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INNOVATIVE METHOD OF BIOMASS COMBUSTION IN THE BINARY FLUIDISED BED

Abstract: In this study, a binary fluidised bed made out of quartz sand and cenospheres for the biomass combustion process was created. Materials were fluidised with air to achieve a vertical density profile (from 0.5 g/cm³ to 1.1 g/cm³) resulting from grains segregation. The density profile was selected to ensure optimal control over the location of the combusted fuel particle. This involved positioning the process as close to the bottom sieve as possible. Fluidised bed combustion was carried out at temperatures of 600 °C, 700 °C, 820 °C and 870 °C using straw, willow and sawmill pellets as fuels. Qualitative and quantitative analysis of flue gases was performed using an FTIR spectrometer. Over 90 % carbon conversion from the biomass to carbon dioxide was achieved at 700 °C. At 820 °C and 870 °C, 100 % of biomass carbon left the reactor as CO₂. The composition of organic compounds in the process products remained low, reaching a maximum of 3.0 % wt. at 600 °C. To gain further insights into the processes occurring in the immediate vicinity of biomass samples, a complementary TGA/FTIR analysis was conducted. This aimed to clarify the impact of the biomass particle decomposition stage in the fluidised bed combustion process. The proposed mechanism for biomass combustion in the binary fluidised bed contains the particle decomposition stage and the subsequent stage resulting from the coalescence of bubbles containing flammable components and bubbles containing oxidiser.

Keywords: biomass, combustion, fluidised bed, fuel density

Introduction

As non-renewable fossil fuel resources are depleting and environmental degradation is advancing, efforts are increasingly focused on decarbonising energy production processes. Considering environmental concerns, the objective is to obtain energy from alternative sources [1, 2]. Biomass, an organic material of plant or animal origin, is gaining increasing attention as a source of renewable energy [3].

In the thermal processing of fuels, ensuring optimal conditions for the process organisation poses a challenge to enable its clean execution. Pieratti et al. [4] investigated the emission characteristics of forest residual combustion in a wood stove at temperatures ranging from 900 °C to 1000 °C. Results indicated that despite the high process temperature, the CO₂ content in the products did not exceed 15 % vol., with an average CO content of 1000 ppm, and harmful NO_x of 200 ppm. Paris et al. [5] examined the combustion of wood pellets in a grate furnace. During the experiments, the temperature in

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the furnace reached 467 °C and in the afterburner chamber 793 °C. The flue gases were analysed using GC/MS system. The presence of several toxic organic compounds was detected, including chloromethane (4.25 µg/Nm³), dichloromethane (0.95 µg/Nm³), as well as aromatic compounds such as xylene and toluene.

Berkowicz et al. [6] investigated the combustion of wood pellets in a fluidised bed (FB) made out of lightweight expanded clay aggregate. FTIR analysis of flue gas revealed that at 700 °C the conversion of biomass to CO₂ was approximately 80 % wt. and above 800 °C a complete conversion to carbon dioxide was achieved. Fluidisation is a type of heterogeneous flow, where the fluidising agent passes through solid particles [7, 8]. In fluidised bed combustion, the fluidising agent is air, which mixes bed and fuel particles, ensuring their excellent access to oxygen and an expanded interfacial contact area [9, 10].

The commonly used material for creating fluidised beds in the combustion processes is quartz sand. Sand is low-cost and is characterised by high mechanical, chemical, and thermal resistance [11]. Vodicka et al. [12] investigated the combustion of woody biomass in a bubbling fluidised bed (BFB) made out of sand. The temperature of the fluidised bed was 800 °C and the chemical composition of products showed that the volumetric share of CO₂ in the flue gases was 18 %. Chirone et al. [13] combusted wood and straw pellets in the fluidised bed made out of sand in temperatures ranging from 600 °C to 700 °C. Due to the relatively low process temperature, they achieved a maximum fuel conversion efficiency to CO₂ of 20 % vol. In order to increase biomass conversion efficiency, co-combustion processes are examined [14-16]. An additional method to enhance the conversion yield of biomass involves extending the fuel residence time in the FB. In the process of solid fuel combustion, the density of the FB affects the reagents' residency time in the reactor. The density of a fluidised bed made out of sand is approximately 1200 kg/m³, contrasting with the biomass pellet density that does not exceed 800 kg/m³ [17]. Biomass pellets are displaced from the fluidised bed made out of sand in accordance with Archimedes' law. Thus, the combustion process occurs at the FB surface and in the freeboard. When fuel is processed in the over-bed zone, all advantages of the fluidisation, such as expanded interfacial contact area, homogeneous temperature and effective access to the oxidiser [18] are not fully utilised.

