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A STUDY OF PARTICULATE AND GASE-OUS EMISSIONS OF A DAMAGED TUBU-LAR COMBUSTION CHAMBER IN A PELLET STOVE

ŠTUDIJ TRDIH DELCEV IN PLINSKIH EMISIJ V POŠKODOVANI CEVNI IZGOREVALNI KOMORI PELETNE PEČI

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Abstract

Wood-burning boilers are a popular source of heating in Slovenia. However, there has been much debate about the potential negative health effects associated with wood smoke in recent years. Wood smoke is increasingly seen as a significant component of airborne particulate matter (PM), especially in the context of the new sort time standard for fine particles in ambient air. Most organic substances will be burnt in the boilers during good combustion conditions with sufficient oxygen supply and high temperature.

This study presents the influence of damaged tubular combustion chamber on smoke fine-particle emissions at small scale pellet burners. This research aims to reduce the particulate matter emissions of small scale pellet boilers and contribute to cleaner air.

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Povzetek

Kotli na lesno biomaso so priljuljen način ogrevanja v Sloveniji. V zadnjih letih je bilo veliko govora o potencialno negativnem vplivu izgorevalnih plinov na zdravje ljudi. Glede na dovoljene vrednosti trdih delcev v zraku, ki jih predpisuje novejši standard, je postal izgorevalni plin v pečeh na lesno biomaso eden od znatnih onesnaževalcev okolja s trdimi delci. V primeru popolnega izgorevanja v pečeh pri višjih temperaturah z zadostno količino kisika, večina organskih snovi izgori.

V tej študiji je predstavljen vpliv poškodovane cevne izgorevalne komore na emisijo trdih delcev v manjših peletnih pečeh. Glavni namen raziskave je zmanjšati možnosti pojava trdih delcev v izgorevalnih plinih peletnih pečeh in s tem prispevati h čistejšemu zraku.

1 INTRODUCTION

Residential wood combustion has been identified as one of the main sources of particulate matter (PM); fine particles are significant because of their adverse effects on human health and the environment, *[1].* Particulate matter is defined as the total mass of suspended particles in the air. PM is typically divided into three subclasses, i.e., PM10, PM2.5 and PM0.1, which are defined as particle matter with an aerodynamic diameter smaller than 10 µm, 2.5 µm, and 0.1 µm, respectively. PM2.5 particles are generally called "fine particles"; however, this term can also be applied to the number or surface area based on particle diameters less than 2.5 µm. In the atmosphere, particles can be solid or liquid; the mixture of particles and gases is called an "aerosol", *[2]*. When particles from combustion sources are discussed, particles with aerodynamic diameters less than 1 µm or 2.5 µm (PM1 or PM2.5) are often used, whereas particles with sizes ranging from 2.5 µm to 10 µm are called "coarse particles". Examples of coarse particle sources include road wear and wind-blown dust, *[3]*. Fine particles are known to have adverse effects on human health and to cause respiratory and cardiac symptoms and even premature death, especially among those with reduced health conditions, e.g., children, the elderly, and those with chronic diseases.

Small scale combustion appliances are mainly used for residential heating in Slovenia. Different types of small-scale combustion appliances, such as wood stoves, pellet burners, pellet boilers, wood log boilers, and wood chip boilers, are commonly used throughout Europe and in Slovenia. Different forms of biomass fuels, such as wood logs, wood chips, wood pellets, sawdust, forest residues, straw, etc., are used as fuel in these appliances.

Wood is the most commonly used biomass fuel in Slovenia due to the large forest base, forest industry, and relatively easy access to cheap wood for many individuals. The use of wood in heat and power production is increasing. Wood pellets are primarily used in continuously operated combustion devices, *[4]*, as an example of renewable energy.

In this study, the influence of a damaged tubular combustion chamber on smoke fine particle emissions from pellet burners is presented. The purpose is to reduce particulate matter emissions from the small scale pellet boilers and contribute to cleaner air.

