PELLET COMBUSTION IN STOVE: PERFORMANCE AND EMISSIONS STATISTICAL APPROACH.

J.C. Moran, E. Granada, J. Porteiro, J.L. Míguez.

Departamento de Ingeniería Mecánica, Máquinas y Motores Térmicos y Fluidos
ETSII, Universidad de Vigo
Lagoas-Marcosende, s/n. 36200-Vigo (Spain)
Phone: +34 986 812183, e-mail: jmoran@uvigo.es

Abstract: Small scale stoves, producing heat and hot water, are suited for domestic purposes. A pilot 24 kWt fixed bed pellet stove has been developed for the study of pellet combustion in laboratory. Its design and construction was done in order to permit its maximum flexibility for the simulation of different stove configurations and operational circumstances. Temperatures, pressures, flows and gas compositions are measured and analysed. An extensive study of different load conditions is presented through the application of an experiment design technique and a subsequent statistical analysis of the results. It is shown that the main features of the plant are controlled mainly by fuel feed rate and by air-fuel equivalence ratio, being very low influenced by the temperature of the water. Very good correlation between the studied parameters have been found together with a great agreement between the predicted and the measured values.

Keywords

Pellets, combustion, fixed bed, stoves, pilot plant, statistical analysis

1. Introduction

The use of biomass, a renewable energy source, instead of fossil fuels in heat and power generation can be a way of reducing the global CO_2 emission problem. Combustion of this CO_2 neutral fuel is an alternative for a sustainable society, reduces sulphur emissions and saves the diminishing fossil fuels. The Renewable Energy Promotion Plan in Spain 1999-2010 (from the White Paper of the European Commission) highlights, concerning with the biomass thermal applications, the need for improvement in the domestic equipment[1] (Typical residential equipment in the power range of 8 to 30 kW).

The main problems in the use of biomass as a fuel is its high moisture content and low heating value per unit volume. Pelletising of biomass - particularly wood- is a densification process which improves its characteristics as a fuel, enhances its volumetric calorific value -less transport and storage costs- and its calorific value -less moisture content- , improves its handling characteristics -higher density, friability and flowable- and combustion efficiency (controllable feeding, more uniform and homogeneity fuel). Pellets made of wood -lignocellulosic materials- present further extra advantages:

- One of its components, the lignin, allows a cleaner and less toxic combustion and at the same time avoids adding any binder to densificate. Therefore, costs reduce.
- Due to the high oxygen proportion of lignocellulosic materials, the amount of needed air is significantly lower than with other solid fuels.

Typical characteristics of lignocellulosic pellets are low moisture content (<10% Wet Basis (WB)), high density (>700 $kg \cdot m^{-3}$) and a heating value around 17000 kJ/kg with a diameter between 5 and 12 mm. The previous mentioned specifications make pellets very interesting for ordinary central heating systems. Moreover, they are an alternative to fossil fuels in small and average size boilers, and also in district heating plants and small scale house heating systems. Pellets burn cleaner than wood because the feeding rate is regulated and coupled with the accurate amount of air in order to obtain an optimum burn rate. That's why they have the potential to operate at significantly lower emission levels than cordwood stoves. However, on a local scale, the emissions from the small scale combustion of biofuels tend to be both an environmental and a health problem. Particularly, the emissions of unburned components such as VOC (Volatile Organic Carbons) carbon monoxide and NO_x tend to be high.

The described experimental plant was specifically design in order to test and analyse the main aspects of pellet combustion in small stoves because biomass pellet combustion technology needs further research.

The experimental part, planning across the "Statistics Experimental Design", demands a minimum number of experiments to avoid lose of generality in conclusions doubt to the heterogeneity of the pellet. The introduction of experiment design techniques applied to the combustion process, and the later statistical analysis of the results are presented. The most appropriate type of experiment and also the number of experiments are determined. These experiment design techniques provide valid conclusions and define which are the most influential factors. They also show the predicted tendencies in order to achieve a better efficiency of the general process. Based on first experiments, the initially considered number of factors are three: amount of pellet, air supply and temperature of water.

2. Experimental

Technical Description Of The Plant (Fig. 1)

Fig. 1 Pilot plant. General view.