In this study, the combustion process of biomass in the form of pellets was investigated in an innovative, binary fluidised bed. The innovation of the method was based on changing the organisation of biomass combustion processes in the fluidised bed reactor. A key aspect of the change was creation of the binary fluidised bed with a variable vertical density profile. It allowed for the control the position of combusted biomass in the fluidised bed and ensured an adequate residence time for gaseous products of biomass decomposition in the fluidised bed. The optimal residence time of gaseous products and turbulent mixing with the oxidiser is crucial for increasing process safety. In such well-organised processes, decomposition of gaseous products takes place inside the fluidised bed. The binary fluidised bed was characterised by a carefully designed vertical density profile. It allowed biomass to freely immerse in the FB volume and combust in a predetermined area. To investigate the composition of gas bubbles generated during biomass decomposition, a supplementary TGA/FTIR analysis was conducted.

Experimental part

Materials

Cenospheres and quartz sand were used to create fluidised bed with a variable vertical density profile [18]. The sand was sieved into a fraction of 0.12 mm - 0.20 mm. Cenospheres were obtained from fly ash resulting from coal combustion at the Polaniec Power Plant (Poland). The cenospheres were sieved into a fraction of 0.14 mm - 0.16 mm. The densities of the sand and the cenospheres were 2.7 g/cm³ and 0.9 g/cm³, respectively

Pellets made out of straw, willow and sawmill were chosen for the combustion tests. Figure 1 shows selected biomass in the raw (I), crushed (II) and pellet form (III). The raw material for the research was obtained as sawdust which was ground in a hammer mill and pelletised in a mechanical pelletiser. The average pellet diameter was 5 mm.



Fig. 1. Biomass selected for combustion tests in the binary fluidised bed: I) raw, II) crushed, III) pellet; a) sawmill, b) straw, c) willow

Methods

Fluidised bed reactor with an FTIR analyser (model DX-4000, GASMET Technologies Oy), schematically shown in Figure 2, was used in the combustion tests. Additionally, a thermogravimetric analyser (TGA 8000 by PerkinElmer) with an FTIR analyser (AtmosFIR by Protea) was utilised. Hydrodynamic measurements were conducted in the fluidised bed reactor, with a particular focus on the FB density measurements at various heights from the bottom sieve. The composition of gas leaving the biomass particle decomposition zone was determined using the combined TGA and FTIR apparatus.

Fluidised bed hydrodynamics

The studies were conducted for fluidised beds made out of sand (600 g), cenospheres (260 g) and for a binary sand-cenospheres fluidised bed (600 g, 260 g). Fluidised bed reactor with an outer diameter of 102 mm and a height of 50 cm was used for the tests [6, 18]. Air was used as the fluidising agent. After placing the materials in the reactor, fluidisation curves were determined by gradually increasing the gas flow and after achieving stable fluidisation decreasing it to 0. Changes in pressure drop beneath the bottom sieve were recorded as a function of superficial gas velocity.

Fluidised bed densities

The density of the fluidised beds was determined at its specific height using Pascal's law. Pressure drop measurements were conducted using differential pressure sensors (Honeywell, ABP series) with a probe immersed in the FB. Density profiles were examined at a gas velocity equal to 160 % of the minimum fluidisation velocity (in the case of the binary fluidised bed, 160 % was referenced to the U_{mf} of the lower layer of the FB, i.e. quartz sand).

Biomass fluidised bed combustion with FTIR analysis

Biomass combustion was tested in the binary fluidised bed. Stable fluidisation was achieved by supplying 60 % excess of fluidising gas (air) above the minimum fluidisation velocity of the sand. The FB was heated to temperatures of 600 °C, 700 °C, 820 °C, and 870 °C. Biomass was introduced into the binary fluidised bed at a controlled temperature of ± 10 °C. Combustion gases were directed through a pipe heated to 180 °C to the FTIR spectrometer. Simultaneously, infrared radiation was passed through the cuvette and Michelson interferometer, allowing for the acquisition of interferograms. These interferograms were transformed into absorption spectra of the gas mixture using Fourier transformation. The spectra of the evolving combustion product mixture were recorded every 6 seconds.

