

PRESENT AND FUTURE OF MIXED PELLETS BASED ON AGRICULTURAL CROPS RESIDUES (HERBACEOUS AND WOODY) FOR THEIR USE IN THE RESIDENTIAL SECTOR (MHWPELLET PROJECT)

P. Canalis-Martínez¹, J. Royo¹, D. Quintana¹, A.Rezeau^{2*}

¹ University of Zaragoza – Department of Mechanical Engineering – Zaragoza – Spain

² CIRCE – Centre of Research for Energy Resources and Consumption – Zaragoza – Spain

*Corresponding author: Phone number: +34-976-761863 e-mail: arezeau@fceirce.es

ABSTRACT: Growing energy demands regarding the thermal use of biomass in Spain indicate that new biomass sources such as agricultural crops residues should be considered in the solid biofuel energy mix. Nevertheless, it is widely known that the use of these sources requires new challenging developments regarding their energy conversion to guarantee their sustainable use. Main constituents found in agricultural crops residues, specially their inorganic matter (ash), are linked to agglomeration, deposition, corrosion and erosion phenomena, which minimise both thermal efficiency and the conversion unit working life. In addition, particles emissions generated during combustion of these solid biofuels are responsible of important health diseases. In order to reduce impacts related to the above mentioned ash matter effects, actions concerning the fuel quality and conversion technology should be the target. Concerning the former, the ISO 17225-6 standard establishes quality guidelines that non woody pellets should fulfil. Taking into account these recommendations, an optimization of mixtures containing agricultural crop residues is suggested. Regarding conversion technology, the state of the art of existing boilers is focused on fixed grate units specialised on woody pellets class A1 (according to ISO 17225-2). This fact indicates that research efforts should be focused on the achievement of fixed bed combustion boiler properly designed for these new fuels. Considering all the aforementioned aspects, the MHWPellet project (ENE2015-68809-R (MINECO/FEDER-UE) arises. In this paper, in addition to detailing the objectives of the project, exposing the methodology and describing the available facilities, the first results obtained will be presented.

Keywords: agricultural residues, pellet, fixed bed, reactor, ashes, thermochemical conversion.

1 INTRODUCTION

Thermal conversion of biomass in Spanish residential sector continues undergoing a significant and sustained growth [1]. Price increase of fossil fuels, needs for self-sufficiency of thermal market, as well as the implementation of regulations (regarding fuel quality and equipment), have reinforced the role of biomass in the residential sector, representing nearly 50 % of total biomass consumption. This scenario along with future perspectives of development and availability of biomass resources at competitive and stable prices [1-3] have contribute to a growing interest in promotion and introduction of these biofuels with a different origin from 'conventional' woody biomass (pine pellets primarily).

These new resources intended to complement the existing offer includes, apart from energy crops, agricultural crops residues: herbaceous crop residues and pruning residues of permanent woody crops, with an estimated potential of 6,392 ktoe per year [2].

Peletization results in one of the most widely used treatment for biomass in the residential sector [4-6]. This process uses extrusion of raw materials to transform fuels with low bulk and energy densities into others which can compete with fossil fuels. This treatment also allows improving fuel stability and durability [4].

Due to biomass variability, it is required to classify the pellets according to their chemical composition and shape to ensure the quality. For that purpose there are some standards, including EN 14961-2:2011 [7] which regulates woody pellets for non-industrial use. This standard sets three quality categories (A1, A2 and B). It must be highlighted that raw materials needed for producing the highest quality pellets (class A1) have limited availability and, therefore, their cost is significantly higher. By comparison, ISO 17225-6:2014 standard [8] establishes the requirements for non-woody pellets, including those made of agricultural biomass residues and which are presented as a very attractive

alternative for meeting the growing demand in the residential sector.

It is remarkable that thermal conversion of agricultural biomass residues behaves differently to woody biomass, mainly due to ash characteristics (mass and chemical composition). Ashes are linked to agglomeration, deposition, corrosion and erosion phenomena, which minimise both thermal efficiency and the conversion unit working life. In addition, particles emissions generated during combustion of these solid biofuels are responsible of important health diseases. For this reason, incorporation into residential market of agricultural biomass residues requires action to solve the two main barriers to take off in this sector: reliability during operation, meaning that its performance becomes similar to A1 wood pellets; and compliance with increasingly demanding requirements of emissions. It is needed for both lines of research to develop and broaden the knowledge of mechanisms that take part in both aforementioned problems and the factors involved: effect of fuel chemical composition as well as technology role.

