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Front velocity in the combustion of blends of poultry litter with straw

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ABSTRACT

The paper presents experimental studies on the burning characteristics of poultry litter and its blends with straw in the context of their potential usage in small-scale heat and power generation. For comparison purposes classic fuel such as wooden pellets was also investigated. The samples were analyzed in terms of water content, chemical composition and devolatilization, heating values, ash composition and ignition temperatures. An experimental analysis was performed of the combustion process of various sample beds in a small laboratory reactor that covered the temperature measurements and visual observations. This resulted in estimation of the speeds of ignition front propagation in the studied fixed beds, which is of general importance in the design of grate-fired furnaces. The combustion dynamics was discussed in terms of the physical properties of the bed, such as bulk density and porosity. The authors concluded that the main issue regarding the efficiency of poultry litter combustion was closely connected to a low bulk density of the fuel bed, which led to faster combustion front propagation but lower temperatures compared to a more dense fuel bed such as a wood pellet bed.

1. Introduction

An increasing demand for poultry meat and eggs has made the poultry industry one of the most intensively growing industries worldwide. Poland, with the production exceeding 2.5 million tons of poultry meat in 2014 [1], has become a leader in production [2] and one of the largest exporters in Europe. The intensively developing production however leads to increasing generation of waste, basically litter. Such waste is a mixture of manure, bedding material, feathers and waste fodder. Since it contains nutrients, namely, nitrogen, potassium and phosphorus, it has traditionally been treated as natural fertilizer. However, if improperly applied, it can cause air pollution and ground water contamination, the spread of pathogens [3, 4] and emission of greenhouse gases. Under the provisions of EU legislation regarding spreading of nitrates on land [5], the method of disposing of poultry litter by direct land application is no longer an advisable one. Direct combustion of such waste is an alternative solution for reasonable management of them, in addition to composting or anaerobic digestion [6]. In contrast to other treatment methods mentioned, this one makes it possible to produce heat and power in combined systems. It therefore provides on-site waste utilization and at the same time, the reduction of poultry farming costs. The only process residue is ash, which is odour-free, sterile and due to the mostly remaining concentration of primary nutrients, may further serve as an easy to use organic fertilizer. The potential of poultry litter as an energy source has been discussed in numerous works over the previous decades. This includes the analyses of its possible utilization for energy purposes with use of the valuable byproduct as fertilizer [7], the basic fuel analysis [8, 9] and its devolatilization behavior [10], as well as considerations in the context of various high-temperature thermal processing [11], combustion [12-14], co-combustion with natural gas [15], coal [16] and olive pomace [14] or gasification [17, 18], with special emphasis on the emissions.

An increasing interest in utilizing poultry-derived wastes for energy purposes in Europe has been directed rather to their combustion for electricity generation in large-scale central units [2]. This refers mainly to installations in UK, which started being implemented in 1992, and those built in the Netherlands [19, 20]. As stated in [19], in the UK there is also an interest in on-farm burning that would reduce the cost of heating energy. It would also remove the problem of waste transportation to the central unit. On-site litter combustion, basically due to the economic benefits, has also become attractive to Polish farmers. Since an average Polish poultry farm generates about 200–300 tons of litter annually, small-scale units are of concern. Such units, in contrast to large-scale ones that mostly employ the fluidised bed combustion technology, are in general based on grate-fired boilers. Their design is bound to face a number of other technical issues, particularly when being considered for the utilization of waste fuel. To meet environmental restrictions and to provide an efficient technical solution for solid fuel combustion, the facility designing and optimizing requires knowledge about the characteristics of combustion process. This includes in the first place the velocity of the ignition front, which plays a

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vital role in the combustion process in both fixed and moving beds. In small-scale boilers, the possible design error margin due to smaller unit dimensions is low compared to large units, thus the precise determination of the time and the rate of fuel burning is of crucial importance. Meanwhile, despite the growing interest in the energy potential of poultry litter wastes, there is a lack of research devoted to the aspect of burning front propagation in beds of such waste materials. This issue has rather been analyzed numerically and/or experimentally with respect to the combustion of biomass in a fixed bed [21-26], providing data on the effect of fuel type, particle size and air supply. The therein reported ignition front propagation speeds were determined based on temperature measurements within the bed.

This paper solely aims to recognize the burning behavior of poultry litter in terms of its use as an alternative fuel in small-scale heat and power production systems. Two types of poultry litter, derived from layer and broiler farms, as well as mixtures of the first one with straw were studied experimentally to show the possible difference in fuel characterisation and its potential use for heat generation. Considering the fact that the dynamics of reaction front propagation is one of the issues crucial in the process modelling, particularly in the context of the grate design, the main emphasis is on the estimation of burning front propagation speeds. With regard to such waste fuels these are virtually non-studied in the literature. The investigation performed may provide information on the limitations on the required fuel supply speed. We propose different methods for the determination of the reaction front velocities. Apart from using the usually applied procedure based on temperature measurement, an approach utilizing process visualization data was developed. The observations of process dynamics allowed a more detailed insight into the process characteristics, leading to better understanding of the driving mechanisms.

