GASEOUS EMISSION IN AUTOMATIC RESIDENTIAL HEATING APPLIANCE USING RICE HUSKS AS SOLID BIOFUEL

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The experimental work extended recent empirical information on rice husks in conventional thermochemical applications. These agriculture residues were characterized as the potential solid biofuel option with considerable net heating value of 15800 kJ/kg and observed first sign of ash deformation at the temperature of 1450 °C. A commercial residential heating unit with automatic pelletized fuel loading and horizontal flue gas outlet was assembled as the test appliance. Major components in flue gas stream during steady-state operations confirmed typical emission fluctuating profiles of solid biofuel in residential heating appliance. Mean values of carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), sulfur dioxide (SO_2), total organic carbon (TOC) and particulate matter (PM) were summarized referred to 13% oxygen (O_2) in standard reference conditions or energy content of fuel (mg/MJ). The obtained emission profiles highlighted distinct correlations between volume fractions of gaseous components depending on the elemental contents presented in rice husks. Particulate matters emitted containing unburnt carbonaceous solid and inorganic material remained as by-products showed significant high mass concentrations due to the poor combustion conditions in small-scale installation agreed with earlier work. The intermittent and short maintained steady-states caused by extensive rice husks ash agglomeration occurred on the fire chamber and ashtray were remarked for further investigation.

Keywords: rice husks, solid biofuel, biomass combustion, residential heating, emission

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1. Introduction

In the context of sustainable bioeconomy, energy security and environmental concerns constantly raise the motivation of renewable energy diversification [1]. Global bioenergy reviews pointed out that the limited availability of fossil fuels steadily increases the demand and transition to biomass viable options as a significant part of future energy [2, 3]. Considering the conventional bioenergy routes, processes or systems, solid biomass is highlighted as the CO_2 neutral form for energy conversion processes due to its commodity and widely availability [4, 5]. Particularly, it is estimated that solid biofuel currently accounts from 10% to 14% to the global energy supply, subsequently following the conventional coal, oil and natural gas, and thus ranks the fourth common used energy resource [6, 7]. Beside the traditional sources of solid biofuel such as forestry wood, waste wood and residues, the agricultural by-products, residues and wastes are also considered as abundant carbonaceous materials for local heat processing and electricity production [8]. World Energy Council described that the greatest energetic utilization and end-use application of main field based residues would potentially be observed in high rice and corn cultivation regions, relatively to their low production cost [9]. It is estimated that, the amount of residues along with global rice production is approximately 1.27 billion metric tons annually, covering 1.12 billion metric tons of rice straws as the main field drying residues and subsequently 0.15 billion metric tons of rice husks as post harvesting residues. Specifically, rice husks contribute to one-fifth of overall dry mass fraction in the paddy produced in rice post harvesting processes [10]. As the crop residues of rice cultivation for centuries, rice husks are characterized as a potential solid biofuel in the rice production countries, particularly Asia and America [11]. In practice, rice straws are commonly dried, chipped and baled while rice husks are pretreated and pelletized in commercial diameter of 6-8mm and 5-30mm length.

Beyond the convenience of reducing bulky volume for transport, their high density and high energy content per unit volume are the key advantages of pellets to be widely used for energetic utilization in thermochemical conversion systems [12-14]. From this approach, direct combustion or co-combustion for heat processing and power generation is considered as the simplest and economical conversion options. A number of studies reported that the highest efficiencies are obtained in applications with power generation above 100 MW, while small-scale pellet boilers or burners perform lower efficiency and inadequately controlled of gaseous emissions [15-17]. These small-scale combustion installations with nominal heat output up to 50 kW were mainly intended for heating and provision of water or steam in residential and commercial/institutional sectors worldwide [18]. In some specific circumstances, they might extend to residential and commercial cooking or agricultural crops drying and greenhouses heating [19]. Approximately 26% domestic applied thermal energy in European households generated from solid biofuel combustion, especially during the winter season [20].

Combustion techniques applied for residential space heating appliances including small-scale fireplaces, stoves, cookers, heaters and small boilers diverse strongly depending on country and regional factors, then influencing by fuel characteristic, units design, operating condition, relevant individual parameters, and techniques employed, and thus consequently perform a wide range of efficiencies and emissions [21]. Indeed, these heating installations have been identified as significant sources for emission of aerosol particles and gaseous pollutants, contributing large impacts on air quality and public health, considering toxic and carcinogenic constituents. Therefore, a number of countries have introduced special concerns and specific requirements for pelletized biofuels, residential heating appliances on the market controlled basis, the suitability and compatibility of those in practice [22].