- Influence of chemical composition: as it has just mentioned, unlike woody pellets, those which are made of agricultural residues contain a bigger concentration of elements such as N, S, Cl, K and a high percentage of ashes. Both facts constitute a hindrance to the good global performance of combustor according to the present characteristics of boilers in Europe. The need to accomplish minimum quality requirements, as well as those established in ISO 17225-6:2014 standard for herbaceous pellets of class B, makes it necessary in some cases to modify the composition of the fuel mixing biofuels of different origins. Previous research [9-12] also hold that mixing biofuels has a great potential for improvement of operation and reduction of particulate matter and others pollutants as NO_x.

- Effect of technology: there are also parameters related to technology (both design conditions and operation conditions) that affect ash behaviour in the conversion equipment. Operative conditions can be optimized to achieve ash retention mainly in the grate (which would imply reducing fouling problems and particulate matter emissions), besides a lower sinterization degree. However, these conditions could influence both directly and indirectly the formation of other compounds like CO, NO_x or COV.

In order to overcome these problems related to the use of mixed pellets, MHWPellet project (ENE2015-68809-R (MINECO/FEDER-UE)) comes into being. In this paper, in addition to detailing the objectives of the project, exposing the methodology and describing the available facilities, the first results obtained will be presented.

2 OBJETIVES

The project, named as “Mixed pellets based on agricultural crops residues (herbaceous and woody) for their use in the residential sector: optimization for their composition and conversion parameters”, will allow to increase the understanding of thermal conversion of agricultural crops residues. This advance would help to reach solutions to operation, reliability and emissions issues typical of these fuels and attributable to their high ash content and its chemical composition. These resources are of high interest due to their availability, local production as well as low cost, and it is hoped that in the short term they could complement with guaranties others biofuels in the growing thermal residential sector.

As the project title implies, it is focused on two main areas:

- Mixed pellets made up of agricultural residual biomass: optimized design of mixtures using predictive methods and evaluating its performance in experimental facilities.
- Fixed bed combustion: influence of several operation conditions (flow rate and temperature of primary air) over MHWPellets performance, especially regarding ash behaviour.

In addition to these general objectives, activities accomplished during the project will allow to fulfill some more specific:

- Optimum design, from the point of view of problems associated to ash behaviour (bed sinter and particle emissions) of mixed pellets based on herbaceous and woody agricultural crops residues (MHWPellets).
- Quantifying, by means of reactor tests, the effect of pellet chemical composition on fuel reactivity, its conversion degree (unburned solids) as well as ash behaviour.
- Quantifying, by means of reactor tests, the effects of operation conditions (flow rate and temperature of primary air) on pellets reactivity, its conversion degree (unburned solids) and ash behaviour.
- Corroborating tendencies observed during reactor tests in commercial fixed-bed boilers of small power (nearly 50 kW).

In the next sections, it is going to be detailed those aforementioned activities and planned future actions to achieve each of these targets.

3 MIXTURES DESIGN

First task carried out in the project was selecting fuels which afterwards have been tested in the reactor. On the basis of data obtained from FAO [13] and information about LHW and fuel moisture of different databases, two woody agricultural biomass (vineyard and olive pruning residues) were preselected and three herbaceous biomass fuels (wheat straw, corn cob and barley straw) for their high energy potential in Spain and in the UE28 as a whole. From all those, and taking current uses into account, it was decided to select as raw materials for MHWPellets vineyard pruning residues, corn cob and barley straw. As reference pellets, pine pellets (pellets A1, according to ISO 17225-2:2014 [14]) and vine pellets (pellets II –except for ash content-, according to the same standard) were chosen.

Once fuels were selected, next stage was determining how mixtures would be formed looking for a sufficient performance in boiler. It should be remembered that biomass combustion consists of very complex physical mechanisms and numerous chemical reactions among fuel elements, mainly those which constitute ash. Apart from biomass composition, combustion progress is also heavily dependent on boiler technology [12, 15-17] besides several operating variables as air excess ratio and inner temperature [18]. For these reasons, it is hard to predict mentioned problems related to fuel ashes for mixed fuels.

In order to solve this key aspect, many coefficients have been developed which use fuel composition to predict or detect behaviour or tendencies related to ash issues. A review of predictive coefficients was made within the project according to relevance in predicting corrosion, sinter and slag formation along with biomass combustion. Even though many of them were created initially for coal [19], in previous research their suitability has been proved for biomass. Even so their effectiveness is still uncertain due to the fact that they can provide contradictory values (see, for instance [20]). Both for the appropriate application and for the analysis of the results that they show, it must be taken into consideration in which conditions they have been obtained (empirically, the most usual) and which technology has been used [15-17]. Additionally, utilization of mixed fuels could lead to misunderstanding about the results given by these indexes. They have been mostly developed considering pure fuels, and this is the reason why the application of a certain index can generate erroneous values [12, 15-16].

