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Thermal utilization of meat-and-bone meal using the rotary kiln pyrolyzer and the fluidized bed boiler – the performance of pilot-scale installation

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Abstract: Thermal utilization of meat-and-bone meal (MBM) is subject to stringent regulations that are meant to provide elimination of any potential pathogens. Incineration as well as other possible routes for thermal conversion of MBM are still at the research state. The universal technology was developed that allows to combust various types of waste organic materials, including animal waste, municipal solid waste and sludge, mixed at any ratio with different types of biomass. It provides the possibility to utilize the waste-and-biomass fuel blends of up to 90%wt of moisture content, while maintaining the allowable pollutant emissions and soil contamination. This regards mainly NO_x, SO_2, HCl and VOC. Contrary to the typical large scale grate boilers used for waste burning, the developed operating pilot-scale plant with a capacity of 12MW offers the complete combustion of MBM, resulting in a flue gas which is proved to be free of flammable gaseous components and sooty particles in slag and fly ash. The thermal decomposition and combustion of waste using this technology ensures thermal conversion of chemical energy contained in waste and biomass. The efficiency of the prototype installation varied between 84.8 and 88.4% depending on the facility load.

Keywords: MBM; pyrolysis; combustion; particulate matter emissions; gas emissions

1. Introduction

The worldwide trends to move towards reducing carbon footprint and to promote sustainable development has led to an increased focus on biomass as an alternative energy source [1]. Apart from commonly used woody biomass [2], of interest is also waste biomass of different kind, including large variety of organic by-products from industry and agriculture, as well as municipal solid waste or sewage sludge. Biomass is the subject of extensive studies in terms of various conversion technologies. Even though the direct combustion still remains the basic one [3], other processes allowing to transform organic materials into useful gaseous and liquid calorific products has also been considered, including pyrolysis [4-6] and gasification [6-10]. Another possible pathway for environmentally beneficial and economically justified utilization of organic wastes that may contribute to meet the target of increased share of biomass in energy supply, is the anaerobic digestion [11,12], which consists in breaking the feedstock down to biogas that can be directly used in combined heat and power systems.

The efficiency of conversion process and system operation safety however appear to be a technical challenge. This stems from the variety of composition and structure of biomass that largely determine the course of physicochemical processes [13,14]. Therefore, numerous research are carried out on the pretreatment processes to enhance the biomass properties [15,16], and thereby to improve its suitability for further use in energy generation [3,17]. This also applies to a large extent to sewage sludge, which needs special treatment due to high moisture and ash contents, the presence of pathogens and organic contaminants [18].

Considerable proportion of alternative fuels in the energy sector nowadays is a group of waste from meat industry. Constantly increasing worldwide production of meat translates into the increased amounts of animal waste that require management. This refers to meat-and-bone meal (MBM) [19], poultry litter [20] and feathers [21]. The major attention and analyses has been dedicated to MBM, as due to the risk of the Bovine Spongiform Encephalopathy (BSE) that arised in 1980s and 1990s this type of waste started being considered as hazardous [19,22-24]. Since then, implemented regulations, restricted its use as an additive to cattle feed and direct disposal in landfilling as natural fertilizer [25,26]. Addressing the need for environmentally safe destruction of this type of waste, the efforts have been undertaken to develop efficient thermochemical technologies that would allow its energy utilization with low emissions [19,27-30]. Since MBM is classified as harmful to environment and human health, its thermal utilization requires special processing conditions to ensure destruction of any pathogens, namely, the relatively high temperatures (above 800^{o}C) and the appropriate residence time. Therefore it used to be incinerated in cement kilns that are able to meet these requirements [31-34]. The rotary kiln technology for the on-site burning of animal waste in the meat-processing plant has also been implemented [35]. MBM is also considered as an alternative fuel in combustion and co-combustion with other solid fuels. This include the combustion in grate boilers [36], as well as in fluidized bed combustors [22,26,31,37,38], which offer high process temperatures, long residence times and flexibility in dealing with fuels of various nature [26,39-41]. Clearly, the composition of MBM differs depending on the origin of raw material, however it has appeared to feature good calorific value as compared to conventional fuels. The gross calorific value of MBM has been reported to range typically between about 14.2 and 19.2 MJ/kg [6,26,33,42,43], thereby giving an average level of about 16.6 MJ/kg. Other study shows even the value of 30 MJ/kg [31]. On the other hand, the problems may arise during MBM combustion due to its chemical composition, characterized of relatively high contents of minerals, including nitrogen, phosphorous, sulphur, calcium and potassium, as well as trace metals. This may specifically lead to boiler operation problems related with fouling and corrosion [42,44], bed agglomeration [28] and to an increase in nitrogen oxides emissions [42]. In this context, particularly the fluidized bed combustion has been considered to be beneficial as providing low NO_x emissions and giving the possibility to combust fuel with high efficiency [37].