There is a numerous research attention on the emissions from small-scale combustion unit fired by variable wood types from the Northern European [23-28], Western Mediterranean woods [29-31], European Alpine wood types [33-34], Northern America wood types [35, 36], and Asian mixed wood residues [37]. On this approach, the suitability of rice husks pellets in a 10 kW automatic residential space heating appliance was tested.

2. Experimental

In a lab-scale condition, the experiment was setup for residential space heating appliance fired by rice husks pellets in accordance with the requirements of European Standard EN 14875. This standard method specifies requirements concerning to the design, manufacture, construction, assembly, safety and performance (including efficiency and emissions), instructions and marking together with associated test methods and selected biofuel for type-testing residential space heaters fired by pellets, and mechanically fed up to 50 kW nominal heat output.

2.1. Appliance installation

A commercial unit of residential space heating appliance with horizontal flue gas outlet was assembled as the test installation as illustrated in Figure 1. The appliance consists of a pellets container, a screw conveyor, a combustion chamber with a fuel pot and an electric ignition, flue gas/air heat exchanger and a combustion chamber door with glass window flushed on the backside. The screw conveyor was powered by an electric motor and transported fuel to the top of drainpipe, the feed into the burner pot.

The combustion air was sucked in with the aid of the exhaust fan via the air inlet. The hot combustion gases were discharged via the flue gas/air heat exchanger surfaces and the flue pipe. A door with a glass window was also used for cleaning of the combustion chamber. The ash was tilted by an automatic tipping grate into an ash pan which was located below the combustion chamber.

Figure 1. Test bench assembly with horizontal flue outlet

The performance of the pellet stove can be electronically controlled using a touch screen. The combustion air can either be taken from the room or from the outside in appliance for room sealed operation.

The device type, technical parameters and characteristics of product range are described in Table 1.

Table 1. Technical data of the tested appliance

Type of device	residential heating	
Fuel		pellets
Nominal heat output	[kW]	10
Heat power range	[kW]	3 - 10
Fuel rate	[kg/h]	2.2 / 1.36
Weight with ceramic cover	[kg]	237
Fuel hopper capacity	[kg]	49
Base area	[mm]	793 x 434
Height	[mm]	1115
Flue gas pipe diameter	[mm]	100

The designed shape and dimensions of the components and assembled equipment ensured that, when operated in accordance with the provisions of the combustion test and exposed to the associated mechanical, chemical and thermal stresses, the appliance operated reliably and safely such that during normal operation.

Component parts such as covers, operating controls, safety devices and electrical accessories were arranged under the described test conditions that their surface temperatures did not exceed those specified by the manufacturer or relevant component part standard. The used thermal insulation was made of non-combustible material and non-hazardous to health in its applied position. Component parts which acted as a seal were located securely to ensure that no combustion gases posing a hazard could escape. Where a seal was made with fire cement, the cement was supported by adjacent metal surfaces.

The appliance met the requirements as appropriate to the material of construction and intended usage. It was capable of operating safely at the permissible maximum operating pressure declared by the manufacturer and met the requirements of the type pressure test. The appliance was installed into the test assembly following the manufacturer's instructions, and the flue spigot/socket was connected to the measurement section.

2.2. Test-bench setup

The test-bench is shown together with the measurement devices in Figure 2. A small amount of flue gas was taken out of the exit flue gas stream for analysis. The first step was to remove the dust from the sample gas using a filter made from quartz wool. The sample gas was then transported along a pipe heated to approximately 180 ºC to the next preparation stages. The majority of the water was then removed from the gas by cooling to about 5 ºC.

After these preparatory stages the gas sample was fed to several analysis equipment (O_2, CO_2, CO, NO and SO_2). The flame ionization detector (TOC) was supplied with sample gas through a separate heated pipe (180 ºC) equipped with a filter. To determine the particulate matter mass concentration, a small gas stream was extracted from the flue gas. The particulate matter of this gas stream was collected by a filter. The gas samples were dried in drying tower and its volume was metered with a gas meter. The evaluation was carried out according to EN 14785.