Based on the experience of the research team and attempting to minimise those limitations which have been just mentioned about their use with mixed pellets, selected indexes were finally the following:

- For the prediction of sintering: alkali index [19-21], base-to-acid ratio (B/A) [19-20, 22] and alkaline oxides ratio [23].
- For the prediction of deposits formation: alkali index [21] and alkalis over Cl and S index [15,19].
- For the prediction of corrosion: S/Cl index [15, 19-20] and Cl/K ratio [16].

After indexes were chosen, software was developed in order to obtain optimized mixtures in a theoretical base considering ash behaviour. Ranges from bibliography for each index were applied.

With this analytic tool and thermochemical characterization of raw materials, predictive assessment has been done for mixtures performance during combustion. As a result, these were the chosen mixtures (see Fig. 1):

- 70% Vineyard pruning + 30% Barley straw (PVB)
- 70% Vineyard pruning + 30% Corn cob (PVC)
- 60% Vineyard pruning + 20% Corn cob + 20% Barley straw (PVCB)

Despite the fact that all three mixtures meet the requirements of ISO 17225-6:2014 standard for a A/B class pellet [8], it has not been possible to be within the acceptable range for all selected indexes. This fact was not considered negative, since it would be useful to confirm or not the efficacy of indexes and their reference values, with the goal of trying to improve them.



Figure 1: Photograph of Pine Pellet (PP) and Mixed Pellets designed (PVB, PVC and PVCB)

4 REACTOR TESTS

4.1 Goal

Since obtaining accurate data of combustion processes in commercial systems is, in most cases, very complicated, this project aims at defining the most suitable operating conditions for each fuel type using an experimental reactor. Afterwards, those same conditions will be evaluated in several commercial boilers. This is the core activity of the project. During two experimental campaigns it will be analyzed the influence of the composition of the fuel and that of the operating parameters of the process of conversion of the mixed pellets, as well as the fractioning of the ashes. The objective of these tests is to determine the conditions under which, for each fuel, the maximum velocity of conversion (maximum load of the grate, kW/m^2) is attained, while minimizing the effects of its inert matter (build-up of mass in the bed and formation of particulate material).

4.2 Experimental facilities

In order to perform the tests, a reactor designed and set up by CIRCE under project HBE “New furnace for the efficient conversion of non-conventional biomass (from emerging market) ref. RTC-2014-2719-3 [24], has been adapted. It consists of a vertical cylindrical combustor chamber, a grate, the air supply system and a weighing scale, as shown in Fig. 2.

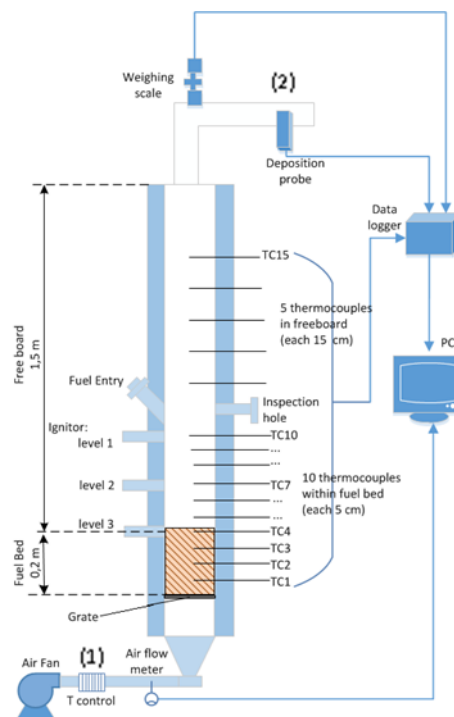


Figure 2: Scheme of the experimental test facility

The chamber is made of stainless steel AISI-310S having a height of 1700 mm, an inner diameter of 200 mm and 8 mm thick. Fifteen thermocouples are inserted along the chamber wall; five of them in the freeboard (each 15 cm) and the other ten are located within fuel bed (each 5 cm). Air is supplied from the bottom of the arrangement, through the grate and the fuel bed, providing an adequate distribution over the whole transverse area. In addition, a hot-wire anemometer measures the air flow rate continuously and sends the signal to the PID controller for adjusting the frequency of the fan. The reactor is suspended from a weighing scale that allows monitoring the mass loss of the fuel bed. All the measured data (temperatures, reactor weight and air flow rate) are registered, for every 2 seconds.

The aforementioned reactor was modified by adding a system for air conditioning (see Fig. 2 (1)), such that air is supplied at a constant temperature, independent of the ambient conditions. Besides, the facility has been completed by installing a deposition probe with a removable sampling ring in the chimney of the reactor (see Fig. 2 (2)) [25]. This is a usual device used to simulate the deposition of ashes in furnace pipes and heat exchangers [26]. The sampling ring used to extract samples of the deposits is cooled by compressed air, allowing to keep its surface at an appropriate temperature for deposition [25].

4.3 Information obtained from the tests

During the tests, the temperatures measured by the 15 thermocouples inside the reactor, the velocity and flow rate of inlet air, are continuously recorded (see Fig. 2).

