Theoretical analysis of the thermal conversion of RDF fuel in the context of Waste Management

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Abstract. The European Union strives to introduce waste-free or low-waste closed-loop technologies using material and energy recovery to manage natural resources in a rational manner. Therefore, European regulations require member states to progressively restrict the amount of landfill waste. The article presents the current shape of waste management in Poland, and also introduces the dominant form of RDF management in the cement industry. Nevertheless, the capacity of cement plants is limited, and the energy use of fuels from waste encounters difficulties related to a significant reduction in pollutant emissions, which is why the use of modern installations for the thermal conversion of waste such as pyrolysis and gasification is increasingly considered. Taking into account the promising energy properties of secondary fuels obtained during the pyrolysis process, the chemical composition of gas from RDF pyrolysis was modeled for a pilot installation operating in Poland. Determination of the combustible components allowed the calorific value of pyrolysis gas to be estimated, ranging from 28.2 - 28.7 MJ/m³. The obtained calorific encourages wider use of the waste pyrolysis process in order to obtain secondary fuels with promising energy parameters. It will contribute to a further reduction in the amount of deposited waste, and thus to creating environmentally-friendly closed-loop waste management.

1. Introduction
Currently, many developing countries are struggling with the problem of managing an increasing amount of generated municipal waste [1], determined by the rapid pace of economic development, and consequently, growing consumption. A similar situation applies to Poland, which has been generating increasing amounts of municipal waste in recent years. In order to meet European requirements regarding closed-loop waste management as well as environmental protection, a number of changes have been introduced in Poland to national regulations, clarifying new rules for dealing with waste.

2. Characteristics of RDF
The desire to meet the ever more restrictive European levels of recovery and recycling of municipal
waste, forces Poland to increase the rights of regional municipal waste treatment installations (RIPOK), as well as to expand the possibilities of managing waste fractions there. One of them is RDF (Refuse Derived Fuel), a product obtained from the reject fraction created in regional installations dealing with mechanical-biological treatment or stabilization. Residues from the MBT process (reject fraction) are subjected to the process of removing non-combustible parts, e.g. metals, and then are repeatedly crushed to reduce the volume and moisture content. Furthermore, to enhance the uniformity, as well as easier storage and transport, RDF is often subjected to a pelleting process.

Currently in Poland, RDF is most often used as an alternative fuel in the cement industry. The MBT/MBS reject fraction (RDF) processed in plants can be used in the co-combustion process with coal dust, both in the main burner of the rotary kiln and in the secondary burner, in the process of initial decarbonisation. In the second case, there are no problems related to ensuring proper combustion conditions, hence it is possible to use up to 100% of alternative fuel from waste, whereas in the main burner of the furnace it is necessary to ensure the appropriate temperature difference in the sintering zone (> 400K), between the temperature of the clinker being burned and the exhaust gas temperature. Ensuring this temperature regime is possible with a calorific value of RDF greater than 22 MJ/kg. A lower calorific value of the said fuel contributes to a decrease in efficiency and an increase in heat consumption. [2–8].

3. Thermal conversion technologies
In recent years, the technology of thermal transformation of waste has become increasingly more important in Poland, which is why it seems that the development of innovative technologies for thermal conversion of waste will contribute to further reducing the amount of landfill waste, and thus creating environmentally friendly management of recyclable waste [9–12].

Due to the fact that cement plants can use only about 1 million Mg of alternative fuel from waste during a year, other effective methods of its management should be sought, therefore this article compares three methods for the thermal conversion of RDF: combustion, pyrolysis and gasification. In order to compare the methods of thermal conversion of alternative fuel from waste, particular attention should be paid to the quality of the fuel used for testing. RDF is characterized by a variable chemical composition, therefore in order to be able to use these technologies successfully on an industrial scale, one should know the physico-chemical characteristics of the above-mentioned fuel, as well as its thermal properties. It seems particularly important to control the content of sulfur and chlorine in RDF, contributing to the emission of sulfur oxides, as well as dioxins and furans during its combustion, negatively affecting human health and the environment. However, one of the key parameters determining the choice of alternative fuel is its calorific value. In the case of RDF, it is on average 16-18 MJ/kg [1]. Depending on the type of waste from which RDF was created and thus its chemical composition (Table 1), the calorific value of this fuel can assume different values, determining its subsequent use [6, 13-15].

Table 1. Chemical composition of RDF fuel

|          | [3]   | [16]  | [17]  | [5]   | [18]  | [19]  |
|----------|-------|-------|-------|-------|-------|-------|
| Carbon [%] | 49,40 | 41,00 | 59,20 | 47,10 | 54,60 | 49,40 |
| Hydrogen [%] | 6,50  | 5,70  | 8,22  | 7,10  | 8,37  | 6,70  |
| Nitrogen [%] | 1,50  | 1,20  | 0,52  | 0,70  | 0,91  | 1,00  |
| Sulphur [%] | 0,30  | 0,20  | 0,00  | 0,26  | 0,41  | 0,30  |
| Chlorine [%] | -     | 0,40  | -     | 0,60  | -     | 0,70  |
| Oxygen [%] | 36,10 | 17,50 | 26,75 | 29,40 | 34,40 | 28,10 |
| HHV [MJ/kg] | -     | 21,47 | 27,63 | 21,2  | -     | 20,30 |
| LHV [MJ/kg] | 15,20 | 19,99 | -     | -     | 22,60 | 16,90 |
Considering the data presented in Table 1, one can notice the relationship between the content of combustible components in RDF and its combustion heat. The higher the content of combustible components (carbon and hydrogen) in the said fuel, the higher the value of the heat of combustion. Considering the above, it seems important to strive to ensure the highest level of homogeneity of RDF, conditioning the willingness of its wider use in industrial activities. In addition, reducing the share of biomass in alternative fuel, through its greater separation at the processing stage in MBT plants, will allow the moisture content to drop, thus increasing the calorific value of fuel from waste [13,20].