The key aspect in combustion of a waste fuel such as MBM is to ensure the process stability, which allows to keep the emission levels of SO_2, NO_x, HCl and CO possibly low [27,45]. The analyses of co-combustion of MBM with other solid fuels indicate that the levels of SO_2, CO and NO_x depend on the fraction of MBM in a combusted fuel blend. Research on combustion of MBM with brown coal in a pilot-scale fluidized bed furnace has shown the reduction in emissions of SO_2 and NO_x with an increase in MBM amounts in a blend [26]. The

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concentration of SO_2 for 100% of MBM was 14 mg/Nm^3 at 11% O_2. Simultaneously, concentration of NO_x was 398 mg/Nm^3, although it has also showed the decreasing tendency with an increasing share of MBM, despite the fact that the nitrogen content in MBM is far higher compared to coal. Low emissions has also been obtained from burning of MBM with peat in fluidized bed combustors [37,38]. The trials resulted in SO_2 concentration ranged between 91 and 383 mg/Nm^3 at O_2 content in flue gas varying within 5.9-6.5%, whereas HCl between 5 and 65 mg/Nm^3. Slight decrease in SO_2 concentration with an addition of MBM up to 20% has also been observed in the case of its co-combustion with coal for the air-excess number λ ranging between 1.3 and 1.6. The concentration levels referred to 6% O_2 oscillated around approximately 770 mg/Nm^3. The test results have however revealed an increase in CO and NO_x emissions. These changed within the range from ~400 to 1400 mg/Nm^3 and from ~758 to 1300 mg/Nm^3, respectively, depending on a coal type and air ratio. Regarding the NO_x emissions, the investigation outputs has led to a conclusion that small percentages of MBM in fuel blend do not introduce enough volatiles to activate the NO_x destruction mechanism.

Additional issue is that MBM ashes poses valuable properties. Being free from potentially harmful pathogens and, primarily, rich with macronutrients such as phosphorous, calcium, magnesium and potassium compounds [28,42,43], they may serve as a natural fertilizer, allowing to substitute the synthetic one. This seems to be advantageous noting in particular the increasing agricultural production that involves an increasing demand for phosphate fertilizers [46]. In this way, the combustion of MBM as the save disposal method, contributes to the idea of sustainable development and to the reduction of pollutant emissions.

To carry out environmentally sound and efficient thermal conversion of meat industry by-products that would meet the stringent regulations, the in-depth recognition of sub-processes and phenomena occurring during the process is needed. This also refers to the material properties and its behavior as the basis for the determination of the potential use of this kind of waste for energy purposes [24,47]. It shall be added that thermal treatment of waste fuel, either in existing or in new dedicated facilities, may involve a number of other issues, such as the waste heat utilization [48] or, when considered in terms of co-processing with fossil fuels, the explosion safety [49] and the flexibility of system devices to fuel change [50].

In order to meet the aforementioned needs the staged incineration technology was developed, which proved to be thermodynamically efficient and to provide low levels of contamination and dust emissions. The paper presents the detailed characterization of the system and shows the key performance parameters of a pilot-scale plant of 12MW capacity when utilizing MBM. The facility tests carried out covered also the monitoring of gaseous emissions for NO_x, SO_2 and VOCs, in particular. Special attention was paid to the analysis of ashes in terms of their chemical composition and the presence of combustible parts.

2. The system details

The described herein technology [51,52] provides the possibility to incinerate not only the animal waste, but also other types of organic waste such as sewage sludge, municipal solid waste and biomass of different kind. It allows to utilize the biodegradable waste of the overall moisture content up to 90%wt and whilst preserving the maximum permitted levels of the atmosphere and soil contamination.