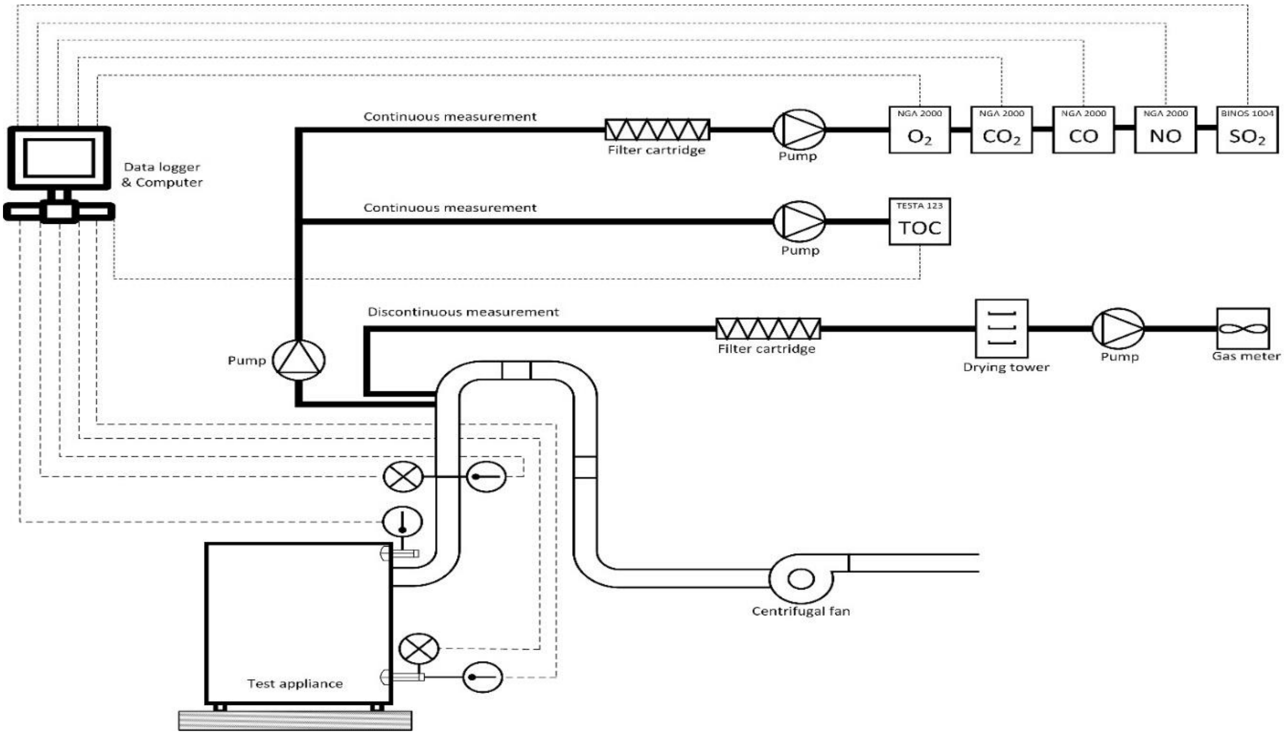

Figure 2. Scheme of the equipment used in the test-bench

2.3. Flue gas temperature

The measurement section was provided with means of measuring the temperature and composition of the flue gas and with means of measuring the applied flue draught pressure. This section was fully lagged with nominal 40 mm thick mineral fiber in order to provide a thermal conductivity of at least 0.04 W/m.K at an average temperature of 20 °C. The dimensions of the measurement section was sized and fitted according to the diameter of the flue gas outlet of the test appliance.

The flue gas temperature was measured by a sensing element Pt-100 resistance thermometer located inside a suction pyrometer probe, with the sealed end touching the opposite wall of the measurement section and with the open outlet end connected to a suction pump. A sheath was used to protect the thermometer. A suitable fitting was provided to give a gas-tight seal between the suction pyrometer and the wall of the measurement section and between the sensing element and the outlet of the pyrometer.

The suction pyrometer probe had 3 sampling holes, each of 2.5 ± 0.5 mm in diameter, one positioned at the center of the measurement section and the other two positioned either side at one quarter of the flue diameter distance from the side walls of the measurement section. The inside diameter of the suction pyrometer was 5 ± 1 mm and the flow rate was adjusted in order to obtain a flow velocity within the range of 20 m/s to 25 m/s.

2.4. Flue gas sampling

The suction pyrometer probe was also used for flue gas sampling. The outlet end of the suction pyrometer was connected to a flue gas analysis system meeting the accuracy requirements specified EN 14785. Means of cooling, cleaning and drying the flue gas sample was incorporated in the sampling line as shown in Figure 2. The materials used for the gas sampling line and probe connections was resistant to the expected temperature and did not react with or allow diffusion of flue gases. There was no leak in either the sampling probe connections or the gas sampling line.

A tube, with an internal diameter of 6 mm, was located into the measurement section. The end of the tube was sealed within the inner wall of the measurement section. The pressure was measured using pressure measuring equipment (Digima LPU, Special Instruments) with a measuring range from 0 to 200 Pa.

The appliance flue spigot/socket was connected to the measurement section by an uninsulated flue gas connector and an insulated flue gas adaptor. The flue gas connector was made of unpainted mild steel with a thickness of (1.5 ± 0.5) mm. Its length was (330 ± 10) mm and correspond to the diameter of the flue spigot/socket of the appliance. A flue gas adaptor was connected between the measurement section and the flue gas connector. The flue gas adaptor had the same diameter as the measurement section and was insulated to the same level. For the tested appliance with horizontal outlet, the flue gas adaptor had a radius of (225 ± 5) mm at its center.