2 EXPERIMENTAL SECTION

Combustion experiments were performed in a laboratory environment with a small-scale 25 kW pellet boiler suitable for household heat production. The pellet boiler operates with an overfed fuel input and includes a Ferroli Sun P7 prefabricated burner (Figure 1). This type of pellet burner is the most popular in Slovenia due to its reasonable price. The burner can be operated continuously between loads of 14 and 30 kW. It is equipped with logic-controlled fans for the supply of combustion air. The primary air was fed in through holes before the grille at the bottom of the cylindrical furnace, i.e., a tubular combustion chamber with 3 mm steel wall thickness. The width of the grille was approximately 100 mm, and the diameter of each hole was approximately 6 mm. Commercial wood pellets originating from Slovenia were used in the study. The primary pellet raw material was pinewood.

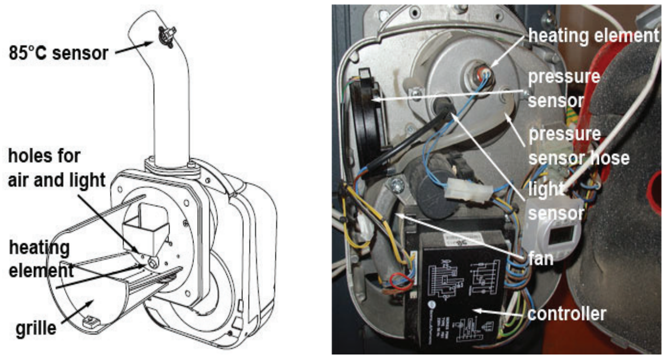

Figure 1: *Sketch of the pellet burner used in this study*

The tubular combustion chamber should be made of high-temperature-resistant steel that contains a prescribed amount of Cr and Mo due to the high flame temperature, which can exceed 600 °C (point M17). The distribution of the flame temperatures was measured with a Testo 890-2 infrared camera, as shown in Figure 2 and Table 1.

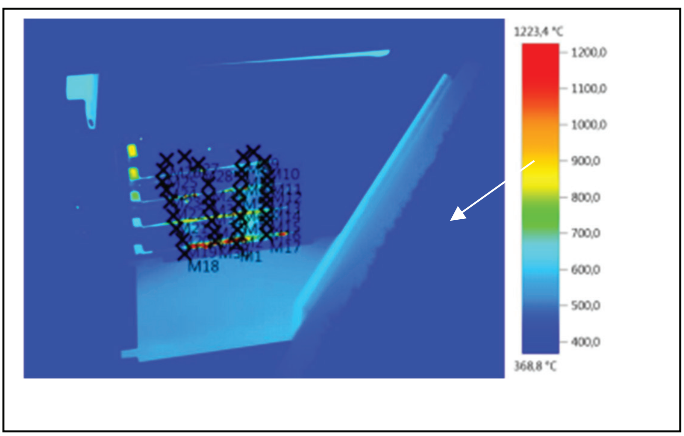

Figure 2: *Flame temperature measurement at the tubular combustion chamber of pellet burner*

Table 1: *Temperature distribution at pellet burner's flame*

Measure point	Temp. [°C]	Emiss.	Refl. Temp. [°C]
Measure point 1	573.5	0.13	20.0
Measure point 2	514.7	0.13	20.0
Measure point 3	575.8	0.13	20.0
Measure point 4	545.9	0.13	20.0
Measure point 5	513.8	0.13	20.0
Measure point 6	442.0	0.13	20.0
Measure point 7	492.7	0.13	20.0
Measure point 8	418.8	0.13	20.0
Measure point 9	394.2	0.13	20.0
Measure point 10	529.6	0.13	20.0
Measure point 11	460.4	0.13	20.0
Measure point 12	615.2	0.13	20.0
Measure point 13	460.6	0.13	20.0
Measure point 14	413.4	0.13	20.0
Measure point 15	569.8	0.13	20.0
Measure point 16	493.7	0.13	20.0
Measure point 17	643.0	0.13	20.0
Measure point 18	237.7	0.13	20.0
Measure point 19	329.2	0.13	20.0
Measure point 20	386.1	0.13	20.0
Measure point 21	348.9	0.13	20.0
Measure point 22	416.4	0.13	20.0
Measure point 23	322.1	0.13	20.0
Measure point 24	439.1	0.13	20.0
Measure point 25	302.9	0.13	20.0
Measure point 26	391.0	0.13	20.0
Measure point 27	391.2	0.13	20.0
Measure point 28	318.1	0.13	20.0

Measure point 29	327.3	0.13	20.0
Measure point 30	409.9	0.13	20.0
Measure point 31	353.3	0.13	20.0
Measure point 32	424.9	0.13	20.0
Measure point 33	390.3	0.13	20.0
Measure point 34	393.8	0.13	20.0

The shape of the pellet burner's flame can be seen in Figure 3. The arrow marks the area with the highest measured temperature (point M17), 643 ℃ (Figure 2 and Figure 3 and Figure 4).

