

EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF SPANISH BIOMASS BOILER RESIDENTIAL TECHNOLOGY: VOC FORMATION AND CONTROL

Díaz-Ramírez, M¹ *, Sin A.¹, Sala S¹, Canalís P.^{1,2}, García-Galindo D.¹

¹ Research Centre for Energy Resources and Consumption (CIRCE), Mariano Esquillor, 15 - Edificio CIRCE. Zaragoza, Spain

² University of Zaragoza, Department of Thermal Machines and Motors, Campus Río Ebro – University of Zaragoza, Spain
* corresponding author: mdiaz@fceirce.es Phone: +34-876555661, Fax: +34-976 732 078

ABSTRACT: Biomass heating generation has been extensively positioned as a strong market in many European Countries. Nevertheless, it can result into a source of undesired air pollutants, such as particulate matter (soot and ash particles) and also including products of incomplete combustion, such as carbon monoxide (CO) as well as volatile organic compounds (VOC). The latter are especially hazardous due to may cause negative health effects which varies greatly from those that are highly toxic to those with no known health effect. Due to the VOC impact, stricter emission limits have been set by the European standard EN 303-5:2012 for residential boilers up to 500 kW_{th}. As a result of the current situation, the Spanish sector governments and industries are investing to develop high performance technology focused on the achievement of zero emissions. To be successful on the VOC reduction task according to the EN-303-5 restrictions, it is needed to attain a deeper knowledge on the VOC formation influencing factors. It has been identified that VOC emissions vary significantly depending on fuel, boiler design and operation conditions. Accordingly, objectives of the paper were: i) To present an overview of the more relevant conditions that affect VOC formation and ii) To present VOC emissions results when burnt woody reference pellets into a study-case 32 kW_{th} grate-fired boiler. This paper is presented as an attempt to evaluate effects of those factors on VOC emission formation and to identify key aspects to attain a higher performance technology.

Keywords: biomass, combustion, emissions, wood pellet.

1 INTRODUCTION

Last decades biomass use for supplying heating demands has substantially increased. This application offers several advantages although it may also introduce some difficulties related to both fuel properties complexity and conversion needs.

Besides problems related to the ash fraction, one barrier associated with burning biomass is that it is a source of air pollutants, including products of incomplete combustion. Among them are counted carbon monoxide (CO), particulate matter (PM), as well as volatile organic compounds (VOC). Their emissions may affect local air quality and may have influence on human health. Particularly, the VOC emissions are especially hazardous mainly due to their carcinogenic effects validated by several epidemiological and combustion studies [1-3]. They comprises Organic Gaseous Carbon (OGCs) compounds, which are constituted by the most harmful substances usually found to be Poly-aromatic hydrocarbons or Polycyclic Aromatic Hydrocarbons (PAH's), and dioxines.

Due to the VOC related impact, specific emission requirements for biomass combustion in a residential level have been set by the European standard EN 303-5:2012. This standard refers to residential boilers up to 500 kW_{th} and classifies the boiler performance into three categories taking into account thermal efficiency, total particles concentrations as well as CO and VOC emissions. Considering the strictest boiler category by this standard, Class 5, VOC emissions should be lower than 20 mg/Nm³ at 10% O₂.

Accordingly, a well positioning technology should guarantee an appropriate control of the VOC emission level.

Many of the investigations arising from biomass combustion, focused on this pollutant type, have provided more insight their nature and formation. It has been elucidated that VOC emissions are affected by several conditions, which can be grouped as factors related to

both the fuel type and the combustion conditions applied to the fuel thermal conversion stage.

Concerning the former, the biochemical biomass composition and its thermal decomposition have been considered to be relevant influencing conditions. Generally, it can be considered that thermal decomposition of hemicelluloses takes place between 200 and 260 °C, cellulose degrades at 240-350 °C, and lignin at 280-500 °C. Particularly, thermal degradation of lignin leads to release of benzene, phenol and their related compounds, eugenol and its derivatives, and oxygenated compounds. It has been also proposed that carbonhydrates-to-lignin ratio is an important factor in predicting VOC emissions from biomass combustion [4].