2.5. Flue gas measurement

The measurement equipment used was selected to ensure that for each measurement parameter the uncertainty of measurement requirements were in accordance to EN 14785. The peak values of the measured parameters were in the range of the measurement equipment used. Lower detection limit was 1% of the span value with margin error 1%. Oxygen, CO_2, CO, NO were measured continuously based on the NTIR using NGA 2000 manufacture by Emerson with uncertainty ≤ 2% of the limit value of 0.06%. Sulfur dioxide (SO_2) was measured continuously based on the UV absorption principle using Binos 1004. TOC was measured continuously based on the flame ionization detector principle using Testa 123. PMs were determined based on the gravimetric principle. Humidity was measured continuously using type 175-H2 data logger manufactured by Testo. The determination of the amount of fuel carried out with a balance Sartorius type QA 160008. The data obtained from the measurements at 10 seconds time interval was recorded electronically using a data logger connected to a computer.

2.6. Fuel characteristics

Rice husks pellets were selected as the non-woody solid biofuel for the test runs. The pelletized pieces were cylindrically shaped with a diameter of 8 mm and a mean particle length of 15 to 20 mm. The pellets was homogeneous in quality, appropriate for small-scale fuel-feeding units and capable in thermochemical conversion appliances. Table 2 summarizes the proximate and ultimate analyzed values on dry basis of selected solid biofuel according to standard methods, outlines a principal baseline for experimental investigations.

Table 2. Characteristics of the rice husks as solid biofuel

Parameter	Unit	Value
General		
Moisture	[%]	7.4
Volatile	[%]	68.5
Residual char	[%]	31.5
Ash content	[%]	15.0
Higher heating value	[kJ/kg]	16900
Lower heating value	[kJ/kg]	15800
Elemental analysis		
Carbon (C)	[%]	43.16
Hydrogen (H)	[%]	5.18
Nitrogen (N)	[%]	0.47
Oxygen (O)	[%]	51.04
Sulphur (S)	[%]	0.06
Chlorine (Cl)	[%]	0.09
Ash melting		
Deformation temperature	[°C]	1450

2.7. Steady state operation

The performance test was carried out at the settings given by the manufacturer to achieve the required output of measurements. It consisted of two parts: an ignition following by one pre-test period and a test period. The test started from cold, not followed another test. Thus, the pre-test period was preceded by an initial ignition and pre-test. The duration of the pre-test period was sufficient to ensure that stable conditions were established.

Multiple separated test determinations of the necessary test parameters were performed. These determinations were obtained from two test periods conducted on either separate occasions and preceded by a pre-test period or from at least two consecutive refueling charges. Then the test results were determined separately for each re-fueling interval. The hopper was loaded with sufficient amount of fuel quantity to ensure ignition of the test fuel and a sufficient pre-test period, then the electrical ignition system started.

The appliance was operated during the pre-test period at a specific burning rate. The ignition and pre-test period was ended when the stable conditions were obtained for approximately 30 min. and the flue gas temperature did not change more than ±5K.

The ashtray was replaced and emptied. The installation hopper was fully loaded with feedstock pellets for the test period. The test started immediately after loading the appliance with fuel conversion controlled at the rate of 2 kg/h. The range of operating parameters for the experimental test runs in normal conditions, including values of the fluid dynamics, are summarized in Table 3.

Table 3 Parameters during the steady state operations

Test operation in full load	Unit	Value
Fuel quantity	[kg]	0.6
Fuel power	[kW]	6.5
Fuel consumption	[kg/h]	1.7
Average negative pressure in the flue gas draught	[Pa]	11.6
Barometric pressure	[mbar]	987.1
Atmospheric relative humidity	[%]	35.5
Room temperature	[°C]	28.8
Air ratio (lambda)	[-]	3.1
Specific flue gas volume, dry gas	[m^3/kg]	11.3
Specific flue gas volume, wet gas	[m^3/kg]	11.9
Gas flow rate	[m^3/h]	19.5
Flue gas mass flow rate	[g/s]	7
Average flue gas temperature in the flue spigot	[°C]	203.6
Average flue gas temperature in measurement	[°C]	183.7
Average specific heat capacity of water vapor	[kJ/m^3K]	1.52
Average specific heat capacity of dry flue gas	[kJ/m^3K]	1.32
Loss of sensible heat in the flue gas	[kJ/kg]	2440.6
	[%]	16.8
Loss through CO in the flue gas	[kJ/kg]	10.6
	[%]	0.2
Loss through combustible constituents	[%]	0.1
Thermal efficiency	[%]	82.9
Thermal output total	[kW]	5.45

The fuel load was calculated with the formula:

$$B_{fl} = 360\,000 \times P_n \times t_b / (H_u \times \eta) \qquad (1)$$

where:

B_{fl}: mass of fuel load, in kg;
H_u: lower calorific value of rice husks, in kJ/kg;
η : minimum efficiency, in %;
P_n: nominal heat output, in kW;
t_b : minimum refueling time or duration, in hour.