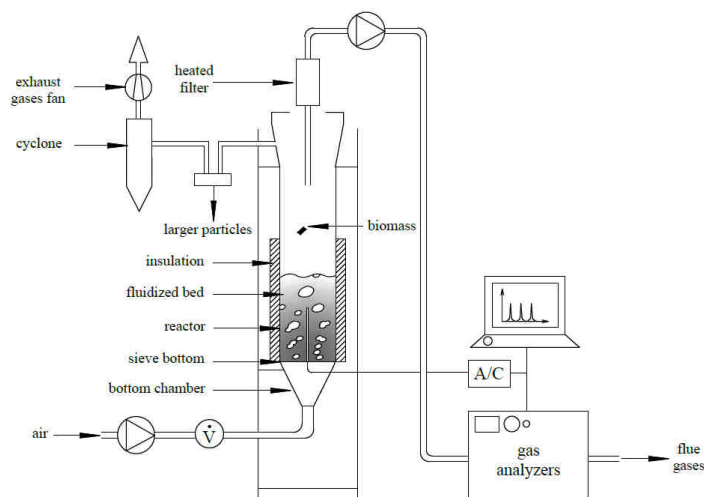


Fig. 2. Equipped fluidised bed reactor for biomass combustion tests

Thermogravimetry with FTIR analysis

Biomass decomposition in the thermobalance was carried out in a carrier gas flow containing 2 % vol. O₂ in a stream of N₂ (4 mL/min O₂, 196 mL/min N₂). The thermobalance furnace was heated from 50 °C to 900 °C with a temperature ramp rate of 40 °C/min. The gas composition leaving the thermobalance was monitored using an FTIR spectrometer.

Results and discussions

Fluidised bed hydrodynamics

In the case of fluidised beds made out of one material, fluidisation curves represent relationships of the pressure drop as a function of the superficial fluid velocity known from the literature [19, 20]. The minimum fluidisation velocities were 2.40 cm/s for quartz sand and 0.80 cm/s for cenospheres, respectively. The fluidisation curve for the binary fluidised bed (Fig. 3a) showed two local maxima: at a gas velocity of 0.80 cm/s, associated with the initiation of fluidisation of cenospheres in the binary FB and at 2.40 cm/s, indicating the start of sand fluidisation and, consequently, the introduction of the entire binary fluidised bed into a fluidised state.

Fluidised bed density

Measurements of the fluidised bed density were conducted for the same materials for which minimum fluidisation velocities were determined. The research was carried out ensuring a 60 % excess compared to the U_{mf} (minimum fluidisation velocity) value. After achieving stable fluidisation, a measurement probe was introduced into the FB for pressure drop examination and values were recorded at various heights for 10 minutes at a frequency of 10 Hz. Subsequently, the determined pressure drop values (dp) were converted to FB density using equation (1).

$$\rho(h) = \frac{g^{-1} \cdot dp(h)}{dh} \quad (1)$$

where: $\rho(h)$ - fluidised bed density at height h [kg/m³], $dp(h)$ - differential pressure changes at height h [Pa], g - acceleration of gravity [m/s²].

Density profiles in three examined FBs are presented in Figure 3b. Fluidised beds made out of one material were characterised by a constant density value. The density of the FB created from cenospheres averaged (430 ± 4) kg/m³, while the density of the fluidised bed made out of quartz sand averaged (1201 ± 5) kg/m³.

The binary fluidised bed showed variable density, ranging from (1012 ± 8) kg/m³ (at the bottom sieve) to (557 ± 12) kg/m³ (at the surface). On the density profile, three regions were identified. Region I was located closest to the bottom sieve, extending up to 4 cm above the gas distributor. Density remained constant at approximately 1010 kg/m³, which is a lower value than the density of the FB made out of quartz sand. This indicates that the lower layer of the binary FB contained mainly sand grains with a small addition of cenospheres. In region II (beyond region I) density of the FB decreased as an intense mixing of sand and cenospheres grains occurred. Region II extended from 4 cm to 10 cm above the gas distributor and the density dropped from 1010 kg/m³ to approximately 550 kg/m³. Region III of the binary fluidised bed was identified above region II and was characterised by a constant density value of 550 kg/m³. It indicates that cenospheres

dominated this region with a minor contribution of sand grains. Additionally, a rarefied zone with a density of around 150 kg/m^3 was observed above region III.

