DESIGN AND EXPERIMENTAL INVESTIGATION OF A TOP-FED PELLET BURNER

Rade KARAMARKOVIĆ[1], Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia
Vladan KARAMARKOVIĆ, Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia
Miloš NIKOLIĆ, Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia
Milan MARJANOVIĆ, Technical Faculty in Čačak, University of Kragujevac, Serbia

INTRODUCTION

Pellet stoves are stoves that burn compressed biomass pellets to create a source of heat for residential spaces and domestic hot water. They are suitable for the use in homes with a large living room or connected kitchen, living, and dining room as they transfer heat to the room by the heat radiation and transmission through a glass door and by the heat transmission from the rest of outer surfaces. The utilization of the heat loss to the surroundings and the automatic control enable pellet stoves to have the total efficiency larger than 90%.

The main standard regarding the examination and performance of pellet stoves is EN 14785:2006 [1]. This is not a stringent standard as it requires: (i) the mean carbon monoxide concentration calculated to 13 vol% oxygen (O_2) content in the flue gas level should not exceed 500 mg/m^3_N and 750 mg/m^3_N at nominal and reduced heat output, respectively; and (ii) the measured total efficiency should be larger than 75% and 70% at nominal and reduced heat output, respectively. However, in some countries national laws set more stringent requirements regarding the pollutant emissions and stove efficiency. Regarding these additional requirements, the primary goal was to design as economic as possible pellet stove with the efficiency larger

---
[1] *Department of Energy and Environment Protection, Faculty of Mechanical and Civil Engineering in Kraljevo, Dositejeva 19, 36000 Kraljevo, Serbia, tel. +38136383378, karamarkovic.r@mfkv.kg.ac.rs*

than 92% and steady combustion with the carbon monoxide emissions less than 100 mg/m^3_N at 13 vol% of O_2 in the dry flue gas. Based on the testing of the developed stove, shown in Fig.1., and operational problems of pellet stoves the aim of this paper is to present:

1. the developed burner cup and pollutant emissions from the stove. In addition, to address operational, construction and and fuel-relating problems.
2. solution for glass cleaning, and
3. a simple constructional modification of the burner cup that could enable easier automatic control of the burning process.
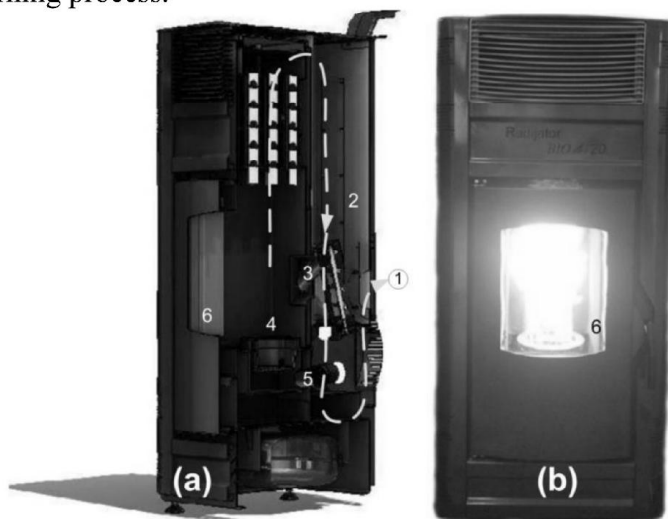

FIGURE 1 – The examined pellet stove: (a) cross section (b) picture taken during the experimental investigations. Numbers designate: 1 - the path of the flue gas; 2 – the pellet silo, 3 – feeding system (screw conveyor), 4 – burner cup, 5 – tube used for combustion air supply, 6 - front glass.

Comparing with exploitation conditions, achieving emission goals defined by the standard and national laws in experimental conditions is easier because the different qualities of pellets are present at the market. Tests are usually performed with the ENplus-A1 pellets [2] made of stem wood and chemically untreated residues from wood processing industry, which have ash content less than 0.7 wt% with a relatively high ash melting temperature. Contrary to the examinations, the stove owners use cheaper pellets with higher ash contents and lower ash-melting temperature. These, if standardized, are typically of ENplus-A2 or EN-B class [2]. Biomass ash sintering and slagging still produces great challenge for the designers of devices for thermo-chemical conversion of biomass. When the combustion temperature exceeds the ash melting temperature for the fuel being burned, the ash will slag and stick to the metal or ceramic material in the burner cup [3]. Ash slagging close to the air supply inlets could lead to their clogging. Reduced air supply could lead to substantial increase in CO and incompletely oxidized organic compound emissions, and to impairment of the automatic control of the combustion process, which is commonly performed by the lambda probe in pellet stoves.