Fig. 3 shows the evolution of the temperatures during one of the tests. The reaction is triggered by an ignitor placed above the bed of fuel. This causes the temperatures of the gases to increase (upper thermocouples). Once combustion is initiated, and biomass is being consumed, the temperature registered by

thermocouples in the centre of the reactor rises: first TC4 (purple), second TC3 (green), third TC2 (red) and finally TC1 (blue). For the last three, the increase in temperature is very fast because combustion is already stable. Once all fuel has been consumed, temperatures start to decrease.

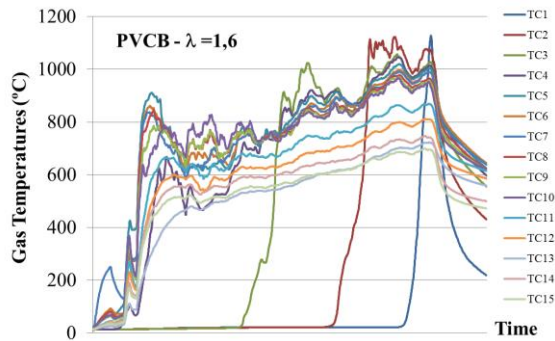


Figure 3: Profiles of temperatures. Reactor test with PVCB- $\lambda =1,6$ – Air Inlet temperature=25°C

From these variables, along with geometrical data and the analysis of the fuel, the following parameters are computed:

- Air excess ratio (λ).
- Average combustion temperature.
- Velocity of the ignition front: it is a measure of how fast the front of the flame moves inside the bed. It is computed from the times the temperature in the bed (in this case, TC3, TC2, TC1) reaches a reference value (500 °C). The velocity is evaluated from the known distance between thermocouples (50 mm) and the measured lapse of time between the registered increments of temperature.
- Ignition Rate, m_{ir} : it is obtained multiplying the velocity of the ignition front by the apparent density of the fuel, which allows comparing different fuels [5]. It is expressed in units of consumed mass by grate surface and time ($\text{kg}/\text{m}^2\text{s}$).

The weight of the reactor is also continuously recorded, allowing to check fuel consumption as combustion proceeds. Figure 4 shows an example for PVB. The stable period of combustion (marked red) corresponds to a stretch of time during which mass variation is almost linear. From the slope of this interval, the Mass Burning Rate (m_b) is computed, which is defined as the variation of mass in the reactor during the test, normalized by the transversal area of the grate ($\text{kg}/\text{m}^2\text{s}$) [27].

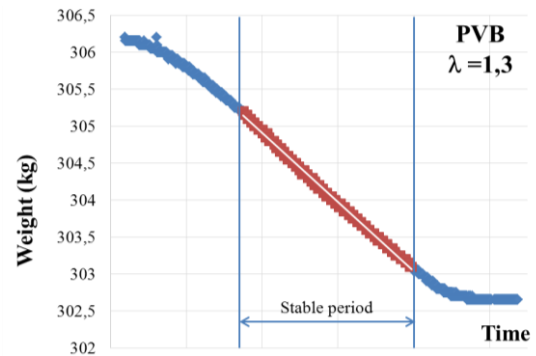


Figure 4: Mass loss. Reactor test with PVB- $\lambda =1,3$ – Air Inlet temperature=25°C

During the stable period of combustion, the deposition probe is inserted in the chimney. The removable sampling ring has been previously cleaned and weighed. The temperature of the gases at the insertion point of the probe and the one of the sampling ring are continuously recorded. The compressed inlet air is adjusted such that the temperature of the sampling ring is around 350 °C. Once extracted, the dirty sampling ring is weighed again to obtain the amount of mass deposited.

From the measurement of the time the deposition probe has been exposed to the gases, and the surface area of sampling ring, the deposition rate is obtained [$\text{g}/\text{m}^2\text{h}$].

Besides the aforementioned variables, once combustion is over and the reactor has cooled down, bottom ashes are removed for weighing and classification. The following classification is used:

- S1: pass through a 3.15 mm sieve. They are considered as not sintered.
- S2: do not pass the 3.15 mm sieve, but are easily disaggregated by hand. Present a low degree of sintering.
- S3: do not pass the 3.15 mm sieve, and are difficult to disaggregate by hand. Present a high degree of sintering.

Since the difference between S2 and S3 is subjective, a fraction S2/3 encompassing both classes is used.

Afterwards, both the samples deposited in the shells and the fractions of ashes S1 and S2/3 removed from the grate, will be analysed by SEM (Scanning Electron Microscope) to determine their composition, as well as the mole and mass fractions of the constituent elements.