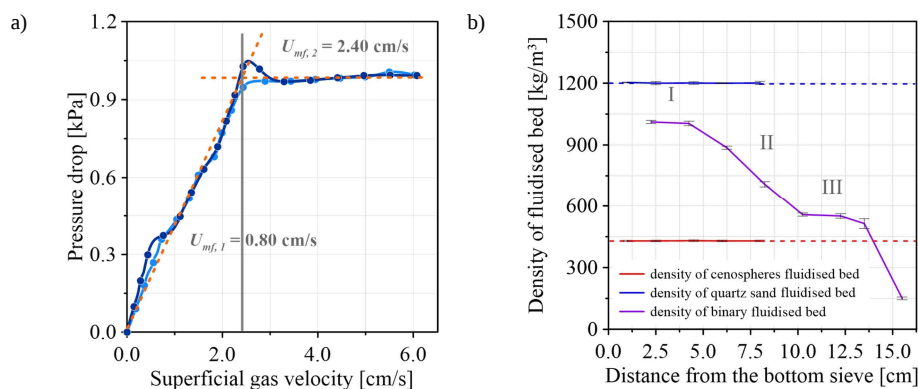


Fig. 3. Fluidised beds analysis results: a) fluidisation curve of binary fluidised bed, b) vertical density profile of fluidised bed made out of sand, cenospheres and sand-cenospheres

The density profile of the binary FB provided suitable conditions for positioning the biomass particle degradation process (bulk density of $(745 \pm 12) \text{ kg/m}^3$) as close to the sieve bottom as possible. Additionally, it created the separation of the sieve bottom from fuel particles to prevent potential blockage of the air inlet openings. Regions II and III created a space that ensured the necessary contact time for the combustion of volatile gas products resulting from biomass degradation to maintain it above 5 % O_2 , ensuring the air excess ratio did not fall below the minimum value of 1.3.

Biomass combustion process

The periodic nature of biomass fluidised bed combustion was observed. Figure 4 illustrates the recorded changes in concentrations of individual gas products generated during the combustion of willow pellets. The oxygen concentration was controlled to maintain it above 5 % O_2 , ensuring the air excess ratio did not fall below the minimum value of 1.3. The integration of peaks resulted in yielded emission values for chemical components (CO_2 , CO , CH_4 , C_2H_4 , C_2H_2 , C_2H_6 , CH_3OH , HCHO , CH_3CHO , CH_2CHCHO) based on biomass type, fluidised bed temperature and sample mass. The carbon mass contained in each gas product was calculated from emission values. Subsequently, carbon content was related to the carbon mass in the samples and the conversion degrees to specific products were obtained. The results are presented in Figure 5. Figure 5a-c illustrate the conversion of carbon from biomass to CO_2 , CO and organic compounds, respectively. Figure 5d shows the contributions of individual compound groups in the organic fraction of flue gases at the lowest temperature applied in the research.

It is necessary to take into consideration the relatively low and potentially variable calorific values of alternative fuels. This may lead to periodic drops of the temperature in the fluidised bed reactor. The temperatures were selected to determine the minimal temperature that allows for high combustion efficiency, leading to the conversion of feedstock into stable products, namely CO_2 and H_2O . The results indicate that the biomass

combustion process in the binary fluidised bed can be conducted with high efficiency starting from 820 °C, achieving a carbon conversion degree to CO₂ of 100 %. At 700 °C, the carbon conversion to CO₂ averaged 96 % (straw: 97.2 %, willow: 96.3 %, sawmill: 94.7 %) and at 600 °C averaged 90 % (straw: 91.6 %, willow: 90.7 %, sawmill: 89.6 %). The concentration of organic products reached a maximum of 3.0 % wt. at 600 °C and approximately 0.5 % wt. at 700 °C. The identified components included short-chain saturated and unsaturated hydrocarbons, acrolein, alcohols and simple aldehydes. Due to the presence of toxic compounds, including acrolein, such a process variant would require an afterburner chamber.

