears as an interesting alternative to the traditional disposal methods and can no longer be overlooked in several circumstances.

However, due to its characteristics, incineration is only suitable for waste within certain properties, such as moisture content (< 50%), the inert rate (< 60 %), the rate fuel fraction (> 25 %) and a sufficiently high Calorific Value (CV).

This study proposes, from the characterization of waste in the city of Ouagadougou, to complete the implementation of the model of the combustible fraction of household waste of this city proposed by [8]. In addition, it aims to compare results from Dulong, Vandralek and direct formula to those of a semi industrial lower calorific value measurement apparatus the above authors had used.

2 LITTERATURE REVIEW

According to [9], the calorific value of a substance is the heat produced by the combustion of a unit quantity of that substance under specified conditions. Calorific value may be expressed as Gross Calorific Value (Gross Heat of Combustion at Constant Volume) Q_v (gross) or Net Calorific Value (Gross Heat of Combustion at Constant Pressure) Q_P (net).

2.1 Relation between heating values

The difference between the two calorific or heating values depends on the chemical composition of the fuel. In the case of pure carbon or carbon monoxide, the two heating values are almost identical, the difference being the sensible heat content of carbon dioxide between 150°C and 25°C.

Sensible heat is heat exchanged by a body or thermodynamic system that has as its sole effect a change of temperature [10][11][12][13].

In contrast, latent heat is added or subtracted for phase transitions at constant temperature, for examples: heat of vaporization or heat of fusion. For hydrogen the difference is much more significant as it includes the sensible heat of water vapor between 150°C and 100°C, the latent heat of condensation at 100°C, and the sensible heat of the

condensed water between 100°C and 25°C. All in all, the higher heating value of hydrogen is 18.2% above its lower heating value (142 MJ.kg^{-1} vs. 120 MJ.kg^{-1}). For hydrocarbons the difference depends on the hydrogen content of the fuel. For gasoline and diesel the higher heating value exceeds the lower heating value by about 10% and 7% respectively, and for natural gas about 11% [14].

A common method of relating HCV to LCV is:

$$HCV = LCV + hv \frac{nH_2O,out}{nfuel,in} \quad (1)$$

Where [15]:
- h_v is the heat of water vaporization,
- nH_2O,out is the moles of water vaporized
- nfuel,in is the number of moles of burned fuel.

Equation (1) can also be rewritten as follows:

$$HCV = LCV + 44.03 \times N \quad (2)$$

Where [16]:

N: number of moles of water produced by the combustion process.

44.03 : the latent heat of vaporization of water which equal to 44.03 kJ.mol^{-1}.

According to [16], the gap between LCV and HCV for a solid fuel (coal) is between 2 and 8%. For wood this gap is between 7 and 8%.

2.2 Difference between HCV and LCV

The difference between HCV and LCV definitions causes endless confusion when quoters do not bother to state the convention being used [17]. Since there is typically a 10% difference between the two methods for a power plant burning natural gas, it is recommend that for only benchmarking part of a reaction the LHV be used [14]. On the contrary, using HCV is recommended for overall energy efficiency calculations. In order to avoid confusion, and in any case the value (HCV or LCV) or convention should be clearly stated.

2.3 Calculation of the CV

Below are some formulas that enable one to directly calculate LCV and HCV provided the elemental makeup of the fuel is known.

Calculation of the HCV [16]:
- *Dulong formula*:

$$HCV = 4.18 \times (78.4 \times C + 241.3 \times H + 22.1 \times S) \quad (3)$$

- *Modified Dulong formula*:

$$HCV = 4.18 \times (78.4 \times C + 241.3 \times (H\frac{O}{8}) + 22.1 \times S) \quad (4)$$