Combustion chamber (Fig. 2): Several components have been used in the experimental plant to maintain its similarity with the original one. The combustion chamber has been modified just to allow the introduction of fresh primary air and fresh or already burnt secondary gas as desired. Almost the entire chamber is surrounded by a water jacket which gets the heat from the combustion chamber. This heat is measured and sent to a heat exchanger. A temperature tracking system, consisting on four motorised thermocouples, has been developed to measure gas temperature at different points. The stove can be described as an open fire stove with updraft combustion (fixed bed).

Feeding system: The feeding line is slightly different from the original system. The hopper has been moved away from the surroundings of the chamber so as to analyse the combustion without the interference of an unknown fuel preheat. The effect of preheating the fuel before it enters the plant can be studied by means of a heated feeding circuit once the fuel has been dosed. The starting of combustion is determined by a staring plug placed in the lower part of the fuel bed.

Primary air supply: Fresh air is forced inside the installation by means of a speed regulated fan which establishes a measured pressure and a mass flow. This flow is conducted towards the combustion chamber through several control valves which can send the fresh air directly to the combustion chamber, sending part of it to the secondary gas line, or through a heat exchanger where it receives heat from the already burnt gases. Pressure, temperature, humidity, mass flow and gas composition are measured just before it enters the combustion chamber.

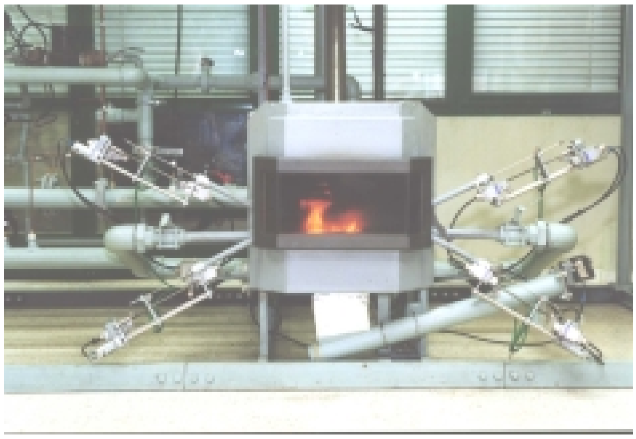

Fig. 2. Stove. Combustion chamber.

Secondary gas supply: As mentioned before, the effect of the secondary gas flow, composition and temperature on the plant's main behaviour is one of the most important parameters intended for study. In this experimental plant, secondary gas composition and temperature are controlled as follows:

- Secondary gas is forced inside the combustion chamber thanks to a speed controlled fan.
- Supply gas to the secondary gas fan is formed by fresh air coming from the primary air supply system and combustion gases coming from the exhaust line.
- The pressure, temperature and composition of the hot gases coming outside the combustion chamber is measured before they reach the control valve which determines the amount of gases that will be recirculated towards the combustion chamber.
- Pressure, temperature and mass flow of secondary gases are measured just before they enter the combustion chamber.
- Secondary gas supply can be done on either side of the combustion which can help to generate turbulence inside the combustion chamber.

Exhaust gases: Gas analysis was carried out using a TESTO-350 to measure gas concentrations of the main components involved: O_2, CO, NO, NO_2, SO_2 (the concentration of CO_2 is calculated).

Power demand control: To control the power demand to the plant the original system used a worm gear (moved by a controlled motor which determines the amount of pellet introduced to the combustion chamber) installed in the lowest part of the hopper. The aim is to set plant consumption at a specific value where different measures and operational situations can be tested.

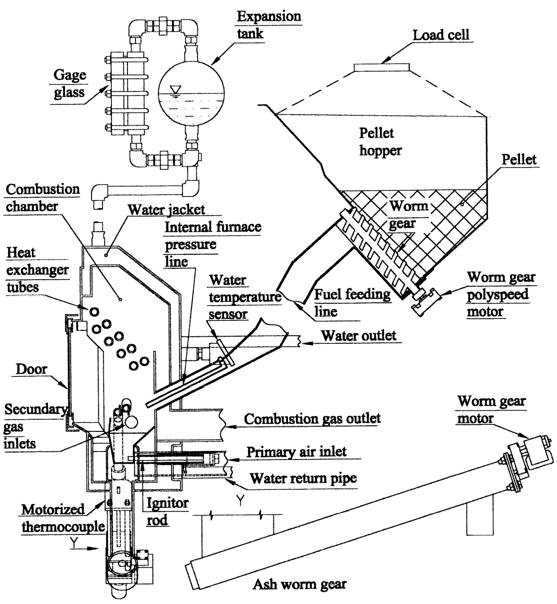

Fig. 3. Combustion chamber section.