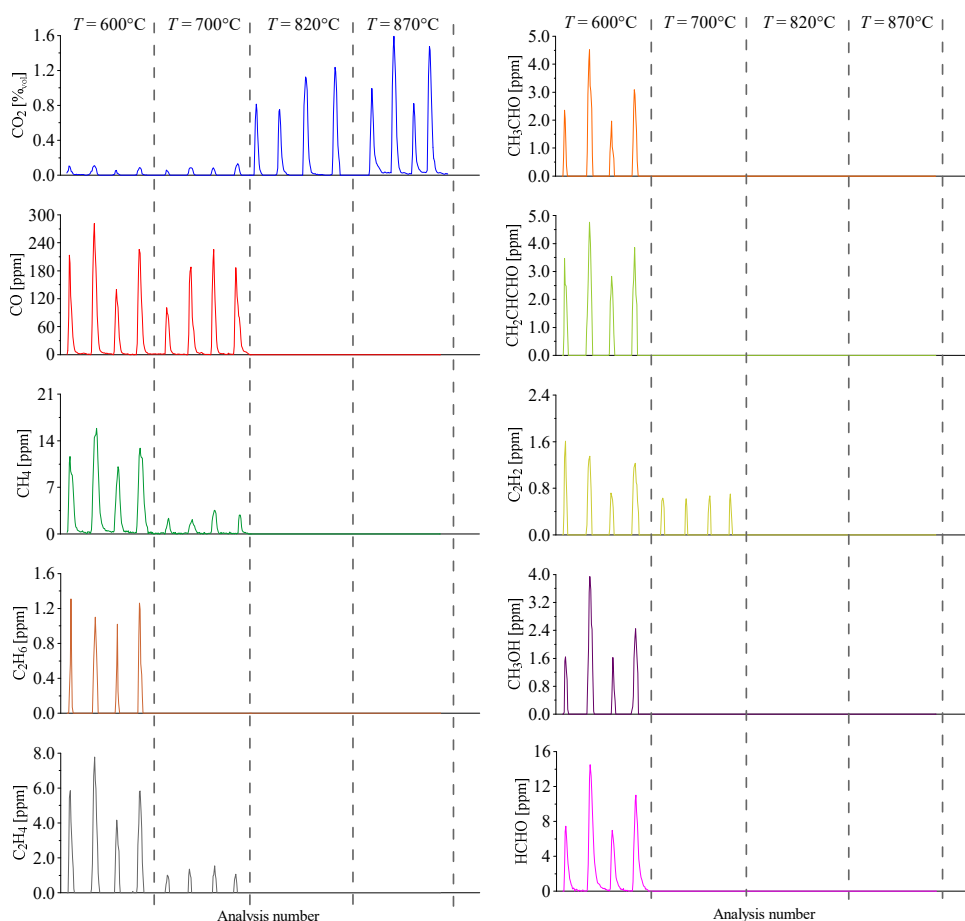


Fig. 4. Emission of gaseous products during willow pellets combustion in the binary fluidised bed