- *Vandralek formula*:

$$HCV = 4.18 \times (85 \times C + 270 \times H + 26 \times (S - O)) \quad (5)$$

Equations [4], [5] and [6] are expressed in $kJ.kg^{-1}$

Calculation of the LCV (direct formula) [16]:

$$LCV = 4.18 \times (94.19 \times C - 0.5501 - 52.14 \times H) \quad (6)$$

3 MATERIALS AND METHODS
3.1 LCV measurement unit

The LCV measurement device was initially developed by EQUADOR in favor of the Laboratory Combustion and Detonation (LCD) of the University of Poitiers, France. The device essentially comprises: a cylindrical boiler surrounded by a tank with a 52 liters of water heat exchanger. Five (05) K-type thermocouples were set at different measurement points, to monitor temperature changes. These jacks temperature are connected via a centralized unit to a Personal Computer with a DASTC data acquisition cable. A Testotherm350® gas analyzer is connected via RS232 bus to the computer and allows for real-time smoke temperature and oxygen concentration. Acquisition program temperatures and gas content was developed using the TESTPOINT software and implemented on the PC. Data acquisition is initiated approximately four (4) minutes before the starting of the combustion. This enable us helps to record the ambient air oxygen content of in the room. The end of combustion is determined by the stabilization of the oxygen content to its starting value. The acquisition is stopped as soon as the oxygen content stabilizes and data are stored in an Excel file type.

3.2 The model waste

Direct studies on industrial facilities are not only too expensive, but also difficult to carry out, mainly because of the heterogeneity of real waste. In addition, because of their heterogeneity and varying composition, experiments with real waste are very complex and difficult to master. For the sake of reproducibility of experiments, we use the model of the combustible fraction of household waste of the city Ouagadougou developed by Nzihou (2005). Waste characterizations methods aim to identify the main components of waste and it's essentials properties. These methods based on statistical techniques shows that highly heterogeneous wastes consist of main components of cellulose's type and plastics. These mains and dominants components control the waste properties. It is then possible to draw a model waste from the real waste that will have the same properties. This enables one to reproduce experimental conditions for researches purposes.

3.3 Experimental protocol

All experiments were performed according to following procedure:
• measuring the mass of fuel with a precision balance,
• launching the acquisition on the PC type computer,
• checking air flow control,
• igniting the fuel and closing the door,
• waiting for the stabilization of water temperatures.

The experiment is terminated when the flue gas temperature falls to a value close to that of water circulating in the device in closed circuit. Before starting another test, the furnace is cooled in the ambient air until the thermocouples indicate temperatures near the initial state. Five (5) measurements were made for the determination of LCV_1 and LCV_2.

4 RESULTS AND DISCUSSION
4.1 The waste model drawing

From the results of waste characterizations, one can then draw a model waste that enable laboratory scales studies, namely combustions test. In this part of our work, we will first give the waste model of the town of Ouagadougou. It is drawn from waste characterizations carried out in the town of Ouagadougou in dry season by [19] and wet seasons by [20]. These two characterizations were chosen in order to cover an entire year of characterization campaign. With the assumptions made by [20], we draw Table 1 below.

Table 1. Town of Ouagadougou's waste makeup

| Components | Assimilation to … | | | |
	Wood	Paper	Plastic	Total
Fermentable	39.50	---	---	39.50
Papers	---	8.56	---	8.56
Textiles	---	5.82	---	5.82
Plastics	---	---	9.56	9.56
Metals	---	---	---	4.18
Glass	---	---	---	2.73
Specials	---	---	1.59	1.59
Unclassed	---	2.27	2.27	4.54
Unclassed	---	---	---	18.49
Composites	---	2.01	2.01	4.02
Total	39.5	18.86	15.43	100

From Table 1, we see that there are only 4.18% of metals in the town of Ouagadougou's household waste. This owe to the fact that in this low level income country, peoples do recycle metals from trash. There is almost nothing significant remaining as metals at the land filling facility, as metals have economic value in this country and is picked out at the upstream for recycling or reuse. Glass also only represents 2.73% of the waste for same reasons. Economical context therefore avoid us to deals with high quantities of metals and glass in household waste.