4.4 First test campaign

Two test campaigns are planned within the project to carry out tests with the reactor. During the first, tests with five fuels have been made: two reference fuels (pine pellets -PP- and vineyard pellets -PV-), and the three mixed fuels previously described (PVC, PVB, PVCB). For each of them, the operating conditions have been changed adjusting two parameters:

- Inlet air temperature: according to this parameter, there are two types of test for each fuel: without pre-heating (inlet air at 25 °C), and pre-heated (inlet air at 80 °C).
- Excess air ratio during combustion: it is adjusted tuning the velocity of inlet air, which implies working with a variable air flow rate for the same amount of fuel. The goal is to work with an excess air ratio between 1 and 2, approximately.

The amount of biomass fed to the reactor in each test

is such that the total height is 210 mm. In this way, thermocouples TC1 and TC4 are initially inside the bed.

A campaign of 60 tests was planned: for each of the 5 fuels, were used 3 values of the excess air, 2 inlet air temperatures, and 2 repetitions of each test. Finally, 75 tests were made in order to improve the reproducibility of some results. Table I shows a summary of the tests performed with the different fuels.

Table I: Summary of tests results

		PP	PV	PVB	PVC	PVCB
Tests	Cold	9	10	9	8	11
	Hot	7	3*	6	6	6
λ (%)	Min	1,00	1,15	1,21	1,20	1,23
	Max	1,82	2,04	2,14	2,09	2,07
m_{ir} (kg/m ² s)	Min	0,0497	0,0438	0,0442	0,0436	0,0422
	Max	0,0778	0,0649	0,0758	0,0787	0,0717
m_b (kg/m ² s)	Min	0,0600	0,0605	0,0508	0,0510	0,0428
	Max	0,0830	0,0781	0,0806	0,0761	0,0695
Bed Temp (°C)	Max	1272	1356	1272	1289	1234
	Average	1164	1241	1199	1191	1155
	Max T ^a					

*Unfinished test campaign

4.5 Results and discussion

From the information gathered, it can be concluded that:

Concerning the progress of the tests:

- The behavior of the five fuels was similar, and no problems arose during combustion. Figures 5 and 6 show the evolution of temperatures inside the bed for the same fuel, for two different values of excess air. It has been found that combustion is more stable for low excess air values, granted they are above 1 (Fig. 5). For excess air values around 2, temperatures are lower and their evolution is slower and more unstable for all tested fuels (Fig. 6).

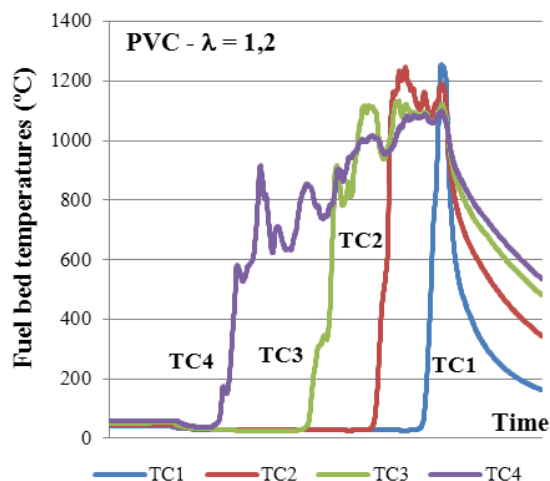


Figure 5: Fuel bed temperatures – Reactor test with PVC - $\lambda = 1,2$ – Inlet Air temperature = 25 °C

- It has been found that the behaviour in the reactor of PV is very similar to that of PP, while for any excess air value, the most unstable temperature evolution was presented by PVB. The higher bed temperatures have been reached by the PV (see Table I)

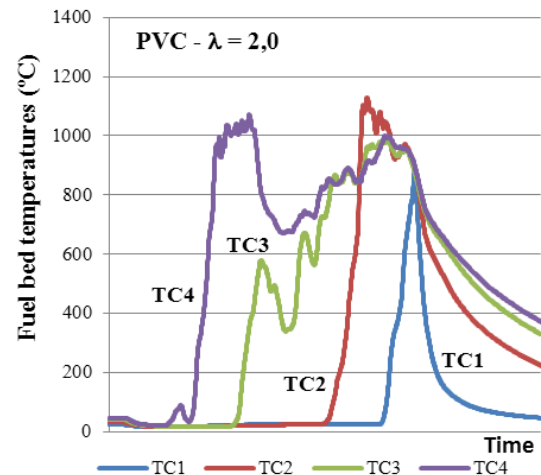


Figure 6: Fuel bed temperatures – Reactor test with PVC - $\lambda = 2$ – Inlet Air temperature = 25 °C.

- As expected, a clear relationship between ignition ratio, excess air and average temperature has been found. Taking into account that air excess ratio values are greater than 1, the ignition ratio decreases as the air excess ratios increases (Fig. 7). The same is true for the average temperature in the bed, which is lower for all fuels when the excess air ratio is high. This can be checked by comparing the temperatures reached during the tests in figures 5 ($\lambda = 1,2$) and 6 ($\lambda = 2$).