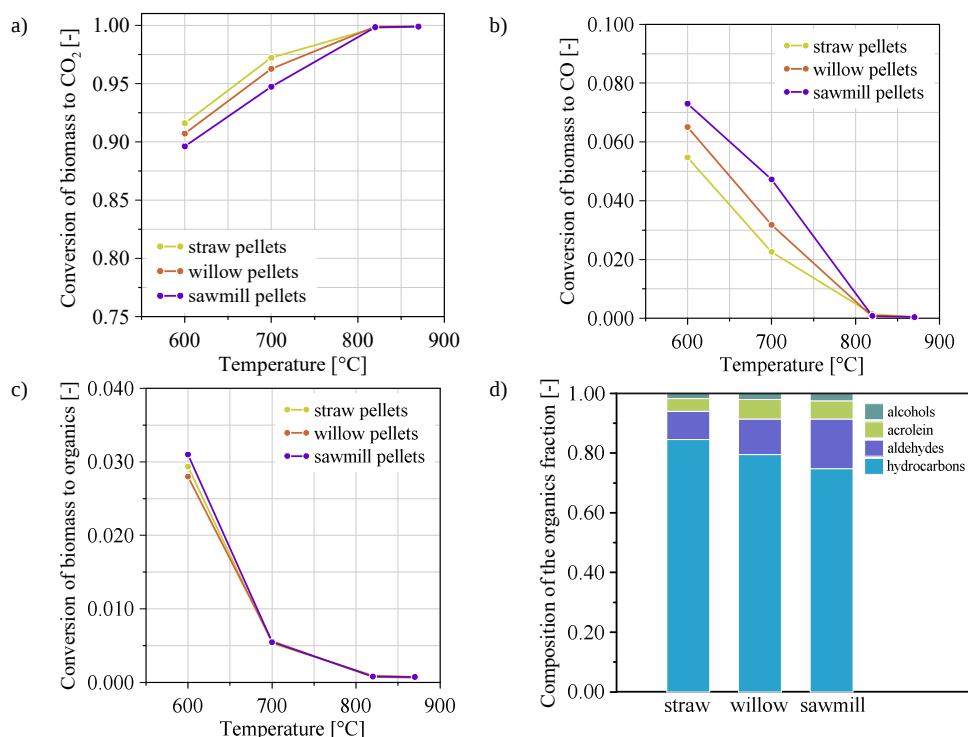


Fig. 5. Conversion of carbon during the combustion in the binary fluidised bed from biomass to: a) CO₂, b) CO, c) organics, d) selected organic groups at 600 °C only

In the binary fluidised bed presented in this publication, biomass was immersed to a depth of approximately 8 cm above the bottom sieve, where the density corresponded to its own density (as per Archimedes' law). Inside the hot fluidised bed, biomass decomposition occurred, leading to the release of gaseous products. This process effectively isolated the fuel particles from the oxygen-rich environment. In order to determine the gas bubble composition arising from the biomass under conditions of low oxygen content, tests were conducted using a combined technique consisting of thermogravimetric and FTIR analysis. The generated gases were analysed similarly to the products of the fluidised bed process. The composition of gas mixtures directly released from biomass is presented in Figure 6. Gas mixture compositions are illustrated in pie charts, showing mass fractions of CO₂, CO and organic compounds (Fig. 6a). Organic compounds are separately detailed in a bar chart (Fig. 6b). The analysis results indicate that during biomass decomposition, samples generated a gas mixture consisting of 31.3 % wt. - 36.7 % wt. CO₂, 13.8 % wt. - 15.7 % wt. CO and 47.6 % wt. - 55.1 % wt. organic compounds, depending on the biomass type. The organic decomposition products included methane, ethylene, acetylene, acrolein, formic acid, acetic acid, acetaldehyde, formaldehyde, benzaldehyde, furfural, anisole, pyrrolidine, triethyl orthoformate and toluene.