In terms of technical factors, there are some experiences that describe the influence of conversion conditions on the VOC formation. Depending on the fuel type and technology used the technical factors can be grouped as the ones related to temperature, reducing or oxidizing atmosphere and load effect [5-7].

Despite the fact that some research advances have been attained concerning the conversion technology and control of VOC emissions, state of the art of the formation influencing factors is relatively scarce. Research efforts focused on elucidating specific control actions are currently demanded.

In Spain, governments and industries are investing to develop high performance combustion technology focused on the achievement of zero emissions. Due to the negative health effects attributed to the VOC emissions, the definition of specific strategies towards their control is a main concern among the Spanish biomass boiler developers.

Taking into account the current demands of industrial developers and existing state of art of the VOC emissions, the aim of this paper was to advance on the knowledge of the conditioning factors and technology improvements focused on the VOC emissions reduction in a real conversion unit. To achieve this aim two main objectives have been defined: i) providing an overview of

of the more relevant factors of influence on the VOC formation; ii) characterizing VOC emissions from a real commercial residential boiler (study case 32 kW_{th}) considering a methodological study of fuel, technology design and operating condition effects based on the European Standard EN 303-5:2012 testing procedure.

2 GENERAL OVERVIEW OF INFLUENCING FACTORS ON VOC EMISSIONS FORMATION

Similarly to other products of incomplete combustion, the concentration of VOC is strongly influenced by the combustion conditions. Specifically, temperature, turbulence and residence time (3T's criterion) have an important effect on the VOCs formation. Main factors related to these three main categories will be explored in this section.

2.1 Temperature

It has been identified a good correlation among the VOC formation and temperature. Generally, it has been considered that formation and destruction of tars and

PAH need high temperature and reaction severities for thermal destruction.

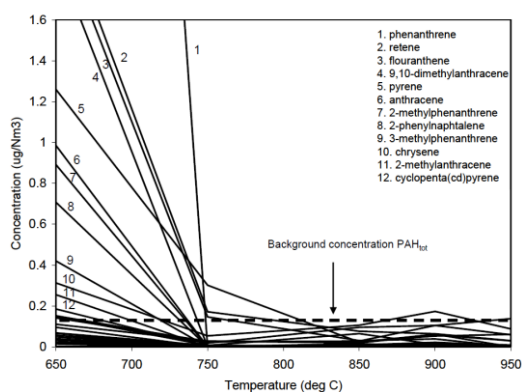


Figure 1: Concentrations of separate PAH compounds in the flue gases during combustion of softwood pellets as a function of temperature in the post-combustion zone after the fuel bed. Adapted from [8].

As it is shown in Figure 1, there is great potential for reducing the concentration of PAHs, if temperatures are greater than 800 °C in the post fuel bed area [8]. However, this trend may be different for other fractions.

Table I: Characteristic smoke components emitted from biomass burning with different combustion efficiencies. Adapted from [9].

Comb. Condition	Compounds	Technology
Incomplete (<700 °C)	Methoxyphenol and 1,6-Anhidroglucose	Fire-place, Tiled stove
Mid efficient (700-900 °C)	Benzene and polycyclic aromatic hydrocarbons	Wood boiler
Efficient (>900 °C)	Low concentration of benzene and polycyclic aromatic hydrocarbons	Ecolabelled wood boiler Wood pellet burner

It can be seen from Table I that the VOC fractions can differ among different technology types according to the temperature working range of each case. Particularly, it has been identified that incomplete combustion at relatively low temperatures in traditional appliances, such as wood stoves and open fireplaces, emits large amounts of organic compounds [9]. These are mainly primary decomposition products of the lignin, cellulose and hemicelluloses of the fuel and their total proportion decreases between 600°C and 1000°C. On the contrary, the proportion of secondary combustion products, such as the health hazardous benzene and polycyclic aromatic hydrocarbons, increase with increasing combustion efficiency [9]. This trend is exemplified by the high concentrations of benzene achieved at the more advanced technologies, as it is shown in Figure 2.