Material

Table 1: 1st pellet properties.

Diameter (mm)	7
Length (mm)	7-21
Density[1] ($kg \cdot m^{-3}$)	1166
Bulk Density ($kg \cdot m^{-3}$)	640
Moisture (% WB)	8.5
PROXIMATE ANALYSIS (wt % dry basis)	
Volatiles	81.6
Ash (550 ºC)	0.68
Fix Carbon[2]	17.7
ULTIMATE ANALYSIS (wt % dry basis free of ash)	
Carbon	51.7
Hydrogen	6.7
Oxygen[2]	40.7
Nitrogen	0.17
Sulphur	< 0.05
Chlorine	0.01

[1] Geometric method.
[2] By difference

The 1st and 2nd series of experiments were carried out using two relatively different kind of pellet. The characterisation of the 1st pellet (1st series of experiments) is showed in table 1. Other important properties related to combustion behaviour are thermal conductivity (0.219 W/mºC) and specific heat (1503 J/kgºC at 25ºC), which were estimated by bibliographic formulas [2].

The detailed characterisation of the 2nd pellet (2nd set of experiments) is described in table 2. The homogeneity in size is higher in this case.

Table 2: 2nd pellet properties.

Diameter (mm)	6.6
Length (mm)	10-15
Density[1] ($kg \cdot m^{-3}$)	943.4
Moisture (% WB)	9.5
Low Heating Value (LHV kJ/g	17.0
PROXIMATE ANALYSIS (wt % dry basis)	
Ash (550 ºC)	0.90
ULTIMATE ANALYSIS (wt % dry basis free of ash)	
Carbon	52.0
Hydrogen	5.3
Oxygen[3]	42.0
Nitrogen	0.92
Sulphur	< 0.05

[1]Geometric method. [2]Supposed, not experimental data.
[3]By difference

Theoretical basis

Previous experiments showed that relevant factors were the stove water temperature t_w (ºC), the stechiometric ratio n and the pellet supply m_p (gr/s). The following five variables, Heat in water Q_w (kW), heat in smoke Q_s (kW), stove efficiency η_{st} [$Q_w/m_p \cdot LHV$ (WB)], combustion efficiency η_c [$(Q_w+Q_s)/m_p \cdot LHV$ (WB)] and smoke composition were studied.

Table 3: 1st experiment factor levels

m_p (gr/sg)	n	t_w (ºC)
1.262	1.822	66.1
1.262	1.822	83.9
1.262	2.178	66.1
1.262	2.178	83.9
1.738	1.822	66.1
1.738	1.822	83.9
1.738	2.178	66.1
1.738	2.178	83.9
1.100	2.000	75
1.900	2.000	75
1.500	1.700	75
1.500	2.300	75
1.500	2.000	60
1.500	2.000	90
1.500	2.000	75
1.500	2.000	75
1.500	2.000	75

In order to study the general behaviour by mean of response surfaces, complete and fractional factorial experiments designs are extremely useful. 1st series of experiments, conducted according to an orthogonal, rotatable and central composite design, was carried out [4, 5, 6, 7]. An uncertain behaviour and not clear results were found. Nevertheless, variance analysis showed that t_w is not a significant factor. Central composite design consists of a factorial design which allows the estimation of a second-order polynomial equation. 2^k+2k+1 points are required and k represents the number of factors. Table 3, before randomising, gives the different levels of the factors in the 1st set of experiments.

After detecting and removing some of the previous causes of uncertainty, a 2nd set of experiments was carried out conducted according to a complete 3^2 factorial experiment. Table 4 shows the different levels of the factors taken into account, n and m_p.