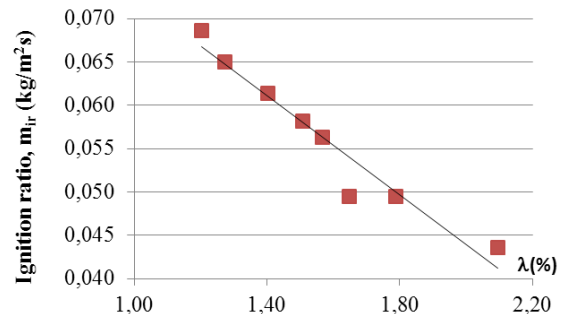


Figure 7: PVC Tests results - Air Inlet temperature = 25 °C

Concerning the ashes collected at the bottom of the grate, besides the amount, which depends mostly on the ash content of the fuel itself, it is crucial to define their degree of sintering, given the troubles they generate in the equipment and during the development of combustion:

- In the case of PP (see Fig. 8), the amount collected is very small compared to the total amount of biomass. Besides, in all cases, collected ashes were included in group S1.

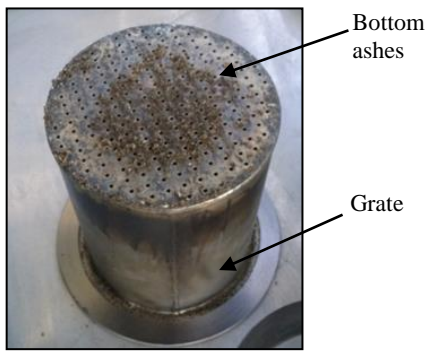


Figure 8: Bottom ashes. Reactor test with PP- $\lambda=1.3$ – Inlet Air temperature=25 °C.

- For PV the amount collected is bigger, and the difference between fraction S1 and S2/3 can be seen. As can be checked in Fig. 9, while thin ashes present a light colour and are located in the lower area, the sintered ones locate in the upper area and are darker. Anyhow, in the case of PV, once sieved, less than 10% of the ashes collected belong to fraction S2/3.

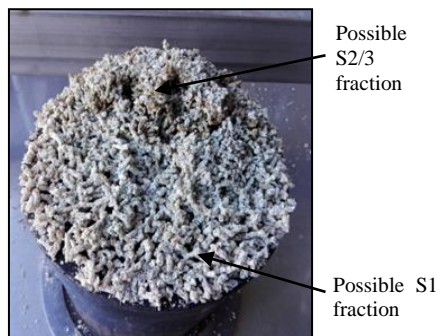


Figure 9: Bottom ashes. Reactor test with PV- $\lambda=1.3$ – Inlet Air temperature=25 °C.

- In the case of the three mixed pellets (PVC, PVB and PVCB), there is a much more compact sintered fraction (see fig. 10). Its percentage seems to be inversely related to the excess air in all cases, thus directly related to the temperatures reached in the bed. The biggest S2/3 fraction is obtained for PVB. On average, 74% of the collected ashes during the tests belong to this fraction. The other two mixed pellets presents lightly lower, but similar, percentages.

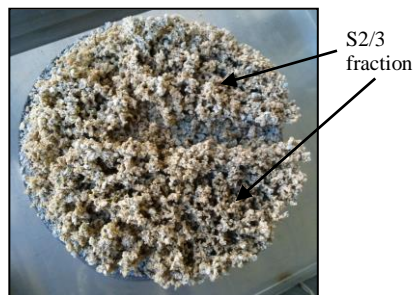


Figure 10: Bottom ashes. Reactor test with PVCB - $\lambda=1,9$ – Inlet Air temperature=25 °C.

Concerning the deposition ratio: important differences have been found between the reference pellets and the three mixed pellets:

- The appearance of the dirty sampling ring of the deposition probe is very different in the case of PP tests from the rest. In the case of the reference pellet there is a low amount of ashes deposited, and they present very low adherence (Fig. 11). For the rest, colour is whitish. In the case of PV, there is a layer adhered to the shell, while for the three mixed pellets the white layer is much bigger (Fig. 12).

Frontal area of sampling ring with deposited ash

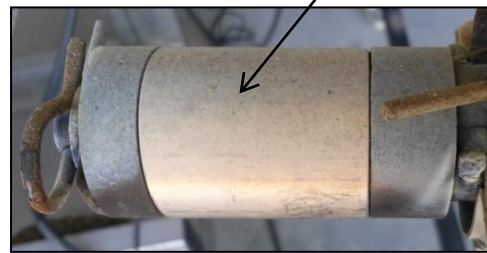


Figure 11: Removable sampling ring. Reactor test with PP - $\lambda=1.3$ – Inlet Air temperature=25 °C – Ash deposition rate 2 g/m²·h.