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The energy recycling of hazardous and non-hazardous waste implementing the two-stage technology that use the rotary reactor to pyrolyze the feedstock and the fluidized bed chamber to combust the pyrolysis gas and the remaining char, ensures thermal conversion of waste with flue gases free from any environmentally harmful dioxins and furans. The combustion process is supplemented with the liquid or gas fuel, which is added in an amount ranging from 0.015 to 0.070 kg per kilogram of a feedstock, depending on its moisture content. The physical structure of waste to be utilized may be solid, as well as in form of a pulp or a dense slurry. In each case, the technology provides the optimum thermal effect. In view of this, the presented waste/biomass-to-energy technology allows to obtain the maximum levels of thermal efficiency and protection to the environment and human health and, additionally, the optimum economical effect.

The primary fuel in this case is an animal waste, biomass of different kind and alternative fuels. As aforementioned, the auxiliary fuel used to initiate the process is either gas or liquid fuel. However, it is preferable to use the renewables as supporting fuels since all the energy generated in the system would then come from the renewable energy sources. The minimum amount of feedstock material for which the installation can be operated is 20% of its nominal efficiency, whereas maximum reaches 150% at a moisture content of 80%wt.

The combustion takes place under conditions that comply with the relevant requirements of the directives and regulations concerning the safe utilization of animal waste. Namely, it is carried out at temperatures higher than 850^{o}C, with oxygen content exceeding 8% and the residence time longer than 2 seconds.

The reported method of thermal utilization is a continuous-type process that proceeds in a system of integrated devices. These are equipped with measuring and control instruments for reading local parameters and remote transmission of signals to control units. Automatic control is performed according to the prescribed operation algorithm. The control system covers the course of a technological process, its visualization, archiving of operation parameters and occurring events, and monitoring of parameters of substances leaving the installation. And thereby, it enables direct and immediate interference with the process course in order to preserve the required parameters.

The schematic of the installation for thermal utilization of animal waste, including the rotary pyrolyzer and the fluidized bed boiler is shown in Fig. 1. The MBM to be burnt is fed into the boiler storage tank (6) together with the limestone in a quantity corresponding with a stoichiometric ratios needed to neutralise the sulphur and chlorine content in a fuel. They are mixed there and then transported by the fuel feeder (5) into the rotary kiln pyrolyzer (1). The mixture falls into the pyrolyzer chamber via the chute of a feeding unit. In order to ensure an even fuel feed into the chamber, the waste is supplied in a stream of flue gases that flow in a gas-box (11) surrounding the feeder. The exhaust gas is pumped through the pipeline (12) into the gas-box using the re-circulation fan (13), and taken out using the suction fan (77). The amount of flue gas required for the process is adjusted by opening or closing the flap (14).