As mentioned, rice husks as a selected solid biofuel were initially loaded for performance tests runs using full loads in a test period of 180 minutes, respectively. The obtained steady-states were intermittent in periods of approximately 30 minutes due to the ash agglomeration in the fire chamber. The total heat output was reached at approximately 5.5 kW with relatively thermal efficiency 83%. The loss of sensible heat in the flue gas was recorded in the rates of 2440 kJ/kg. The temperature was recorded and the flue gas components were measured at the flue gas mass flow rate of 7 g/s.

3. Results and discussion

Corresponding to the non-woody solid biofuel, flue gas stream from the test of rice husks primarily consists of CO, CO_2, NO, TOC and PMs. In addition, SO_2 adherence was also detected at mass concentrations of 22÷24 mg/m^3. Mean values of the major flue gas components are summarized in Table 4 in mg/m^3 at normal conditions referred to 13% O_2 in standard reference conditions or in mg/MJ referred to energy content of fuel.

Table 4. Criteria flue gas components in the gas streams on the full load test run of rice husks

Measurement readings	Unit	Value
Oxygen (O_2)	[%]	13.9
Carbon dioxide (CO_2)	[%]	6.6
Carbon monoxide (CO)	[ml/m^3]	73
Nitric oxide (NO)	[ml/m^3]	147
Total organic carbon (TOC)	[ml/m^3]	1
Sulfur dioxide (SO_2)	[ml/m^3]	7
PM determination	[mg/m^3]	46
Mass concentration, referred to 13% O_2		
Carbon monoxide (CO)	[mg/m^3]	104
Nitric oxide (NO)	[mg/m^3]	343
Total organic carbon (TOC)	[mg/m^3]	2
Sulfur dioxide (SO_2)	[mg/m^3]	23
PM determination	[mg/m^3]	55
Specific emission, referred to energy content of fuel		
Carbon monoxide (CO)	[mg/MJ]	70
Nitric oxide (NO)	[mg/MJ]	228
Total organic carbon (TOC)	[mg/MJ]	2
Sulfur dioxide (SO_2)	[mg/MJ]	17.5
PM determination	[mg/MJ]	36.5
Volume fraction of oxygen reference		
PM determination	[%]	14.3

Profiles of six major components in the flue gas stream during the steady-state operation on the test run of rice husks are shown in Figure 3. The obtained patterns firstly confirm that there were a distinct correlations between volume fractions of CO_2 represented by the red profile and O_2 illustrated in blue fluctuating profile, which was not the limiting parameter for CO, oxidation during combustion conditions, respectively represented by the yellow profile.