Table 4: 2nd experiment factor levels

m_p (gr/s)	1.0	1.5	2.0
n	1.2	1.6	2.0
Coded level	-1	0	+1

3. RESULTS AND DISCUSSION

1st set of experiments

Analyses of these results were not conclusive. The depending variables were affected by all the selected factors, but statistic could not yield to a model because of the randomness of the phenomenon. Therefore, more factors should be considered or erraticity should be reduced. In any case, temperature of the stove, t_w, seemed not to have a outstanding influence between 60ºC and 90ºC (usual temperatures for domestic water). In figure 4, for each fixed temperature (horizontal behaviour), stove efficiency fluctuate more depending on other variables (vertical behaviour), like m_p or n.

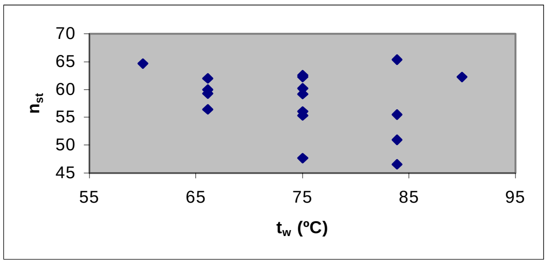

Fig. 4. 1st series of experiments. η_{st} against t_w(ºC).

In order to reduce instability some changes were introduced:

1. Temperature of the stove, t_w, was neglected due to the above mentioned first results, so that all future experiments were carried at 70 ºC, usual temperature in domestic heating water systems.
2. Feeding instability of the pellet, m_p, was reduced by using the previously described "2nd pellet", and homogenising the size by mean of a sieve.
3. Experiment length was increased from 20 minutes to 60 minutes.
4. Mass flow range of pellet was increased in order to obtain a characterisation both for low and high demand of energy.
5. When high stechiometric ratios (n>2.0) were experienced (first set of experiments) many incandescence particles of pellet were hurled out of the bed. This fact should be avoid if we want to keep the better combustion efficiency values obtained. The best efficiency and emissions results were found using an stechiometric value between 1.4 and 1.7. Hence, the new stechiometric ratio range was established between 1.2 and 2.

2nd set of experiments

After the realisation of a second set of experiments, a first analysis of the obtained data was carried out.

First results showed a clear dependency between some of the studied variables (Q_W, Q_S ,CO, NO and O_2) and the two relevant factors (m_p and n). Most of these relationships seemed to be approximately linear, and even a parabolic behaviour could be seen in some cases. This pointed out that the obtained data were appropriate to be assessed by SPSS, in order to find a mathematical and statistical based relationship.

Each variable was individually treated and most of them showed that more than one possible equation was possible. However, the subsequent statistical analysis, let us known which was the most appropriate. The equations and the criteria taken into account, as well as a brief explanation, are described below.

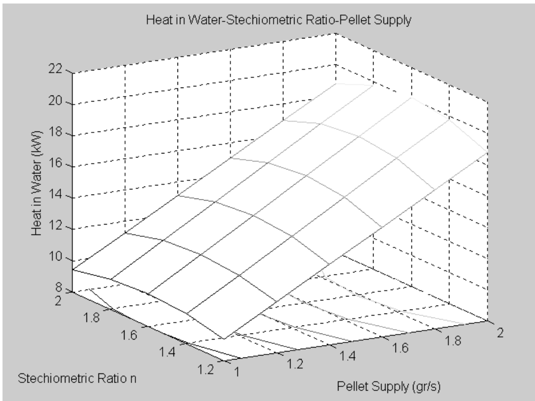

Fig. 5. Heat in water (kW) representation.

As a general result, it is important to note that values of Adjusted R Square ranged from 98.1% to 99.9%. A general fulfil of expectations and an statistical analysis model agreement were found. In any case, the concrete results of each studied variable are presented one by one in the following paragraphs.