The most common technology of thermal conversion of RDF in Poland is its combustion, while in the face of the constant reduction of pollutant emissions in European legislation, other, more environmentally friendly methods for managing alternative fuels from waste are being sought such a pyrolysis or gasification.

The above-mentioned processes are included in thermal waste conversion methods, however, they are characterized by quite different parameters. Combustion is a thermal process taking place in the best case with excess air, aimed at reducing the volume of generated waste, as well as destroying potentially harmful compounds, while recovering energy and certain chemical substances from waste. In turn, gasification involves the conversion of any carbonaceous fuel into a gaseous form in the presence of an oxidizing agent, e.g. air, oxygen, water vapor, etc., taking place with an air shortage. As a result of the analyzed process, synthesis gas is obtained, the calorific value of which depends on the gasifier used, from 5 MJ/m$^3$, for air and steam, up to 10 MJ/m$^3$ for pure oxygen. The obtained gas can be used in gas engines to produce electricity or due to the relatively low heating value, co-combusted with other gaseous fuels in heating devices [21]. In contrast, pyrolysis is called the endothermic process of thermal transformation of carbon-rich substances, taking place in an anaerobic environment or containing negligible small amounts of oxygen, which results in pyrolytic gas, pyrolytic coke, as well as pyrolytic liquid (Fig. 1.) Taking into account the mentioned processes of thermal conversion of waste, one can see the fundamental difference between combustion, ensuring the recovery of electricity [22] and heat, and pyrolysis and gasification, allowing the recovery of chemical energy. Chemical products obtained as a result of the above processes can be used as raw materials for other processes or as secondary fuels, which in the face of decreasing deposits of conventional fuels, gives a chance for greater diversification of fuel and energy sources. In addition, in order to increase the efficiency of the analyzed processes of thermal waste conversion, they are combined in one installation, which increases the overall energy recovery [18,23–28].

**Figure 1.** Scheme of RDF pyrolysis
4. Results and discussion

Among the methods of municipal waste conversion described in the article, the most promising method was chosen for further analysis, namely pyrolysis. Using the licensed Chemkin Pro software, the chemical composition of gas from RDF pyrolysis was modeled for a pilot plant operating in Poland. Determination of the combustible components allowed the calorific value of the pyrolytic gas to be estimated for the changing conditions of the process, i.e. the temperature and residence time of the reactants in the zone of the highest temperatures. A detailed chemical mechanism developed by the CRECK Modeling Group [29–33].

The contributions of selected combustible pyrolysis gas components obtained as part of the calculations, namely: CO, H\textsubscript{2}, CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{2}, C\textsubscript{2}H\textsubscript{4} and C\textsubscript{6}H\textsubscript{6} are summarized in Fig. 2. as a function of the pyrolysis temperature. Analyzing the obtained results, one can observe an increase in the content of combustible components of gas, i.e. hydrogen, acetylene and benzene, as well as a decrease in the content of carbon monoxide, methane and ethene, as the temperature rises between 800-900°C. There is high convergence with the results obtained by (Hwang et al. 2014) [34] for hydrogen and carbon monoxide, whose concentration in pyrolysis gas increases and decreases, respectively, in the above-mentioned temperature range. It is worth mentioning that in these studies an increase in the methane concentration was observed, while the concentration of other hydrocarbons remained stable. In turn, the results of calculations carried out for the Polish pyrolysis plant indicate a decrease in the methane content in the gas composition, in favor of an increase in the concentration of other hydrocarbons (acetylene, benzene) under analogous temperature conditions.
5. Conclusions
The increasingly more stringent European regulations on environmental protection and waste management encourage limiting the use of conventional fuels to seek new sources of fuels and energy, while minimizing the role of landfill in waste management. It seems that thermal waste conversion is a good response to these challenges. As a result of thermal processes, it is possible to produce electricity and heat, but also to obtain new secondary fuels such as pyrolytic gas, suitable for energy use. Chemkin Pro software is an invaluable tool that helps choose the optimal parameters of these processes, helping select fuels with the expected properties. Therefore, the authors of this article undertook the task to estimate the calorific value of gas from RDF pyrolysis.

At present, cement plants are not interested in increasing the use of the solid fraction of the said fuel due to its too low calorific value. Nevertheless, large surpluses of alternative fuel from waste encourage its energy use. Energy and heat engineering are cautious about this issue, due to poor exhaust gas treatment systems, and additionally the amount of incinerated waste is also to be limited to a maximum of 30%, therefore the development of pyrolysis technology seems to be the right direction.

The results obtained during numerical calculations allowed the approximate calorific value of the pyrolytic gas (28.2-28.7 MJ / m$^3$) to be determined. The high calorific value of the said gas encourages its wider use both in the heating sector and in the metallurgical industry. The gas from RDF pyrolysis may be co-combusted with natural gas, which will contribute to its lower consumption, and may also be a substitute for coke oven gas for heating furnaces. These premises show that the pyrolytic gas from RDF may be an interesting alternative to conventional fuels, at the same time contributing to limiting the role of landfilling waste and raising the level of environmental protection.

Acknowledgements
Publication was supported financially under Contract No. 944/P-DUN/2019 from funds of MNiSW intended for dissemination of science (DUN).

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