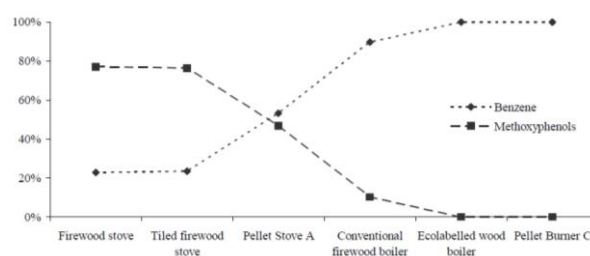


Figure 2: Relation between methoxyphenols and benzene sorted after increasing combustion efficiency by applying different technologies. Adapted from [9].

Based on the comparison of the trends presented from previous studies, it can be anticipated that although the effect of high temperature is important for achieving a reduction of total VOC concentration, this factor also favors an increase of the carcinogenic components relative fraction. In addition, it is well known that high temperatures may cause adverse control of other pollutants such as NO_x (i.e., Thermal NO_x) and on the melting point of biomass ash. Accordingly, a proper control of temperature is important not only because of the effect on VOC formation but also on other biomass related problems attributed to its combustion.

2.2 Air supply and turbulence

These two factors have a direct relationship with design parameters and operation of combustion equipment. In particular, the design parameters primarily involve the combustion chamber dimensions and the air distribution system. Regarding the operating conditions, the total amount of combustion air and their distribution have special relevance. In biomass combustion, it can be distinguished three combustion regimes considering the level of excess air available in the combustion chamber: low, optimum and high excess air ratio [10].

At low excess air ratio, soot is formed in hot zones in the flame as a synthesis product through the release of hydrocarbons containing primary tars formed during pyrolysis, formation of secondary tars in an atmosphere with lack of oxygen, PAH formation, and finally, release of hydrogen during particle growth, thus resulting in a high C/H ratio.

At optimum excess air, near complete combustion is achieved, if good mixing of combustible gases with air is guaranteed and quenching of the flame is avoided. Control of turbulence is crucial for achieving this condition.

At high overall excess air, the combustion temperature decreases and incomplete combustion is found. Due to low temperature, the formation of soot and the release of hydrogen is suppressed, resulting in high concentrations of primary and secondary tars formed during pyrolysis consequently leading to condensable organic compounds in the flue gas with low C/H ratio.

If good mixing between the air supplied and flue gases is achieved, the concentrations of uncombusted pollutants can be reduced to levels close to zero. An operation at low excess air is possible (i.e., excess air $\lambda < 1.5$), thus enabling high efficiency and high temperature with complete burnout [11]. However, an accurate process control (e.g. CO/ λ -controller with use of sensors for CO and λ) is needed to ensure optimum excess air in practice. For this purpose, self-adjusting control systems with use of sensors for CO and λ (CO/ λ -controller) or for CO and temperature have been developed.

2.3 Residence time

In general, this parameter must be adjusted to provide sufficient time for reactions that take place in the fuel bed and in the combustion chamber. It will greatly be affected by the combustion boiler geometry.

The effect of residence time has been suggested to be less significant than the impact of temperature on the VOC formation. The importance of residence time at high temperature ($>850^{\circ}\text{C}$), air rich and well mixed conditions was shown for wood pellets to be limited for 0.5-1.0 s in the post combustion zone to obtain complete combustion conditions with almost a total depletion of PIC's. [8]

Temperature and residence time after the bed section in the reactor was varied according to statistical experimental design covering the ranges 650-970 $^{\circ}\text{C}$ and 0.5-3.5 s, respectively. Higher temperature resulted in lower PIC emissions with no significant effect of residence time as it can be seen from Figure 3.