Heat in water (Q_W): The heat transferred to water strongly depends on the amount of pellet supplied (m_p). The influence of the stechiometric ratio (n) is not so meaningful, although the maximum of Q_W square with the average value experienced (in our case, n=1,6). Adjusted R^2= 99.8%.

$$Q_W(kW)=10.070\cdot m_p- 4.211\cdot m_p\cdot(n-1.6)^2 \qquad \text{(Fig. 5)}$$

Heat in smoke (Q_S): Although the heat in smoke increases linearly with the contribution of both m_p and n, compared to the stechiometric ratio (n), the m_p factor is more influent. No major problems in the regression were found. Adjusted R^2= 99.1%. Nevertheless, it should be noted the following to accept the model:

- When the collinearity is analysed, Eigenvalue λ=0,0351 < 0,05 appeared. In any case, all other three criteria are fulfil (Correlation Matrix Index, VIF and Condition Index).

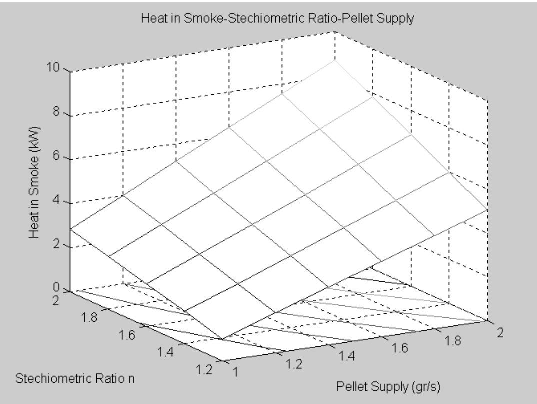

Fig. 6. Heat in smoke (kW) representation.

$$Q_S(kW)= -3.058 + 4.977\cdot m_p + 2.299\cdot m_p\cdot(n-1.6) \qquad \text{(Fig. 6)}$$

CO emissions (ppm, dry smoke): The influence of m_p in the CO emissions was assessed but finally the best results were described using the stechiometric ratio (n) as the unique dependent factor. This expression gives us, both the simplest relationship between the variables and the CO emissions, and the best statistical model analysis results.

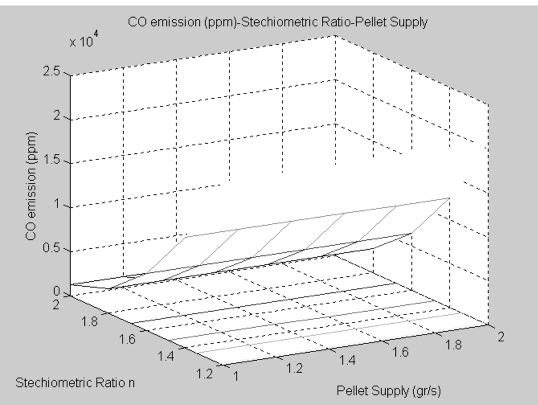

Fig. 7. CO emission (ppm) representation.

Within the experienced range, an almost exponential response in CO emission is produced when the stechiometric ratio (n) is decreased.

$$CO(ppm) = 26022 - 7630\cdot n^2 + 36054\cdot(n-1.6)^2 \qquad \text{(Fig. 7)}$$

While the model lead us to the above mentioned equation with an Adjusted R Square (R^2_A) value of 98.2% we have to comment the following. One of the statistics which predicts the influential observations, DFFIT, is completely out of range. Values extremely high 873, 727, 438...>>>1.732 appear. However, Cook distance = 0.542 << 4.76 is below the limit. There were no more discrepancies in other statistics.

NO emissions (ppm, dry smoke): The SPSS lead us to the conclusion that the NO emissions linearly depend on the two involved factors, n and m_p. This time the pellet supply has less influence than the stechiometric ratio (n). Values close to 450 were measured when using a (m_p , n) = (2 , 2) configuration.

$$NO(ppm) = 186.883\cdot n + 61.6\cdot n\cdot(m_p-1.5) \qquad \text{(Fig. 8)}$$

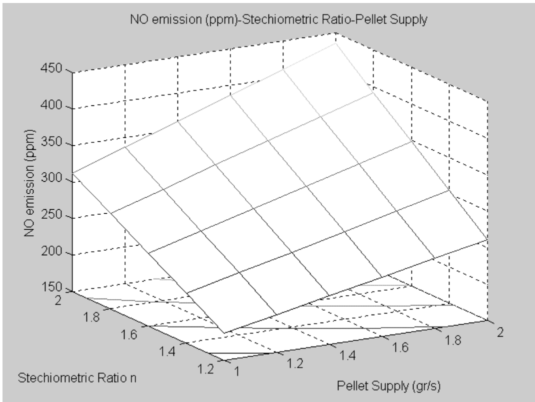

Fig. 8: NO emission (ppm) representation.