EXAMINED CONSTRUCTION, MATERIALS AND METHOD

A burner is a well-designed unit used to continuously burn a certain type of fuel. The three main kinds of burners are fixed bed, moving grate, and burning plate (volcano type). Almost all pellet boilers (99.3%) and wood-log boilers use fixed bed burners [4].

There are three main pellet burner design concepts that are distinguished by the way in which fuel is introduced into the burner ([5] cited by [3]): (i) the underfeed burner, where pellets are introduced from beneath the burner; (ii) the horizontally fed burner, where pellets are introduced horizontally; and (iii) the overfeed burners, where pellets drop down into the burner.

The manufacturer wanted to design a reliable, simple, and economic pellet stove with only one fan, which extracts flue gases from the stove and keeps the combustion chamber and the entire stove at a negative static pressure (see Fig.1). The top-fed burner shown in Fig. 2 is used to burn pellets. This is a reliably solution as the majority of pellet stoves at the market use it. Miguez et al. [4] confirmed this because this type of feeding system is used in 55% of pellet boilers and over 70% of pellet stoves. Feeding from above dominates in low-power (<15 kW) boilers. According to the authors [4], the main advantage is the division between the feeding system and the flame is that it allows better control of the amount of fuel fed. The disadvantage is that the falling pellets produce poor combustion on the bed, increasing the amount of unburned products and dust [4].
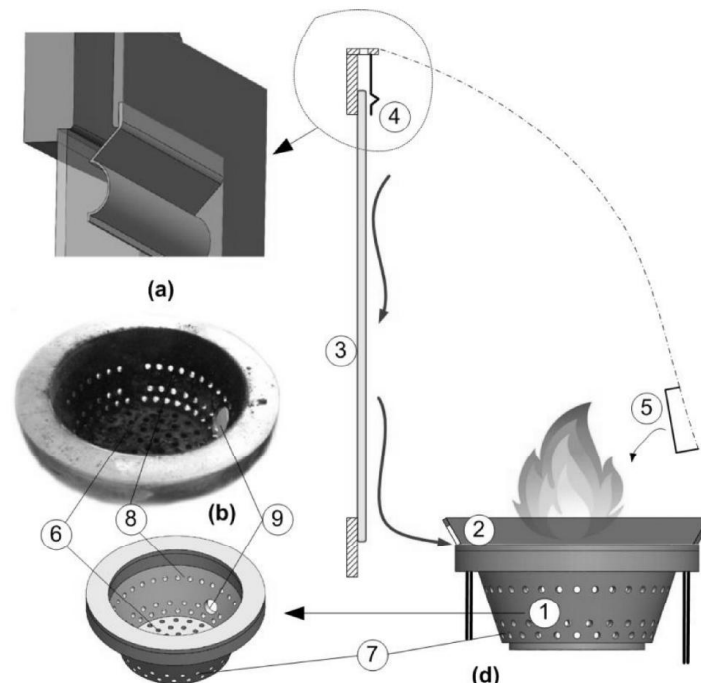

FIGURE 2 – The examined construction: (a) introduction of air used to clean the glass door, (b) picture of the burner cup after the examination, (c) construction of the burner cup, (d) schematic of the burning chamber and front door in the examined stove where, 1 –burner cup, 2 – additional conical ring, 3 – front glass, 4 – metal sheet used to produce Coanda effect, 5 – pellet introduction from above, 6 – bottom openings, 7 – two rows of low side openings, 8 – a row used for secondary air introduction, 9 – opening used for ceramic incandescent rod.

The examined burner cup is designed using the geometrical similarity with the present constructions as well as the constructal law [6]. Figures 1 and 2 show the construction of the cup. It consists of the round openings at the bottom, position 6 in Fig.2, two rows of lower side openings, position 7, one row of high side openings, and a bigger round opening for a ceramic incandescent rod, position 8. The lowest side-row is used together with bottom openings for introduction of primary air. The row above acts as a marker when regulating combustion at nominal operating conditions. The height of the bed should be roughly equal to the distance

between the bottom of the cup and the center of the second side row, which means that both primary and secondary air are introduced through this row of openings. Secondary air is introduced through the highest row of side openings.