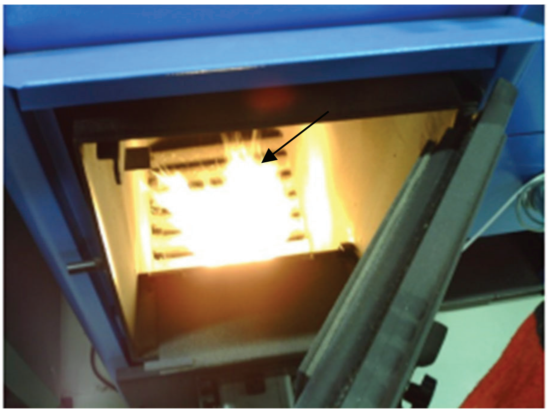

Figure 3: *The shape of the flame in the pellet burner*

The damage of the steel tube (tubular combustion chamber) and the grille occurred after one year of the burner operation time, as shown in Figure 4 and Figure 5.

Figure 4: *Hole as a damage of the steel tube (tubular combustion chamber)*

Figure 5: *Hot cracks as a damage of the steel grille*

Chemical analyses of the steel tube (tubular combustion chamber) and Cr-Mo steel tube was performed with X-ray fluorescence spectrometry (XRF) using an X-ray fluorescence spectrometer (Thermo Scientific Niton XL3t GOLD+) and is given in Table 2.

Measurements were carried out manually (Figure 6) with the target points on the steel tube (Figure 7). Each measurement was repeated three times, and later the average value was calculated. Each measurement was done for one minute.

Table 2: *Chemical composition of steel tube (tubular combustion chamber)*

(%)	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
HSLA Steel tube	0.17	0.57	0.71	0.021	0.004	0.49	0.08	0.028	0.31	0.027
X11CrMo9 Steel tube	0.08	0.41	0.63	O.031	0.002	8.23	0.04	0.96	-	-

The basic mechanical properties of the steel tube were obtained using flat tensile specimens taken from the steel tube in the rolling direction; they are given in Table 3.

Table 3: *Real mechanical properties of steel tube (tubular combustion chamber)*

Designation	R_p (MPa)	R_m (MPa)	Elongation (%)	Charpy toughness (J)
Steel tube	736	817	16.2	79,88,112 at 0 ℃

Figure 6: *Manual measurement of chemical analyses of steel tube (tubular combustion chamber) with X-ray fluorescence spectrometry (XRF) using an X-ray fluorescence spectrometer*

Figure 7: *Target point (number 2) for manual measurement of chemical analyses of real steel tube (tubular combustion chamber)*

Fine particle measurements were made in the chimney tube at a distance of 20 cm from the boiler using a fine particle analyser (Figure 8), which measures fine particles, O_2 concentration and CO emissions in real-time for 15 minutes.

Figure 8: *Fine particle measurement with the Testo 380 fine particle analyser*

3 RESULTS AND DISCUSSION

From the results of chemical analyses (Table 2) and real mechanical properties (Table 3) of the steel tube (tubular combustion chamber), it is evident that the high-strength, low-alloyed (HSLA) steel is used for the construction of the tubular combustion chamber. This steel is typically HSLA carbon steel, with a comparatively mild amount of carbon (0.16% to 0.20%) and a low amount of Cr and Mo, which is less than 0.5% (Table 2). It has ferromagnetic properties. The mild amount of carbon also makes HSLA steel vulnerable to rust. HSLA steel is used in construction as structural steel and is not useful for operation at temperatures higher than 100 ℃ due to the low content of Cr and Mo, as can be seen from Table 2. The characteristic fine-grain bainitic microstructure of the HSLA steel tube is shown in Figure 9. The surface of a metallographic specimen is prepared by polishing and etching. After preparation, it is analysed using a Zeiss Axio A2 optical microscope.