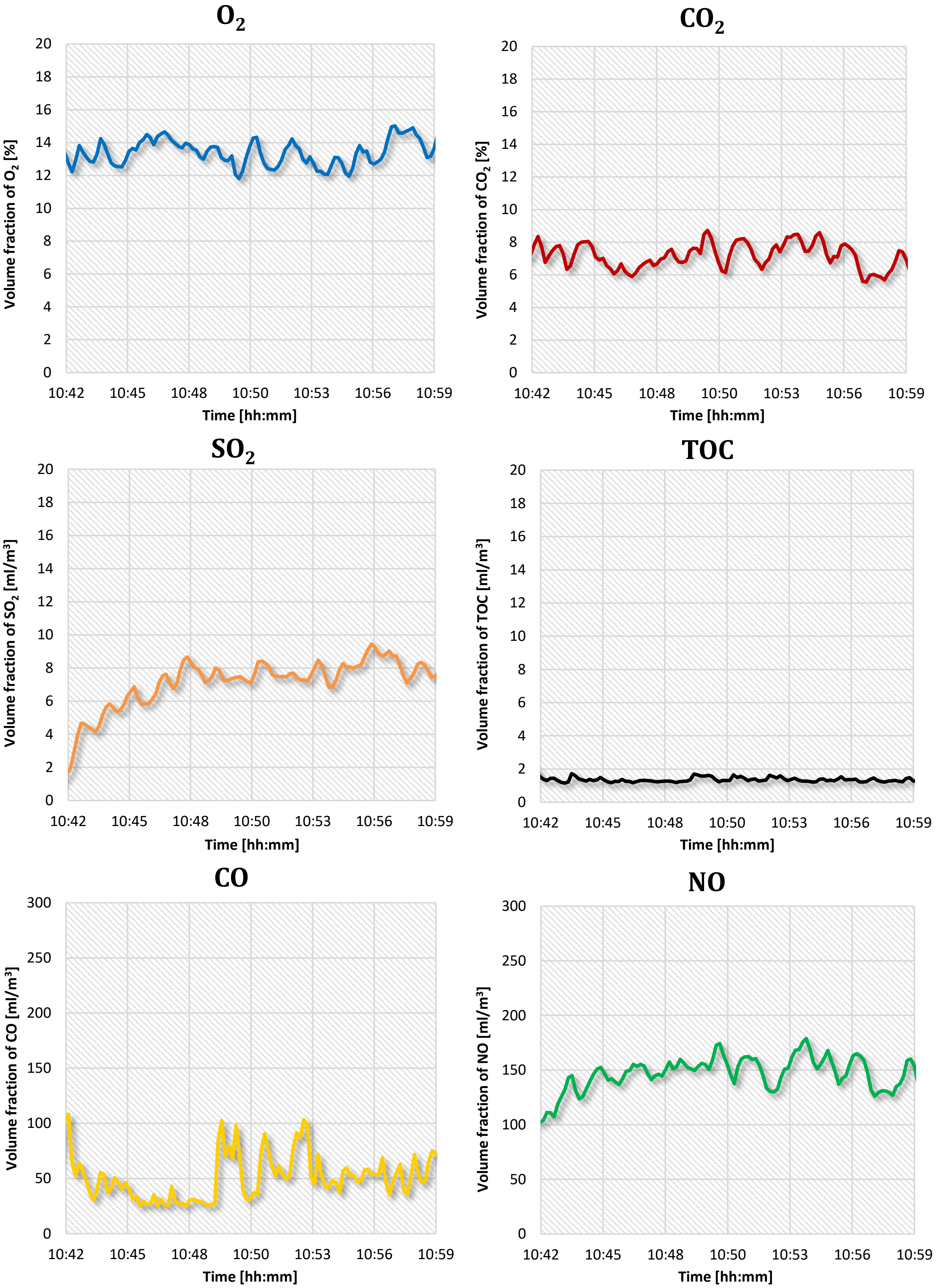

Figure 3. Gaseous component profiles in the flue gas stream during an established steady-state phase

Nitric oxide (represented by the green profile) was in the stable amount of 315÷370 mg/m^3 referred to 13% O_2 in standard reference conditions or 210÷246 mg/MJ referred to energy content of fuel. Nitrogen oxides were formed from combustion air or relatively from fuel nitrogen determined in a mass fraction of 0.47% in rice husks pellets, generally in the form of nitric oxide (NO) with a small proportion present as nitrogen dioxide (NO_2). Although emission of NO_x is comparatively low in the residential appliances compared to larger units, the proportion of primary NO_2 is considerable. No clear effect of excess air on the NO emissions was observed, probably because of a balance between the tendencies of excess air to increase the formation of NO and of the falling temperature to reduce the formation.

Content of total organic carbon showed an averaged value of 2 mg/m^3 as consistent reading values relatively shown in the black profile. Automatic pellet stoves at full load operation emitted a low quantity of detectable gas-phase organic compounds. Higher emissions substantially reported in start-up phase and partial loading operation.

Sulfur dioxide (SO_2), illustrated by orange fluctuating profile with the mean value of 23 mg/m^3, was relatively dependent on the mass fraction of sulfur content of 0.06% determined on dry basis in rice husks pellets. At the actual date of measurements, emission limit value was not specified for small-scale combustion plants with automatic loading of wood pellets for residential space heating purpose. However, those flue gas components reasonably indicate consistent emission profiles of solid biofuel typically recorded in the automatic small-scale residential space heating installations.

Particulate matter (PM) emitted contain both organic material, i.e. unburnt solid material, and inorganic material, i.e. ash particles. Regardless of varied poor combustion conditions in small-scale installations, ash particles always remain as a by-product. Table 3 shows the PM mass concentrations of 55 mg/m^3 referred to 13% O_2 in standard reference conditions or 36.5 mg/MJ referred to energy content of fuel, respectively higher than the limit value of 35 mg/MJ. The significant mass concentration of PM during poorer combustion conditions agree with earlier work since organic and elemental carbon were the key parameters for characterizing combustion aerosol particles. The enhancement of PM emission during poor combustion conditions is due to carbonaceous particles. The emission of non-woody biofuels combustion is predominantly in fine particles (aerodynamic diameter of < 2.5 μm), thus a variable extensive emission of $PM_{2.5}$ to the ambient air quality can be anticipated in a consistent trend during the combustion tests.