The cleaning of the glass of the examined stove is provided by introducing ambient air through openings on the top of the door. To keep airflow downwards along the inner side of the glass, the Coanda effect is used, see position 4 in Fig. 2 (a) and (d). By flowing through the combustion chamber this air is heated and is used as a tertiary air by a conical ring (position 2 in Fig.2), which has a slot only on the side towards the glass.

To ignite pellet in the cup, a ceramic incandescent rod is used. In 56% of pellet boilers and 66.9% of pellet stoves, ceramic ignition is the preferred type of ignition system [4]. The ignition systems using hot air or electricity are also used to ignite pellets in pellet boilers and stoves.

The tests of the pellet stove were performed according to the EN 14785:2006 standard in the laboratory of "Radijator inženjering" company in Kraljevo. For the testing, three types of fuel were used. The majority of the tests were conducted using Firestixx [7] wood pellets. Table 1 shows the characteristics and ultimate analysis of these ENplus-A1 class pellets. The examinations were also conducted with 6 to 8 mm in diameter wood pellets of the class ENplus-A2 and EN B, produced by the company Miraja Kraljevo [8]. Comparing with the ENplus-A1 class, the ENplus-A2 and EN b classes of the wood pellets have higher ash contents and dominate at the market. The ENplus-A2 class has the ash content between 0.7 and 1.5 wt%, whereas the EN B class has the ash content between 1.5 and 3 wt%. These differences in pellet compositions are the most important for this paper, whereas the other differences can be seen in [2]. The CO and O_2 measurements were conducted by Testo 350 XL flue gas analyzer [9].

TABLE 1 – Test fuel characteristics.

Manufacturer	Firestixx [6]	Ultimate analysis	
Class	ENplus-A1	Carbon content kg/kg	0.474
Diameter mm	6	Hydrogen content kg/kg	0.058
Calorific value MJ/kg	17.6	Oxygen content kg/kg	0.401
		Ash content kg/kg	0.002
		Water content kg/kg	0.064

RESULTS AND DISCUSSIONS

Table 2 and Fig. 3 and 4 show the results of the experiments, during which the flue gas draft was 12±2 Pa and 10±1 Pa at nominal and reduced capacity, respectively. Three tests were carried out for 180 minutes, whereas the others shown in Table 2 and the rest carried out with low quality pellets were shorter.

During all the experiments, which have oxygen content in the flue gas less than 11 vol%, air was used to clean the glass door (see detail 4 in Fig. 2). The cleaning mechanism did not altered CO emissions nor oxygen O_2 content in the flue gas. Here, it must be stressed that the flue gas draft was kept in narrow limits, almost constant during the experimentation. This simple, cleaning mechanism functioned reliably during the examinations with all kinds of pellets.

There were no problems combusting high quality pellets at the nominal capacity. Table 2, Fig. 3 and 4 show great repeatability of emissions. The only problem occurred at the end of the work, when an amount of unburned carbon and ash remained in the burner cup. To solve this problem during the extinguishing phase, after stopping the stoking of pellets air flow through the cup

should be kept a bit longer with a larger draft through bottom openings at the end of this period (see position 6 in Fig. 2). The latter, requires a different burner design.

TABLE 2 – The average values of the flue gas emissions in the dry flue gas during combustion of Firestixx wood stem pellets at different capacity. Reduced capacity was 30% of the nominal. The change of the emissions in time is shown in Fig. 3 and 4.