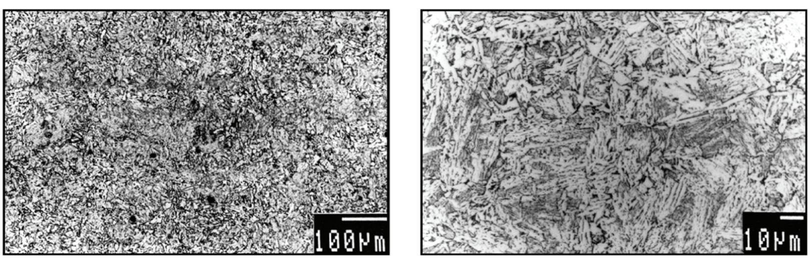

Figure 9: *The characteristic fine-grain bainitic microstructure of a real HSLA steel tube*

The tubular combustion chamber should be made from high-temperature Cr-Mo resistance steel, which contains a prescribed amount of Cr (at least 9%) and Mo (about 1%) due to the high flame temperature, which can exceed 600 °C. The improper selection of base material (HSLA steel) leads to the damage of the steel tube due to the high operating temperatures during the combustion of pellets (Figure 4). The highest flame temperature of 643 ℃ (Figure 2, point M17, see arrow) was measured at the surface of the HSLA steel tube end (Figure 3 and Figure 4, see arrow) with an infrared camera, as shown in Figure 2 and Table 1. Thus, the tubular combustion chamber must be made from a high-temperature Cr-Mo steel, containing a prescribed amount of Cr and Mo.

The damage appeared at the burner tube as holes, as can be seen from Figure 4. The total measured amount of damaged tube surface was 22.75 cm².

Because of this, holes with diameters of 11 mm were drilled into the new steel tube (Figure 10 and Figure 11) made of X11CrMo9 high-temperature-resistant steel to simulate the damage of the tube (tubular combustion chamber) measured with a fine particle analyser (Figure 8).

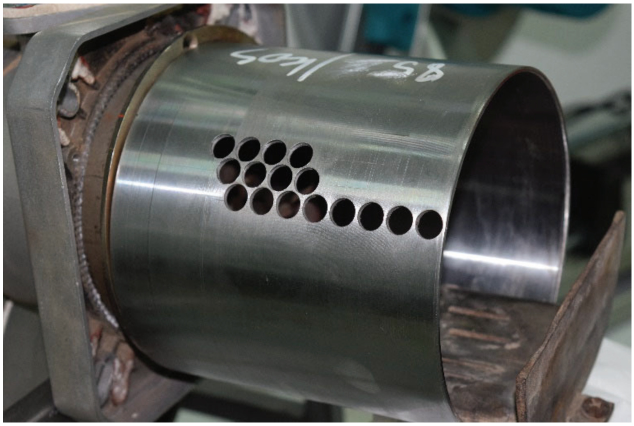

Figure 10: *Cr-Mo steel tube with damaged surface (16 holes)*

Combustion experiments were performed with optimal operational manipulation (loads, primary combustion air supplies). Normal operation was assumed to obtain a nominal load of 25 kW, represented as an optimal baseline.

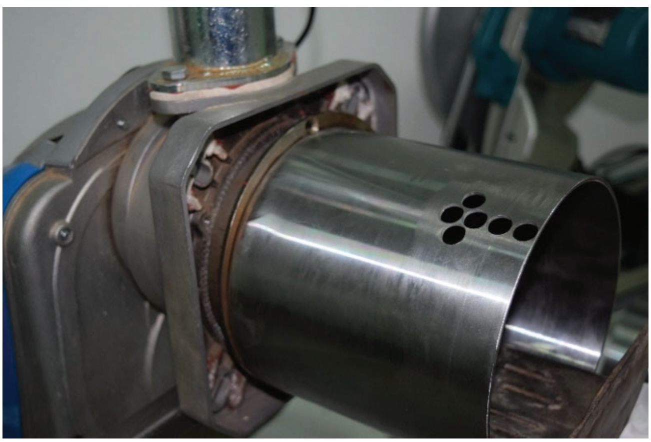

Figure 11: *Cr-Mo steel tube with damaged surface (6 holes) of 5.70 cm²*

Each of the combustion experiments was performed in a preheated pellet boiler. The boiler was turned on one hour before the start of the experiment, and the warming was performed on full load.

The influence of damaged tubular combustion chamber on smoke fine-particle emissions (FPE), O_2 concentration, and CO emissions at the pellet burner is presented in Table 4 and Figure 12. Table 4 presents the total values of smoke fine-particle emissions (FPE), O_2 concentration and CO emissions after 15 minutes of measurements with the fine particle analyser.