Figure 12: Removable sampling ring. Reactor test with PVC - $\lambda=1.3$ – Inlet Air temperature=80 °C – Ash deposition rate 26.5 g/m²·h.

- Table II presents the maximum, minimum and average values of the deposition ratios obtained. PVB presents a deposition ratio higher than the rest, although analysis of these data is still ongoing.

Table II: Deposition ratio (g/m²·h)

	PP	PV	PVB	PVC	PVCB
Average	3,37	16,59	22,01	19,79	19,38
Min	1,59	11,03	15,07	14,16	14,37
Max	6,67	21,29	29,88	24,99	23,82

Regarding the influence of the inlet air temperature: a preliminary analysis shows no significant differences between tests carried out at air temperatures of 25 °C and those at 80 °C.

4.6 Second test campaign

Once concluded the analysis of the results gathered during the first campaign, the trends observed will allow optimising the mixtures in order to reach the defined goals in subsequent tests.

5 TESTS IN COMMERCIAL BOILERS

Although, as already explained, the main experimental tests of this project are carried out in a laboratory reactor, it is considered of paramount importance to check, evaluate and analyse in commercial equipment the results obtained.

To this end, the mixed pellets will also be evaluated in three commercial boilers, under the optimized operating conditions resulting from the test campaign in the reactor. The goal is to assess their behaviour during long runs, and to obtain information regarding thermal performance and emission of gas and particulate material.

During this last campaign, the goal is to reach a compromise (for each fuel) for the values of the parameters which are beneficial regarding ashes behaviour (agglomeration and ashes emissions), combustion efficiency (total air flow rate and unburnt material) and gaseous emissions (CO, COV, SO₂, NO_x).

6 CONCLUSIONS AND FUTURE RESEARCH

The increase in the use of waste agricultural biofuels for home heating, will contribute to a more sustainable, competitive and safe supply of energy; accompanied by an economic growth based on local resources. The results obtained in this project will facilitate the introduction of new biofuels in the market, which are currently set aside mostly due to the technical challenges associated with their conversion.

During the development of the project three mixed pellets (PVC, PVB y PVCB) have been defined, starting from theoretical predictive indexes, and complying with current norms. These pellets and two reference pellets (PP and PV) have been tested in an experimental reactor under different operating parameters (excess air ratio and inlet air temperature) in order to evaluate their influence on conversion properties of the pellet (reactivity and temperatures), as well as on ashes behaviour (agglomeration and deposition).

It has been found that in the absence of significant problems during the tests, there are important departures in the behaviour of the different fuels for the same operating conditions. Thus, PVB turns out to be the most unstable, while PV presents the highest temperatures in the bed. PVC shows the highest deposition rates, although they are similar to those from other two mixed pellets. Regarding bottom ashes, the percentage of sintered fraction (S2/3) is similar for the three mixed pellets and much higher than in the case of PV (the tests carried out with PP do not show this fraction).

The information gathered during the reactor tests is still under analysis in order to find the optimum operating conditions for each fuel. Besides, until the end of the project, work will continue along the following topics:

- To check the suitability of the indices from the results obtained, suggesting modifications if necessary.
- To analyse the results obtained from SEM, both from the deposition probe of the probe and the bottom ashes, for both fractions.
- To carry out a new test campaign with new mixes, optimized using the results so far obtained.
- Tests in commercial boilers.

The results of this project are expected to contribute to the creation of a new market for biofuels based on the mix of waste agricultural biomass, both herbaceous and woody (MHWPellet). This will contribute to the creation of jobs and to the social development in rural and isolated areas, thanks to the exploitation of local resources.

The results of this work will provide, both to the scientific community and boilers and pellets makers, key criteria for future developments (mixtures optimization, new boiler design and adaption of those already operating). This will contribute to overcome current barriers in the use of biofuels from waste agricultural matter for home heating.