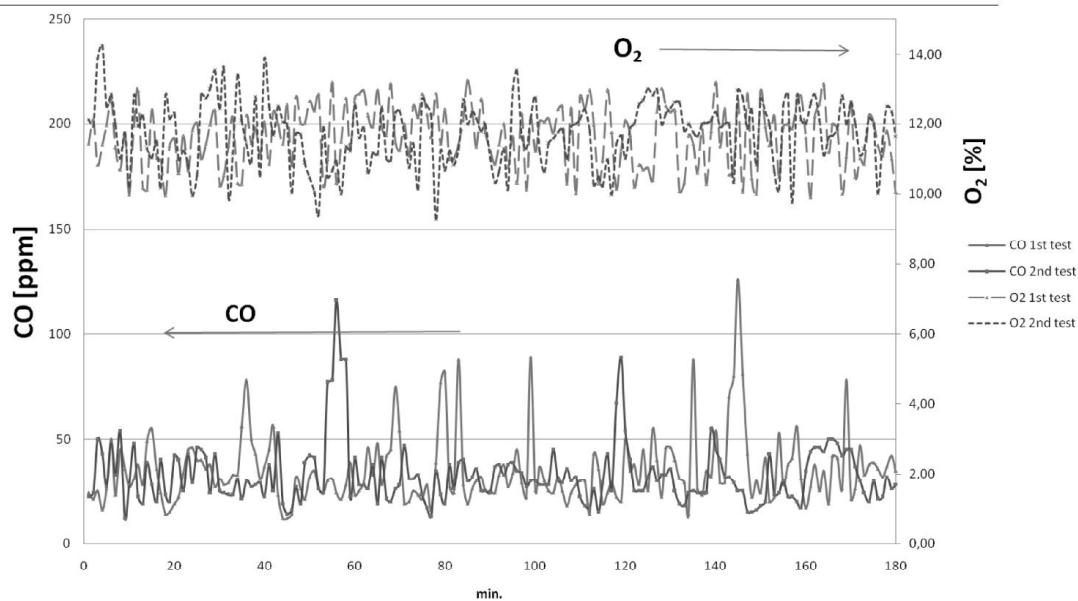| Test duration [min]	No. of samples	Stove capacity	O_2 avg. [vol%]	CO avg. [ppm]	CO at 13% O_2 [mg/m_N^3]
180	540	nominal	11.61	35.04	37.3
180	540	nominal	11.72	32.67	35.2
~120	75	nominal	9.98	35.2	25.6
180	540	min	11.70	32.47	34.91
~60	20	min	10.33	33.5	31.4

FIGURE 3 – Emission of CO and vol% of O_2 in the dry flue gas for two 180 minute tests carried out with Firestixx pellets at nominal capacity of the examined stove. These are average minute values as three samples per minute were taken. Average values are shown in Table 2.

Initially at the reduced capacity, CO emissions were not as good as those shown in Table 2 and Fig. 4. First tests showed a large amount of oxygen in the flue gas and an intensive burning of pellets near the lighter orifice (see position 9 in Fig. 2). There were two reasons: the first was the position of the ceramic lighter, which was initially lifted 20 mm from the bottom plate, and the gap between the lighter and body of the cup. After bringing down the tube that holds the lighter to touch the bottom plate (see Fig. 2) and reducing the gap between the pipe and the lighter, excellent results shown in Table 2 and Fig. 4 were obtained. At nominal capacity, the combustion of pellets is as shown in Fig. 5 (a): some of the particles commence to move within a restricted range, but most of them remain in prolonged contact to form an expanded solid bed. When burning pellets at reduced capacity, combustion is as shown in Fig. 5 (b): the air flows around the solid bed with a very small amount of air flowing through it.

When low quality pellets of the A2 and B classes were used as a fuel, the combustion process was difficult to control. The speed of the extracted fan, which is placed at the exit of the flue gas

from the stove (see Fig. 1), had to be changed several times to obtain proper emissions. The amount of oxygen in dry flue gas varied between 8 and 14.5 vol%, with CO emissions between 10 and 580 ppm at nominal capacity with EN A2 pellets. This means that the stove needs a lambda probe to adjust the fan speed according to the amount of oxygen in the flue gas. The process was not steady and slagging of the ash occurred, which, in the case of B class pellet, produced clogging of the air holes (see position 6 in Fig. 2) at the bottom of the cup. Even with the clogged bottom holes, the cup was able to produce proper combustion at reduced capacity. At the end of tests, the cup was full of ash and unburned carbon.