The waste model we have drawn is restricted to the combustible part of the municipal waste of the town of Ouagadougou. Several chemicals analysis had shown that complexes components as the fermentable and papers had similar properties as simpler components such as wood and cardboard [21], [22]. This led us to assimilate fermentable components to wood. Papers and cardboards are made from vegetal fibbers. Cardboard is obtained by paper agglomeration and it has a similar chemical composition as papers. We then assimilated papers to cardboard. Municipal waste characterizations in France had showed that plastics materials are made with 91% of poly ethylene (P.E.T.) and 9% of polyamide 6-6 [23]. Specials consist of plastics films and their polymers. They are assimilated to plastics. With the others assumptions were made by [14], let us consider the weight of each component in the total burnable material waste. We obtain the Table 2 below:

Table 2. Proportions of components in the model waste

	Wood	Card board	P.E.T.	Polyamid 6-6	Total
Weight	39.5	18.86	14.02	1.41	73.79
Proportion	53.53	25.56	18.99	1.91	99.99
Percentagee	53.5%	25.5%	19%	2%	100.0%

The composition of this model waste is 53.5% of wood, 25.5% of cardboard, 19% of P.E.T and 2% of polyamide 6-6. In practice, P.E.T and polyamide 6-6 are designated und the name plastic with total percentage of 19 + 2 = 21 %. Thus the composition of the used fuel: Wood: 54%, cardboard: 25% and plastic: 21%. Further calculations were done by [18] and led to the following elemental formula for this household waste model:

$$C_{4.24}H_{6.16}O_{2.69}N_{0.01}S_{0.005}$$

4.2 Calculations of the calorific values

Equations (3) to (5) have been used to calculate HCV. Equation (6) gives us the LCV. Experimental data are LCV obtained from the device we have. Thus equation (2) is used to convert the measured LCV into HCV, before comparisons are made.
We will distinguish two cases.

In the first case the experimental value of LCV for the town of Ouagadougou's combustible fraction household waste as determined in reference [8] is LCV = $15,3 \pm 4,4$ MJ.kg^{-1}, results are in table 3 below.

Table 3. HCV comparisons in first case

| Case 1: LCV_1 = 15284, HCV_1=16506.72 | | | |
| Formula | Modified | | |
	Dulong (3)	Dulong (4)	Vandralek (5)	Direct (6') [a]
%	228,15	174,09	202,93	198,60
HCV	22815,25	17409,35	20292,53	19860,06
RE[b]	-38%	-5%	-23%	-20%

(a): HCV = 1.08*LCV
(b): RE =relative error = (HCV_1 − HCV)/HCV_1

In the second case the experimental value of LCV for the model of the combustible fraction of the town of Ouagadougou as determined in a work

under press is LCV = $20{,}22 \pm 4{,}45$ MJ.kg^{-1}. This lead to data in table 4 below:

Table 4. HCV comparisons in second case

Formula	Dulong (3)	Modified Dulong (4)	Vandralek (5)	Direct (6') [a]
%	228,15	174,09	202,93	198,60
HCV	22815,25	17409,35	20292,53	19860,06
RE [b]	-4%	20%	7%	9%

Case 2: $LCV_2 = 20220$, $HCV_1 = 21837.6$

(a): HCV = 1.08*LCV

(b): RE = relative error = $(HCV_2 - HCV)/HCV_2$

Value of the LCV in table 3 is under estimated because sensible heat of fumes wasn't taken into account. That fumes sensible heat was later taken into account and led to a higher LCV. Therefore we will only focus on results from table 4.

The Dulong's formula give us a negative variation which express the fact that the Dulong's formula overestimate the calorific value in our case.

Modified Dulong, Vandralek and direct formulas leads to positive relative errors. This expresses the fact that these three formulas underestimate the CV in our case.

5 CONCLUSIONS

The Dulong formula (-3%) and the Vandralek formula (+7%) gives us the smallest relatives errors when compared to experimental calorific values of the town of Ouagadougou's combustible fraction household waste model. A complete waste characterization requires the knowledge of all the waste parameters (makeup, moisture content, density, granularity, etc. Some of these parameters are not well defined for a waste due to the waste heterogeneity. As the calorific value and elemental makeup of a waste are relatively well defined, the two formulas above can be used for a rapid estimation of the higher calorific value when the waste makeup is known. Other formulas do exist, but require the knowledge could be of great help of parameters not well defined for a waste.

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