2. Experimental details

Poultry manure is a highly heterogeneous kind of biomass. Its composition and moisture content varies significantly based on the source of the sample, depending on whether it comes from a broiler or laying hen farm. In this study, the samples of poultry waste (poultry litter) coming from two Polish farms rearing the laying hens and broilers, respectively, were examined. These were basically the mixtures of chicken excrement (manure) and straw. The samples were thoroughly analyzed in terms of composition, dry matter and ash content, as well as thermochemical properties such as heating value, ignition and combustion temperature. Furthermore, a few samples of egg farm waste mixed in various proportions with straw alongside with poultry litter from a broiler farm were combusted in a custom made reactor to determine the dynamics of the process compared to a classic fuel such as wooden pellets. Based on the study some main conclusions were achieved, regarding the possibility of using this kind of waste biomass as a fuel.

2.1. Fuel characterisation

Drying of wet samples performed using a moisture analyzer showed the level of water content to be similar for both samples. It was, on average, at 63.9 (wt.%) for poultry litter from laying hens, which is lower than those found by Quiroga et al. (74.5%) [8] and Nicholson et al. (65%) [27], and at 60.6 (wt.%) for poultry litter from broilers. The chemical analysis of both samples in comparison with literature data, as well as the composition of the studied wood pellets, is presented in Table 1. Carbon, hydrogen and nitrogen contents were determined using a Flash EA1112 CHNS(O) Analyzer (Thermo Scientific, USA), whereas gross calorific value was measured with the use of a KL–12Mn2 calorimeter (PRECYZJA–BIT, Poland). As observed, the composition differs significantly depending on the source of the sample. As far as poultry litter is concerned this is a matter of bedding material used and the type of fodder. Basically, the level of C content is significantly higher for poultry litter sourced from a broiler farm than for the wastes derived from laying hens. The exception is the data of Toptas et al. [28], which show a value (35.7%) that is within the range of C content found by other authors for laying hen litter (30.8–38.4%). The C content obtained for the investigated wood pellets (43%) is lower than that reported by Paulauskas et al. (49.2%) [29] and is similar to those found in the literature for broiler litter that vary between 35.7 and 45.2%. The comparison of the data reported in the literature and the studied samples shows that while either for laying hen or broiler waste the H content may be assumed as similar, the amount of C varies for each by a few percent. Large differences are also observed between the values of N content concerning the broiler waste. They vary between 3.70 and 9.61%.

As regards proximate analysis, it may be seen that the ash content for broiler litter is, in general, far lower than for laying hen litter. It ranges from 22.5 to 33.3% for laying hen and from 8.2 to 17% for broiler litter. The level acquired in this study in the case of laying hen litter sample is higher than those of Junga et al. [30] and Toptas et al. [28]. The ash content for examined broiler litter sample is lower than that reported by Lynch et al. [9] and one of the two samples analyzed by Yurdakul [31], but comparable to the value obtained by Yurdakul for the other sample.

It is noteworthy that the gross calorific value (HHV) for the broiler litter turns out to be quite high, ranging between 14.4 and 18 MJ/kg. It is far higher than that observed for laying hen litter (11.6–12.1 MJ/kg), and is similar to that for wood pellet (16.8–19 MJ/kg), most certainly because of the lowest ash content and the higher C and H mass fractions. However, it should be noted that the amount of moisture in broiler samples is generally far higher than for wood pellets.

The results of chemical analysis may generally be considered to be in line with the literature data.

To check the devolatilization behavior of poultry litter samples, thermogravimetric analysis was performed (see Fig. 1) using an SDT Q600 TGA analyzer (TA Instruments, USA). The samples, ~ 5 mg each, were heated from room temperature to 700 °C at 15 °C/min heating rate under 100 ml/min nitrogen flow. The results show the maximum devolatilization rate to occur for both samples within the temperature range between 220 and 340 °C, approximately.

Considering the utilization of chicken litter ash as a natural fertilizer, a chemical analysis of selected ash samples that remained after the combustion tests was carried out using an XRF S8 TIGER spectrometer (Bruker Corporation, Germany) and a Flash EA1112 CHNS(O) Analyzer (Thermo Scientific, USA). The results presented in Table 2 show that several times lower contents of nitrogen, carbon and hydrogen remained in ash compared to those obtained for chicken litter samples. However, as seen, the ash is a mixture of nutritious components of calcium, phosphorus, potassium, silica and magnesium. All the considered samples also contain chlorine, which probably originates from straw. Particularly high levels of calcium oxide are observed in case of mixtures of laying hen–derived litter and straw, while higher levels of phosphorus and potassium compounds are observed for broiler–derived litter. This is also characterized by lower content of silica dioxide and higher values of magnesium oxide as compared to other samples. All ash samples also include sulfur and iron compounds. However, the concentrations of sodium, aluminium and titanium were found only in ash samples from laying hen litter.

The variety of nutrients found in the poultry litter ash clearly indicates their potential as natural fertilisers. Multicomponent fertilisers, i.e. mixtures of basic elements (nitrogen, phosphorus and potassium) have increasingly been used. From this point of view, the broiler-derived waste seems to be the most promising since its ashes contain large amounts of phosphate and potash, as well as other microelements such as MgO, MnO, ZnO etc.