To obtain proper combustion of low quality pellets, the primary excess air ratio should be adjusted more precisely. Nussbaumer [10] showed that primary excess air ratio should be kept between 0.4 and 0.8 to produce the lowest NOx emissions. To separate gasification of pellet and combustion of the gas, the assumption is that the primary excess air, for ash rich pellets, should be in this kind of burner near 0.4. This kind of control of the combustion process is impossible with this design of the cup.
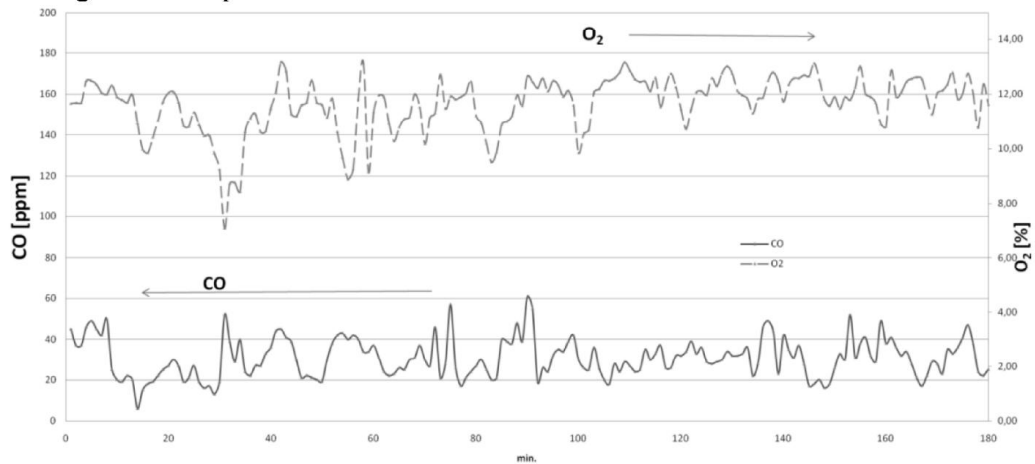

FIGURE 4 - Emission of CO and vol% of O_2 in the dry flue gas for one 180 minute test performed with Firestixx pellets at reduced capacity of the stove. These are average minute values as three samples per minute were taken. Average values are shown in Table 2.

FIGURE 5 – Two ways of combusting pellets: (a) at nominal and at (b) reduced capacity.

BURNER CONTROL IMPROVEMENT

To control the combustion in the analyzed pellet stove there are several options. One extreme case of the automatic control would be to use adjustable fans wherever they are needed. In this design four different fans would be used to control airflows for: primary combustion, secondary combustion, front glass cleaning, and through the lighter during the start-up (see Fig.1). The second extreme case would be to use one fan that extracts flue gas from the stove and four automatically controlled dampers to adjust four previously mentioned airflow streams. These ideas should be considered, especially the first one, for a large biomass heating system but for a pellet stove with the nominal capacity of 20.5 kW they would be uneconomical and would increase the probability of failure. This is why the automatic system consisting of a lambda

probe, an extraction fan and a damper, shown in Fig. 6, is analyzed. This design requires burner cup and air channels that would differ from those presented in Fig. 1 and 2. The burner cup would be divided in two sections. The primary combustion air would be introduced through the bottom holes and the lowest row of side holes. The secondary air would be introduced through two top rows of side holes. This solution requires an additional sealing ring and lifting the middle row of holes (see Fig. 2). This solution should solve problems that occur during start-up and extinguishing phases, and would allow a better control of combustion of low quality wood pellets.
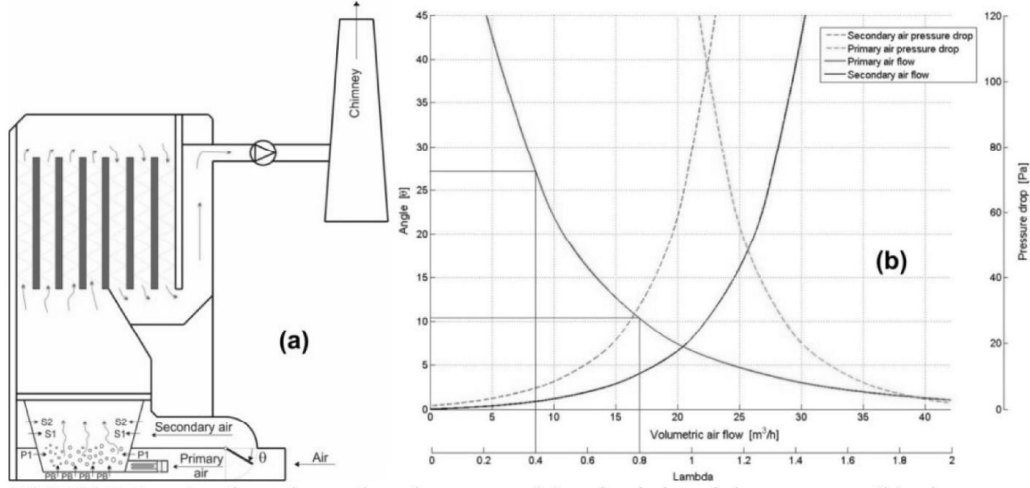

FIGURE 6 – Analyzed regulated system: (a) principle of the system, (b) air pressure drop, airflow (excess air ratio) depending on the damper angle.