In empirical practice, samples were taken during steady-state conditions at stable loading operation when emission rate were presumably consistent and thus uncertainties of results were relatively small. In the automatic pellet stoves, it was assumed that major sources of uncertainties were in a similar quantity from the testing procedure and from analysis. The uncertainty of the automatic firing by solid biofuels of similar type and compositions was considered to be around 10%. Meanwhile the uncertainty for analysis was estimated in a range of 2-5% for mass determination and criteria analytical technique applied for main constituents. In addition, the variations of flue gas component profile signals during steady-state operations were assessed to relative standard deviation of around 5-7%. Above all, the obtained results with the overall uncertainty estimated of around 15-20% was remarkable for small-scale automatic fired and fuel loading applications.

3. Conclusion

The study extended the recent knowledge in the suitability of rice husks pellets as a dedicated biogenic fuel in small-scale thermochemical applications, and thus provided an opportunity for the flexible utilization of this non-woody biomass. Physicochemical property, fuel characteristic, ash composition outlined that rice husks can be qualified as solid biofuels for energetic use. Significant net calorific values relatively provide a potential heat release if appropriate bio-energy technologies applied. High ash softening temperature recorded with rice husks specimens potentially enhances an advantage to avoid the technical issues in the thermochemical conversion systems.

The experiment verified the potential of rice husks pellets in an automatic residential space heating appliance. Major six components in flue gas stream (CO_2, CO, NO, SO_2, TOC and PMs) during steady-state operations confirmed consistent emission profiles of solid biofuel in the small-scale installations. So that distinct correlations between volume fractions of gaseous components depending on the mass fraction of elemental contents presented in rice husks were assessed. The observed particulate matters emitted depended on the total carbon and inorganic fractions due to grade combustion level in automatic pellet stoves, usually lower mass concentrations of particulate matters formed comparing to manual fired small-scale applications reported in earlier research works.

The obtained results enable us to exercise various combustion tests and research on co-combustion of rice husks with conventional mineral fuel and blended woody biofuel, since those are still significant parts of future energy. If so, it is suggested that ash deposit build-up and agglomeration of rice husks are occasionally noticeable and therefore considerably essential for further investigations. Further knowledge in ashes structure, composition and forming mechanism is needed to reduce the potential risks related to technical issues and thus better maintain the steady-state operations.