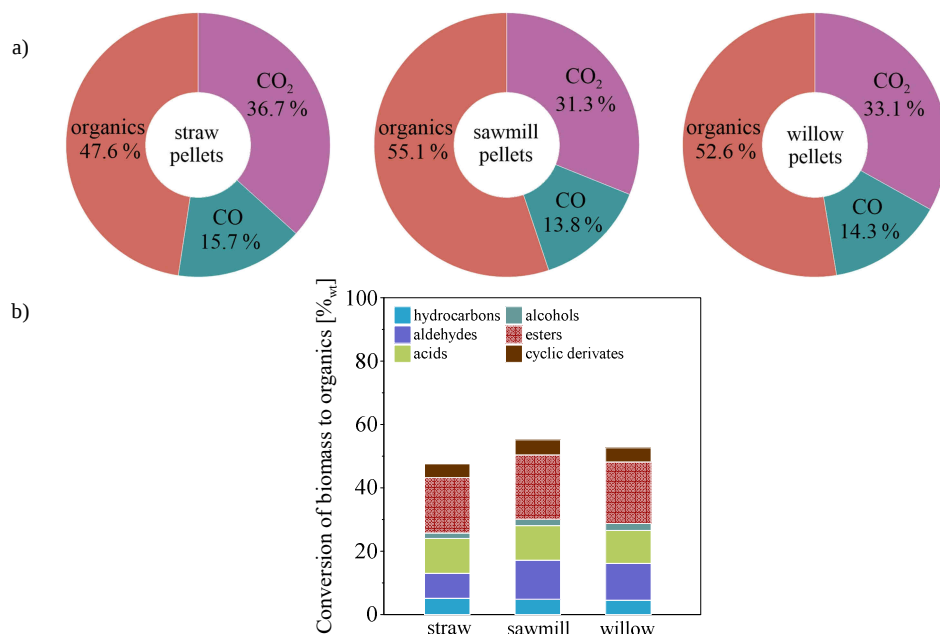


Fig. 6. Composition of gases formed from biomass degradation in conditions of low oxygen concentration: a) main groups, b) organics compounds only

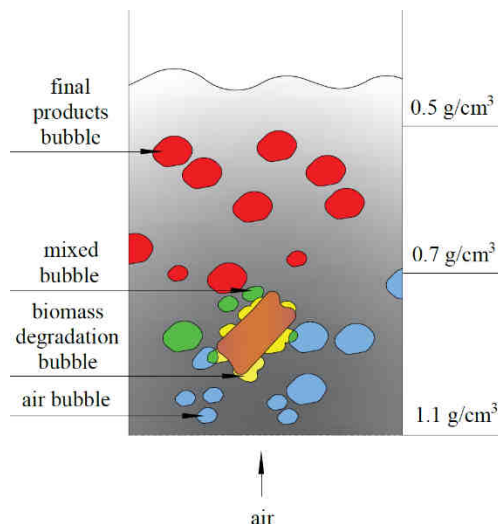


Fig. 7. Scheme of biomass combustion in the binary fluidised bed based on publication [18]

Chemical compositions of flue gases leaving the FB reactor and gases generated during biomass decomposition reveal a significant difference. Considering the density distribution of the binary fluidised bed and the chemical composition of the combustion products,

a general scheme of biomass combustion is proposed in Figure 7. The proper mixing of biomass decomposition products with air in the FB resulted in complete combustion. The entire process is determined by the position of fuel particles. Decomposition of the biomass generates gas products that form fuel-rich bubbles in the bubbling fluidised bed (marked in yellow). Bubbles arising from biomass particles combine with air bubbles, which leads to the creation of flammable gas mixtures (marked in green). These bubbles react and produce bubbles containing final products (marked in red). The composition of these final products was determined through FTIR analysis of flue gases from the fluidised bed combustion process. The composition of gas mixtures leaving the fluidised bed reactor (red bubble) and those formed during biomass decomposition (yellow bubble) indicates that ensuring adequate access to the oxidising agent is crucial in the biomass combustion process. This is to prevent the emission of toxic compounds. Furthermore, achieving the appropriate contact time of gaseous decomposition products with the oxidising agent is necessary. The binary fluidised bed allows for the fulfilment of both these criteria.

Conclusion

It is possible to organise the fluidised bed biomass combustion process to achieve 100 % conversion of organic carbon to CO₂ starting from a temperature of 820 °C. Adjusting the density of the fluidised bed to biomass density is possible by creating the binary fluidised bed with quartz sand and cenospheres grains. The binary FB can show a variable vertical density profile (0.5 g/cm³ to 1.1 g/cm³), allowing for the proper placement of biomass in the FB and ensuring the appropriate contact time of the fuel with the oxidising agent. The study demonstrated that bubbles arising from decomposing biomass constitute complex gas mixtures containing a significant amount of flammable components. Complete combustion of these mixtures is possible from the temperature of 820 °C, with the biomass sample residency in the FB of at least 16 seconds.

Achieving 100 % conversion of organic carbon to CO₂ at temperatures as low as 820 °C paves the way for more efficient and effective biomass combustion processes. The ability to control the fluidised bed density through the binary mixture of quartz sand and cenospheres allows for precise optimisation of fuel distribution and contact time, which are crucial for maximising combustion efficiency. The implications of this research extend to practical applications in bioenergy systems, where this approach can be integrated into biomass power plants to improve energy efficiency, reduce unburned carbon emissions, and support carbon management strategies aimed at mitigating climate change. Furthermore, the scalability of this technique offers potential for advancing renewable energy technologies, contributing to a more sustainable and low-carbon energy future.

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