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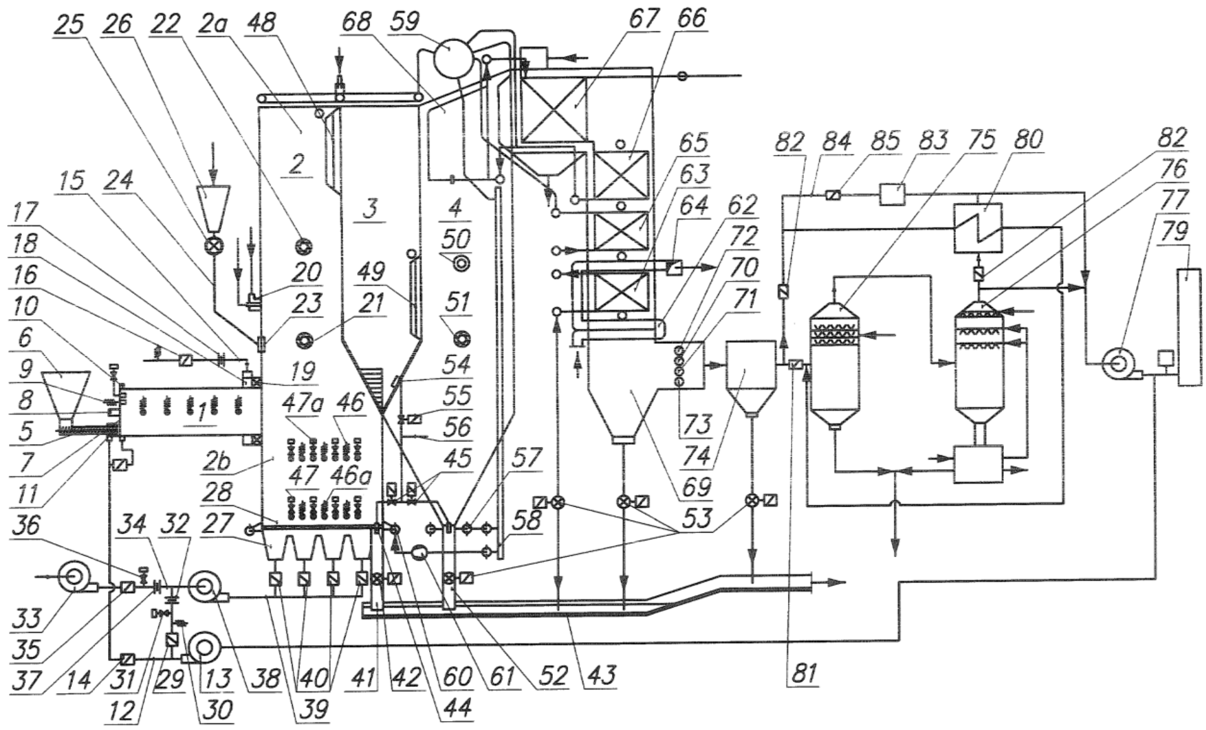

Fig. 1. The schematic of the installation for thermal utilization of meat-and-bone meal.

On the side of fuel charging system, the rotary pyrolysis chamber is closed by a flat front panel (7), which is connected to the chamber through the channel with a labyrinth sealing (10) that is filled with recirculating exhaust gas. Its quantity is controlled via an adjustable slide. In a central axis of the flat front panel is located a supporting burner (gas or oil) (8), used to provide the appropriate thermal conditions for drying and pyrolysis of a fuel. The panel is also equipped with a thermocouple (9) and a pressure plug. The other end of a rotary chamber is connected to the fluidized bed chamber (2). This connection is additionally sealed through an air canal (18) equipped with a swirl unit (19) and the compensating slides of vertical elongations. The canal is supplied with air through the pipeline (15) fitted with the measurement orifice (17), the regulation flap (16) and a thermometer.

In order to ensure the correct course of drying and devolatilization in a rotary chamber, the fuel feedstock is raised up to over 70% of the chamber diameter by the specially designed lifting flights mounted inside. This limits the possibility of sintering and agglomeration of a feedstock, and thereby intensifies the heat transfer within the material and promote the moisture and gas release. Additionally, along the rotary chamber centerline the thermometers are located to control the processing temperature. This, in the case of thermal utilization of meat meal, should remain between 900 and 1200^{o}C. The thermometers enable the proper control of a supplying burner operation so as to ensure the relevant temperature distribution. The rotation speed of a pyrolyzer within a range between 0.5 and 5 rpm provide the residence time of a char in a chamber ranging from 5 to 10 minutes.

Gas mixture and solid carbon residue resulted from the drying and pyrolysis of a meat meal are directed to the fluidized bed chamber. It is built of a sealed membrane-type walls bearing a heating medium. Pyrolysis gas is supplied to the upper part of a chamber and combusted there, whereas char is burned in a fluidized bed in a hopper-shaped lower part of a chamber. At the

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bottom, the chamber is closed by the orifice plate (28), which is covered with a refractory concrete on the fluidized bed side. The orifice plate is closed by a wind box (27), which is divided into a number of sections to allow the adjustment of pressure and the gas flow in each bed zone. The amount of gas supplied to each zone is controlled by opening and closing the flaps (40). It flows in from the collector (39), which is fed by the fluidizing fan (38) with adjustable settings of gas efficiency and pressure. The fan draws in the flue gas from the damper located downstream of the sucking fan (13). The flue gas is supplied to the fan through the duct equipped with the shut-off and/or regulatory slide (29), the thermometer (30), the manometer (31) and the measurement flange (32). To generate the fluidizing gas, the blower (33) provides additional air supply to the fluidizing fan. Air is transported via the pipeline (34), similarly having the shut-off and/or regulatory slide (35), the manometer (36) and the orifice (37). The exhaust and air fans are equipped with the systems for adjusting the quantity and the pressure of supplied media.