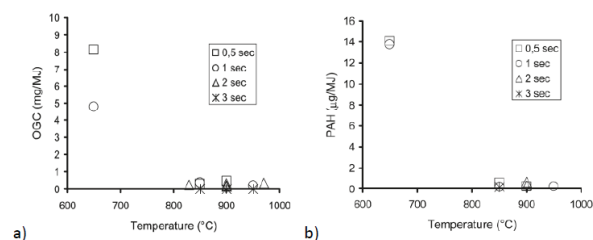


Figure 3: OGCs and PAHs emissions as a function of temperature and residence time in the post-combustion zone. Adapted from [9].

3 STUDY CASE.

3.1 Main system characteristics

The technology selected for the tests was a 32 kW grate automatically feeding biomass heating boiler firing high quality wood pellets (pellets type A). This boiler comprises a vertical exchanging section and automatic burner cleaning. Primary and secondary combustion air is automatically controlled and provided by different nozzles into the burner.

Measured gaseous emissions involving VOC, O₂, CO and NO compounds were carried out in the exhaust gas

directly after the boiler according to restrictions set by the EN 303-5 standard. Continuous measurements of gaseous compounds (O₂, CO and NO) were performed with electrochemical sensor (Flue gas analyzer Testo 350XL). VOC Measurements were done by using a Portable TOC Analyser for Stack Emissions (Polaris Flame Ionization Detector, FID). TOC Conversion into VOC was done following method defined by the EN 12619 standard.

3.2 Combustion tests and results

Different boiler performance tests were carried out at nominal heat output according to the EN 303-5:2012 (UNE-EN 303-5:2013) and ISO/IEC 17025 requirements. These tests were done by accredited personnel of the Electrical Metrology Laboratory owing to CIRCE Foundation. Among other accreditations, CIRCE is accredited by ENAC (Spanish National Accreditation Body) for performing tests in solid fuels boilers, according to the norm UNE-EN 303-5:2013, being the main laboratory in Spain with this acknowledgement.

Recording of data was carried out after stable and stationary conditions were reached. Based on i) knowledge gained by the state of the art of influencing factors on VOC emissions, ii) previous knowledge of the research team as well as the iii) specific boiler characteristics, different factors of influence on the VOC emissions were recognized:

- **Air supply:** rpm of the fan varied in the range 1900-2180. Furthermore, a detailed revision of the boiler structure was done in order to find uncontrolled air entrances. Uncontrolled air may cold the burner temperature, which is of relevance for the VOC control. Total air nozzles amount existing in the burner section were adjusted to provide a better air to fuel mixing.
- **Burner design:** some parameters were evaluated concerning boiler design. Besides nozzles for air distribution, it was also analyzed: boiler dimensions and refractory layers location and dimension.
- **Fuel feeding:** both frequency and duration of the fuel feeding system was varied. Accordingly, fuel feeding rate was set in the range (6.7-7.05) kg/h, which corresponded to an input of (23-37) kW.

After considering appropriate system improvements based on these parameters, results attained at nominal heat output testing were rather satisfactory in terms of VOC emissions. Mean content of OGC was 2,55 mg/Nm³ at 10% O₂ and satisfied the EN 303-5 restrictions set at 20 mg/Nm³ for a boiler class 5.

4 CONCLUSIONS

In this work an overview of the more relevant conditions that affect VOC formation was introduced. Furthermore, a 32 kW_{th} biomass boiler unit burning woody reference pellets was characterized in terms of VOC emissions by applying a methodological research analysis according to the EN 303-5 restrictions.

During the tests, improvements were done in terms of air supply, burner design and fuel feeding to mainly guarantee a successful VOC conversion. The best condition achieved by the system was attained according to the EN 303-5 standard limits. Further steps of this

work will imply the execution of replication tests and assessment of other boiler sizes.

5 REFERENCES

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