The movement of a round damper would be in the range from 0 to 30°. At the start-up the damper would be open a few degrees, at the end it would be closed and in operation between 10.7 and 27.8° depending on the used fuel. These values of angular movement were obtained by calculating Kv value for the airflow through the stove for the nominal capacity of 20.5 kW. The total pressure drop in Pa is:

$\Delta p = \Delta p_d + \Delta p_b + \Delta p_c$, where

Δp_d, Δp_b, and Δp_c are the pressure drops at the damper, through the bed, and through the other passages, respectively.

$\Delta p_d = \xi \frac{\rho w^2}{2}$, where

ξ is the coefficient of local resistance, calculated by cubic spline interpolation of discrete values given in [11], ρ is the air density in kg/m^3. In the previous formula, w is the air velocity, calculated by the use of the following data: the stove nominal capacity is 20.5 kW, the stoichiometric amount of air to combust Firestixx pellets is 4.513 m$_N^3$/kg, the efficiency is 95%, and the excess air ratio is 1.9.

The pressure drop through the bed was calculated by Fig. 10 in [12], whereas the pressure drop through the rest of construction elements is:

$\Delta p_c = Rl + \Sigma \xi \frac{\rho w^2}{2}$.

The first term in this equation is the pressure drop in the straight sections, with R in Pa/m is the unit pressure drop, and the second term is the pressure drop due to all other local resistances. All these values were taken from [11].

For the given airflow and calculated pressure drop, Kv value is obtained by the following equation: $\dot{V} = Kv\sqrt{\Delta p}$, which for the obtained Kv value allows calculating pressure drop for different airflows.

CONCLUSIONS

Using air openings at the top of the front door of a stove and directing it to flow along the glass surface by Coanda effect can reliably be used to clean the glass in steady operating conditions, i.e. when steady negative static pressure is maintained in the combustion chamber. This is relatively easily achievable by variable-frequency driven fan that extracts flue gases from the stove. The air used for glass cleaning could be used as a tertiary air in the combust process.

The designed top-fed burner has very low CO emissions and fulfills the most stringent emission limits. It can be reliably used for wood pellets with less than 1.5 wt% ash. Wood pellets produced with large amounts of virgin wood and bark could lead to the clogging of bottom holes of the burner cup. This could increase the CO emissions above the values required by the legislation.

To keep competitiveness at the market of pellets stoves, the automatic control system should consists of a fan, a screw conveyer, a lambda probe, and a damper. For the examined stove and suggested system, the movement of the damper should be expected in the range from 0 to 30°.

LIST OF REFERENCES

[1] EN 14785:2006, Residential space heating appliances fired by wood pellets – Requirements and test methods, European Committee for Standardization, 23

[2] 2013, Handbook for the Certification of Wood Pellets for Heating Purposes, European Pellet Council, 11,12

[3] Orberg H, Jansson S, Kalen G, Thyrel M and Xiong S, 2014, Combustion and Slagging Behavior of Biomass Pellets Using a Burner Cup Developed for Ash-Rich Fuels, Energy&Fuels, 28, 1103-1110

[4] Miguez JL, Moran JC, Granada E and J. Porteiro, 2012, Review in Technology in Small-Scale Biomass Combustion Systems in the European Market, Renewable and Sustainable Energy Reviews, 16, 3867– 3875

[5] Obernberger L, Thek G, 2010, The Pellet Handbook: The Production and Thermal Utilisation of Biomass Pellets, Earthscan, Ltd.: London and Washington, DC,

[6] Bejan A, Lorente S, 2011, The constructal law and the evolution of design in nature, Physics of Life Reviews, 8, 209–240

[7] http://www.firestixx.org/, (accessed April 2014)

[8] http://www.miraja-pellet.rs/about.htm, (accessed April 2014)

[9] http://www.testo350.com/testo-350/epaetv.html, (accessed April 2014)

[10] Nussbaumer T, 2003, Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction, Energy & Fuels,17, 1510-1521

[11] Todorovic B, 2005. Klimatizacija. Savez mašinskih i elektrotehničkih inženjera i tehničara Srbije, Beograd, 344

[12] Teixeira, G. et al, 2012,Gasification of char from wood pellets and from wood chips: Textural properties and thermochemical conversion along a continuous fixed bed, Fuel, 102, 514-524