By reviewing the results (Table 4 and Figure 12) of measurements of smoke fine-particle emissions (FPE), O_2 concentration and CO emissions, it is clear that the highest values were reached at the largest damaged tube surface at 22.75 cm^2 (24 holes). FPE value is approximately 77% higher than the optimal value at the zero damage surface. The damaged combustion chamber of the pellet burner influences lower O_2 concentration for about 48% and approximately 50% higher CO emissions in comparison with optimal values at the zero damage tube surface.

Table 4: *The results of measurements of smoke fine-particle emissions (FPE), O2 concentration and CO emissions at the damaged pellet burner chamber*

Damage surface (cm^2)	FPE (mg/Nm^3)	O_2 (%)	CO (mg/Nm^3)
0.00	16.7	6.2	68
0.95 (1 hole)	16.9	6.1	69
1.90 (2 holes)	17.1	5.8	72
3.80 (4 holes)	17.9	5.1	75
5.70 (6 holes)	18.1	4.9	79
22.75(24 holes)	29.6	3.2	101

The damage effect of the tubular combustion chamber on smoke fine-particle emissions (FPE), O2 concentration and CO emissions is insignificant at damage surfaces 0.00 cm^2, 0.95 cm^2, 1.90 cm^2, and 3.80 cm^2 (4 holes) for which the measured values did not exceed 7% of optimal values.

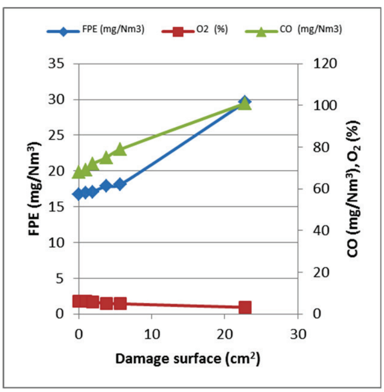

Figure 12: *The influence of damaged tubular combustion chamber on smoke fine-particle emissions (FPE), O_2 concentration and CO emissions at the pellet burner*

The next higher values were reached at the damaged tube surface of 5.70 cm² (6 holes). FPE value is approximately 10% higher than the optimal value at the zero damage surface. The damaged pellet burner chamber also influenced lower O_2 concentration by about 20% and approximately 13% higher CO emissions in comparison with optimal values at the zero damage tube surface.

4 CONCLUSION

Wood is the most commonly used biomass fuel in Slovenia due to the large forest base, forest industry, and relatively easy access to cheap wood for many individuals. The use of wood in heat and power production is increasing. Wood pellets are primarily used in continuously operated combustion appliances. In real applications, combustion conditions are never ideal. Moreover, fuel and combustion air contain several components that affect the combustion process and emission formation. The combustion of solid fuel in real-life applications always require more air than what is theoretically needed.

The tubular combustion chamber of a pellet burner should be made from high-temperature-resistant Cr-Mo steel that contains prescribed amounts of Cr and Mo due to the high flame temperature, which can exceed 600 ℃.

Improper selection of base materials for the construction of steel combustion tubes leads to damage due to the high operating temperatures during the combustion of pellets.

The damage appeared on the burner tube as holes. A damaged tubular combustion chamber in the pellet burner significantly influences smoke fine-particle emissions (FPE), O_2 concentrations, and CO emissions.

The highest values of smoke fine-particle emissions (FPE), O_2 concentration, and CO emissions were reached at the largest damaged tube surface: 22.75 cm² (24 holes). The FPE value is approximately 77% higher than the optimal value on the non-damaged surface. A damaged pellet burner chamber also influences lower O_2 concentration by about 48% and approximately 50% higher CO emissions in comparison with optimal values at the zero damage tube surface. The damage effect of the tubular combustion chamber on smoke fine-particle emissions (FPE), O_2 concentrations, and CO emissions is insignificant at damage surfaces 0.00 cm², 0.95 cm², 1.90 cm² and 3.80 cm² (4 holes) for which measured values did not exceed 7% of optimal values.

Pellet boilers save energy and money, and they are highly durable; however, regular maintenance, especially of the tubular combustion chambers, is essential to keep them working efficiently and contributing to cleaner air.

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