A parallelism can be established between the NO and the CO emissions concerning the problem we found with the DFFIT criteria. In this case, the values are significantly lower than the ones obtained with CO analysis. The maximum is 32.6 >> 1.732. The Cook distance does not represent any problem. R^2_A= 98.1%.

O_2 emissions (%, dry smoke): The contribution of the factors m_p and n to the variable (O_2) is quite different: when the amount of pellet (m_p) is increased the O_2 emission is slightly reduced. The stechiometric ratio (n) is the relevant factor. O_2 emission strongly grows (and linearly) with n. R^2_A= 98.9%.

It must be taken into account that the regression predicted equation has been accepted with the following considerations:

- The dependent factor ($n.m_p^2$) has a signification level of 0.106 > 0.05.
- The Shapiro-Wilks Test fails: SW_C = 0.829 > 0.801 = SW, while Kolmogorov-Smirnov Test is fulfilled.

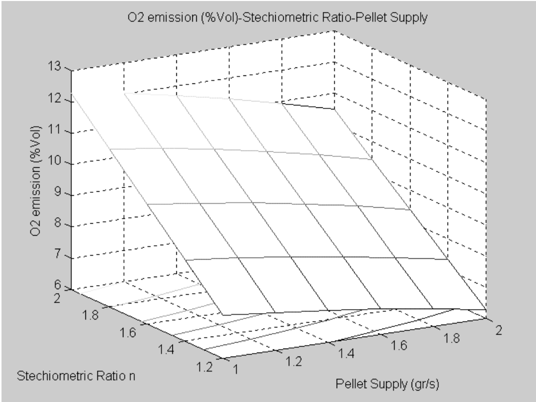

Fig. 9: O_2 emission (%) representation.

$$O2(\%) = 6.439 \cdot n - 0.299 \cdot n \cdot m_p^2 \qquad \text{(Fig. 9)}$$

Stove efficiency (η_{st}): Taking into account the previous definition (2.3) and considering now the relationship $Q_W(n, m_p)$, the following equation is obtained:

$$\eta_{st} = 0.592 - 0.248 \cdot (n-1.6)^2$$

This result shows that the stove efficiency, defined as described, does not depend on the pellet supply and has a maximum ($\eta_{st} = 0.592$) in n = 1.6.

Combustion efficiency (η_C): The connection between the η_C and the heats both to water and smoke can be express as follows:

$$\eta_C = 0.248 \cdot (3.781-n) \cdot (n+0.0363) - 0.18/m_p$$

Combustion efficiency increases with m_p and has a maximum ($\eta_C = 0.903 - 0.18/m_p$) in n = 1.87

Experimental contrast. In order to evaluate the fitting of the different correlation's, a new experiment was tested. Factor levels chosen were n = 1.87 and m_p = 2.0. The goal is to verify the expected maximum of η_C. The predicted and obtained values are in table 6.

Table 5: Experimental contrast

	Predicted	**Real**
Q_W (kW)	19.53	19.60
Q_S (kW)	8.14	7.53
CO (ppm)	1969	1227
NO (ppm)	407.1	480
O_2 (% Vol)	9.8	10.63
η_{st}	0.57	0.58
η_C	0.81	0.80

4. Conclusions

- A general characterisation of the behaviour of a pellet stove plant working in basic configuration (without air preheating, secondary air and smoke recirculation) was obtained. A high correlation index R^2 was obtained in the regressions
- Stove temperature (t_w) seems not to be an influential factor in the range 60-90ºC. Critical factors are m_p and n.
- Pellet feeding rate is coupled with the accurate amount of air in order to obtain an optimum burn rate.
- Pellet feeding (m_p) control is critical to avoid random behaviour in experiments. Pellet homogeneous size is necessary.
- n = 1.6 seems to be the best for predicted η_{st} while n = 1.87 provides the best predicted result for η_c.

5. Acknowledgement

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