The residual ash is removed from the fluidized bed using an ash discharging system, comprising the discharge channel (41) and the remotely operated rotary feeder (42). The channel is situated next to the vertical rear wall of a fluidized chamber hopper. Ash is then directed to the bucket feeder (43), which is placed in a water tank that serves as a water trap for a fluidized bed chamber. The ash discharge channel is also equipped with a compressed air impulse nozzle (44) operated by a remote shut-off valve (45), which supports the ash removal efficiency.

The lower zone of a chamber, namely the fluidized hopper is formed by a vertical front and rear walls, and the side walls inclined toward the chamber center with an inclination angle less than 45^{o}. The hopper is insulated with a refractory concrete to protect metal elements of the walls from erosion.

To ensure the proper operation of a fluidized unit, the hopper is equipped with a relevant measuring system allowing to monitor the bed parameters, and to determine the fluidizing gas composition and the amount of inert material. The system include the temperature sensors (46) and (46a), as well as the manometers (47) and (47a), evenly spaced across the left and right inclined walls of a hopper. Manometers and thermocouples are spaced alternately in a horizontal plane at two heights, namely at the distance of 200÷500 mm and 2÷4 m above the orifice plate. Both, the lower and the upper measuring points in a vertical plane are positioned in pairs to enable the differential pressure measurement in a bed.

As aforementioned, a fluidized bed is generated in a chamber hopper as a result of a fluidizing gas flow i.e., the air/flue gas mixtures with the volumetric ratios ranging from 10%/90% to 90%/10%, through the inert bed material. This is composed of a mixture of silica sand and properly grinded slag, which is blended with limestone in its mass fraction ranging from 2 to 80 %, depending on the sulphur, chlorine and the fixed carbon contents in a fuel. The material is fed into the fluidized bed chamber periodically through the inlet window (23) from the storage tank (26) and through the duct (24) with a rotary feeder (25).

The flow velocity of a fluidizing gas through the bed, lies in a range between 1 and 4 m/s, regardless of the heat load. The fluidization process must be conducted in such a way that the temperature in a bed does not exceed the characteristic ash softening temperature. The process temperature ranges within 750 and 900^{o}C, and the volumetric fraction of oxygen in fluidizing gas varies between 2 and 20%.

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As already stated, the pyrolysis gas is combusted in the upper zone of a fluidized bed chamber. The process is carried out with the use of a burner (20) mounted in a front chamber wall. The burner is powered by liquid or gas fuel and is needed to ignite and stabilize the process of gas combustion. This is conducted at temperatures of 1200÷1300°C and must be controlled so as not to exceed the maximum of 1300°C that fosters rapid formation of nitrogen oxides. To provide the process control the combustion air is distributed. The primary air is supplied through the sealing channel (18) equipped with a swirl vane, which connects the rotary pyrolyzer to a fluidized bed chamber. This air amounts to 0.2–0.4 of the stoichiometric air needed to burn the meal. Of the same quantity are also supplied the secondary and the third air streams, by the nozzles (21) and (22), respectively. Such air distribution helps to extend the combustion zone, leading in result to volumetric heat load of a chamber that allows to prevent from exceeding 1300°C in a burning zone.