7 REFERENCES

- [1] J. J. Ramos, Las grandes preguntas de la biomasa para uso térmicos, (2014), Spanish Biomass Association (AVEBION)
- [2] Institute for the Diversification and Saving of Energy (IDAE), Renewable Energy Plan 2011-2020 (2011), available in <http://www.idae.es/en/tecnologias/energias-renovables/renewable-energy-plan-2011-2020>
- [3] European Bioenergy Outlook 2013 (2013)
- [4] R. Saidur et al, A review on biomass as a fuel for boilers. Renewable and Sustainable Energy Reviews Vol. 15 (2011) pag. 2262-2289
- [5] J. Porteiro et al. Experimental analysis of the ignition front propagation of several biomass fuels in a fixed-bed combustor. Fuel Vol. 89(1) (2010), pag. 26-35
- [6] C. Ryu et al. Effect of fuel properties on biomass combustion: Part I. Experiments – fuel type, equivalence ratio and particle size. Fuel, Vol. 85 (2006) pag. 1039-1046
- [7] EN 14961-2:2001 Solid biofuels - Fuel specifications and classes - Part 2: Wood pellets for non-industrial use (2011)
- [8] ISO 17225-6:2014 Solid biofuels - Fuel specifications and classes - Part 6: Graded non-woody pellets (2014)
- [9] E. Houshfar et al. Experimental Investigation on NOX Reduction by Primary Measures in Biomass Combustion: Straw, Peat, Sewage Sludge, Forest Residues and Wood Pellets. Energies, Vol. 5 (2) (2012) pag. 270-290.
- [10] A. Junemann, G. Legarreta, Inhalación de humo de leña: una causa relevante pero poco reconocida de Enfermedad Pulmonar Obstructiva Crónica. Revista Argentina de Medicina Respiratoria - N° 2, (2007), pag. 51-57.
- [11] D. Tian et al. Assessment of Biomass Burning Emissions and Their Impacts on Urban and Regional PM2.5: A Georgia Case Study Environmental Science Technology, Vol. 43 (2009) pag. 299-305
- [12] D. Bostrom et al. Ash transformation chemistry during combustion of biomass. Energy & Fuels, Vol. 26 (2012), pag. 85-93.
- [13] FAOSTAT, Crop production (2015). Available in <http://faostat3.fao.org>
- [14] ISO 17225-2:2014 Solid biofuels - Fuel specifications and classes - Part 2: Graded wood pellets (2014)

- [15] M. Becidan et al. Optimal Mixtures To Reduce the Formation of Corrosive Compounds during Straw Combustion: A Thermodynamic Analysis. *Energy & Fuels*, Vol. 25 (2011), pag. 3223
- [16] M. Díaz-Ramírez et al. Partitioning of K, Cl, S and P during combustion of poplar and brassica energy crops. *Fuel*, Vol. 134 (2014), pag. 209.
- [17] A. Khor et al. Straw combustion in a fixed bed combustor. *Fuel*, Vol. 86 (2007) pag.152.
- [18] A. Magdziarz et al. Chemical composition, character and reactivity of renewable fuel ashes. *Fuel*, Vol. 176 (2016) pag.135.
- [19] S. Kalisz et al. Full-scale study on halloysite fireside additive in 230 t/h pulverized coal utility boiler. *Energy*, Vol. 92 (2015) pag. 33.
- [20] R. Xiao et al. The physicochemical properties of different biomass ashes at different ashing temperature. *Renewable Energy*, Vol. 36 (2011) pag. 244.
- [21] B.M. Jenkins et al. Combustion properties of biomass. *Fuel Processing Technology*, Vol. 54 (1998), pag. 17.
- [22] M. Pronobis. The influence of biomass co-combustion on boiler fouling and efficiency. *Fuel*, Vol. 85 (2006), pag. 474.
- [23] M.J. Fernandez-Llorente. Comparing methods for predicting the sintering of biomass ash in combustion. *Fuel*, Vol. 84 (2005) pag. 1893
- [24] A. Rezeau et al. Advanced characterization of non-conventional biomass (from emerging markets) in a fixed-bed reactor. 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands (2016)
- [25] M. Díaz-Ramírez et al. Estimation of the deposition on trigeneration system components fueled by ash rich biomass. 20th European Biomass Conference and Exhibition, Milan, Italy (2012) pag. 774.
- [26] L.J.R. Nunes et al. Biomass combustion systems: A review on the physical and chemical properties of the ashes. *Renewable and Sustainable Energy Reviews*, Vol. 53 (2016), pag. 235-242.
- [27] H. Khodaei et al. An overview of processes and considerations in the modeling of fixed-bed biomass combustion. *Energy*, Vol 88, (2015) pag. 946-972

8 NOMENCLATURE

Acronyms

PP: Pellets of Pine

PV: Pellets of Vineyard pruning

PVC: Mixed pellet with Vineyard pruning and Corn cob

PVB: Mixed pellet with Vineyard pruning and Barley straw

PVBM: Mixed pellet with Vineyard pruning, Barley straw and Corn cob.

TCi: Termocouple located in position "i"

SEM: Scanning Electron Microscope

Greek symbols

λ : Excess Air Ratio (%)

9 ACKNOWLEDGEMENTS

The authors would like to grate to the Spanish Ministry of Economy and Competitiveness for funding the project "MHWPellet: Mixed pellets based on agricultural crops residues (herbaceous and woody) for their use in the residential sector: optimization of their composition and conversion parameters" (ref. ENE2015-68809-R (MIMECO/FEDER, UE)).

10 LOGO SPACE