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References

1. European Commission: Innovating for sustainable growth: a bioeconomy for Europe; Official Journal of European Union 8 (2), 2012, 60.
2. Luque R. et al.: Biofuels: a technological perspective; Energy Environmental Science 5, 2008, 542-564.
3. Scarlat, N. et al.: The role of biomass and bioenergy in a future bioeconomy: Policies and facts; Environmental Development 15, 2015, 3-34.
4. McKendry P.: Energy production from biomass (part 1): overview of biomass; Bioresource Technology 83 (1), 2002, 37-46.
5. Kojima T. et al.: Measurement and evaluation of gasification kinetics of sawdust char with steam in an experimental fluidized bed; Fuel Processing Technology 36 (3), 1993, 201-207.
6. Chum H. et al.: In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation; 2012, 209-332.
7. McKendry P.: Energy production from biomass (part 1): overview of biomass; Bioresource Technology 83 (1), 2002, 37-46.
8. Abe H. et al.: Potential for rural electrification based on biomass gasification in Cambodia; Biomass and Bioenergy 31(9), 2007, 656-664.
9. World Energy Council (WEC): World Energy Resources 2016 – Bioenergy; 2016.
10. Natarajan E. et al.: Overview of combustion and gasification of rice husk in fluidized bed reactors; Biomass and Bioenergy 14(5), 1998, 533-546.
11. Pham T.M.T. et al.: Greenhouse gas emission mitigation potential of rice husks for An Giang province, Vietnam; Biomass and Bioenergy 35(8), 2011, 3656-3666.
12. Bhattacharya S. C. et al.: Some aspects of fluidized bed combustion of paddy husk; Applied Energy 16 (4), 1984, 307-316.
13. Fang M. X. et al.: Experimental study on rice husk combustion in a circulating fluidized bed; Fuel Process Technology 85, 2004, 1273-1282.
14. Bhattacharyya S. C.: Viability of off-grid electricity supply using rice husk: A case study from South Asia; Biomass and Bioenergy 68, 2014, 44-54.
15. Maciejewska A. et al.: Co-firing of biomass with coal: constraints and role of biomass pre-treatment; Report of the Institute for Energy - JRC, European Commission, 2006.
16. Jaap Koppejan S. et al.: The Handbook of Biomass Combustion and Co-firing; Routledge, 2012.
17. Li J. et al.: Co-firing based on biomass torrefaction in a pulverized coal boiler with aim of 100% fuel switching; Apply Energy 99, 2012, 344-354.
18. McKendry P: Energy production from biomass (part 1): overview of biomass; Bioresource Technology 83 (1), 2002, 37-46.
19. Peterson, D. et al.: Market assessment of biomass gasification and combustion technology for small- and medium-scale applications; Technical Report NREL/TP-7A2-46190, 2009.
20. Kistler M. et al.: Odor, gaseous and PM10 emissions from small scale combustion of wood types indigenous to Central Europe; Atmospheric Environment 51, 2012, 86-93.
21. McDonald, J. et al.: Fine particle and gaseous emission rates from residential wood combustion; Environmental Science and Technology 34, 2000, 2080-2091.
22. Seljeskog M. et al.: Variables affecting emission measurements from domestic wood combustion; Energy Procedia 105, 2017, 596-603.
23. Hedberg E. et al.: Chemical and physical characterization of emissions from birch wood combustion in a wood stove; Atmospheric Environment 36, 2002, 4823-4837.
24. Johansson L.S. et al.: Particle emissions from biomass combustion in small combustors; Biomass & Bioenergy 25, 2003, 435-446.
25. Johansson L.S. et al.: Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets; Atmospheric Environment 38, 2004, 4183-4195.
26. Sippula O. et al.: Effect of wood fuel on the emissions from a top-feed pellet stove; Energy & Fuels 21, 2007, 1151-1160.
27. Boman C. et al.: Stove performance and emission characteristics in residential wood log and pellet combustion, Part 1: Pellet stoves; Energy & Fuels 25, 2011, 307-314.
28. Pettersson E. et al.: Stove performance and emission characteristics in residential wood log and pellet combustion, Part 2: Wood Stove. Energy & Fuels 25, 2011, 315-323.
29. Gonçalves C. et al.: Characterisation of PM10 emissions from woodstove combustion of common woods grown in Portugal; Atmospheric Environment 44, 2010, 4474-4480.
30. Vicente E.D. et al.: An overview of particulate emissions from residential biomass combustion; Atmospheric Research 199, 2018, 159-185.
31. Ozgen S. et al.: Experimental evaluation of particle number emissions from wood combustion in a closed fireplace; Biomass and bioenergy 50, 2013, 65-74.
32. Schmidl C. et al.: Chemical characterisation of fine particle emissions from wood stove combustion of common woods growing in mid-European Alpine regions; Atmospheric Environment 42, 2008, 126-141.
33. Schmidl C. et al.: Particulate and gaseous emissions from manually and automatically fired small scale

combustion systems; Atmospheric Environment 45, 2011, 7443-7454.
34. Bari M.A. et al.: Wood smoke as a source of particle-phase organic compounds in residential areas; Atmospheric Environment 43, 2009, 4722-4732.
35. Fine P.M. et al.: Chemical characterization of fine particle emissions from the wood stove combustion of the prevalent United States tree species; Environmental Engineering Science 21, 2004, 705-721
36. Roy M. M. et al.: An experimental study of combustion and emission of biomass pellets in a prototype pellet furnace; Applied Energy 108, 2013, 298-307.
37. Sheesley R.J. et al.: Characterization of organic aerosols emitted from the combustion of biomass indigenous to South Asia; Journal of Geophysical Research 108 (D9), 2003, 4285.
38. CEN/TS 14774-2. Solid biofuels - Method for the determination of moisture content. Oven dry method. Total moisture. Simplified method. Brussels: CEN, 2004.
39. CEN/TS 14775. Solid biofuels - Method for the determination of ash content. Brussels: CEN, 2004.
40. CEN/TS 14918. Solid biofuels - Determination of calorific value. Brussels: CEN, 2006.
41. CEN/TS 15104. Solid biofuels - Determination of total content of carbon, hydrogen and nitrogen. Instrument method. Brussels: CEN, 2011.
42. CEN/TS 15148. Solid biofuels – Method for the determination of the content of volatile matter. Brussels: CEN, 2005.
43. CEN/TS 15289. Solid biofuels - Method for the determination of the content of sulphur and chlorine. Brussels: CEN, 2006.
44. CEN/TS 15290. Solid biofuels - Determination of major elements. Brussels: CEN, 2006.
45. CEN/TS 15297. Solid biofuels - Determination of minor elements. Brussels: CEN, 2006.DIN 51719. Testing of solid fuels - Solid mineral fuels - Determination of ash content. German Institute for Standardization, 1997.
46. EN 14785. Residential space heating appliances fired by wood pellets. Requirements and test methods. Brussels: CEN, 2006.
47. EN 14961-1. Solid biofuels - Fuel specifications and classes - Part 1: General requirements. Brussels: CEN, 2010.