Exhaust gases are directed through the upper festoon (48) to the separation chamber (3). The festoon is made of three rows of wall tubes of a separation chamber, to which the U-profiles are attached. These, with their open parts face the flue gas inflow, allowing the precipitation of particulates and the condensation of alkali and heavy metals' vapors. When hitting the U- profile, the exhaust particles decelerate and fall back along the section down to the bed. The heavy metals' vapors condense on a profile wall forming a glassy-like deposit, which is blown away downwards back to the bed with soot blower installed on a top of a chamber, above the festoon tubes. The separation chamber which constitutes the rear chamber wall, is closed by a baffle placed in front of rotary pyrolyzer and the chamber walls. The baffle, being bended in its lower part towards the chamber rear wall at a maximum angle of 45° serves as a tightly closing heated membrane-type surface. The bended baffle surface has the discharge hoppers along the chamber width to drive back the separated particles to the bed using compressed air supplied by the impulse nozzles (54). Rear wall of a fluidized bed chamber is of similar shape, however bended towards opposite direction it closes the separation chamber. The bendings are covered with refractory cement protecting them against erosion. Exhaust gases, partially purified from solids and vapors, change direction when passing upper festoon and flow through the separation chamber. There, due to change in direction and reducing the flow velocity, they are further de-dusted. Next, the treated flue gas flows through the lower festoon (49) to the afterburner chamber (4). The burn out of combustible gases remaining in a flue gas is carried out using oil or gas burner (50), ensuring ignition and the process stabilization. The complete burnout is provided by mixing the exhaust gases with an additional (fourth) air dosed by a nozzle (51) at the amount ranging from 0.1 to 0.3 of stoichiometric quantity.

There is a bulkhead superheater (68) mounted in an upper part of the afterburning chamber, and the second stage superheater (67) with the vapor temperature controller placed in a crossover duct. There are the first stage superheater (66), the water heaters (65) and (63), and the air heater (64) placed in a convection channel. Fumes, free from gaseous and solid combustible components, give off the heat by convection when flowing through the system. They are analyzed at the outlet of the convection part. i.e., in an exhaust duct, in terms of their chemical composition, ash content, pressure and temperature, using spigots (70)-(73), respectively.

Flue gas flowing out of a boiler goes next through the fabric filter (74) to remove particulates. Purified gas is next fed to the water sprinkler (75) and the scrubber (76), where the

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sub-micron solid particles, as well as alkali and heavy metals' vapors are eventually separated, and gaseous molecules of sulphur and chlorine oxides are chemically bonded by a lime slurry sprayed in a scrubber. The parameters of exhaust gases entering the stack are monitored with the use of analyzer (78). These include the temperature and the contents of ash and soot, moisture, carbon oxide, sulphur and nitrogen oxides, and hydrocarbons. In case when temperature exceeds the dew point temperature, the fumes flow through an exhaust fan (77) directly to the stack (79). Otherwise, a flue gas is first directed to the heat exchanger (80) and then to the chimney.

Ash removed from flue gas in the hopper of afterburning chamber, in the discharge hopper of firing zone and convection zones, and in the fabric filter, similarly as in the case of fluidized bed chamber, is conveyed through the channels equipped with rotary feeders. It further goes to a bucket feeder and finally to a disposal site. As regards the water circulation system, the medium is transferred from the heater to the drum (59), from which it is supplied through the down-comers (58) to the wall tube manifold of afterburning chamber (57) and the wall tube manifold of fluidized bed chamber (60). The steam generated in a boiler goes back to the drum, and then is directed to the superheaters and the turbine. The medium flow in a fluidized bed chamber is forced by a water circulation pump (61).

3. Pilot-scale installation of 12 MW capacity

An experimental facility was built in the town of Ostrowite. the Lniano municipality. in Kujawy and Pomerania Province (Poland) It was developed to serve as a source of thermal energy in the form of steam for technological use in an animal waste treatment plant. The system consists of the rotary pyrolyzing reactor, the fluidized bed chamber and the waste heat recovery boiler. As described previously, drying and devolatilization are carried out in a pyrolyzer, whereas the fluidized bed chamber is used to combust the pyrolysis products, namely the gas components in its upper zone and the remaining solid (char) in its lower zone. Burning of volatiles takes place in a controlled manner with the multistage air supply. Char combustion in a fluidized bed is controlled by an oxygen concentration in a fluidizing gas, which is a mixture of air and recirculating flue gases. The exhaust gas generated in a fluidized bed chamber undergoes cleaning in a separation chamber in the first place to extract the fly ash. After partially purified, the flue gas is directed to the shell-type heat recovery boiler that produces steam at pressure of 5 bars and temperature of 250^{o}C. The views of the installation are displayed in Figs. 2-4.

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Fig. 2. General view of the installation.

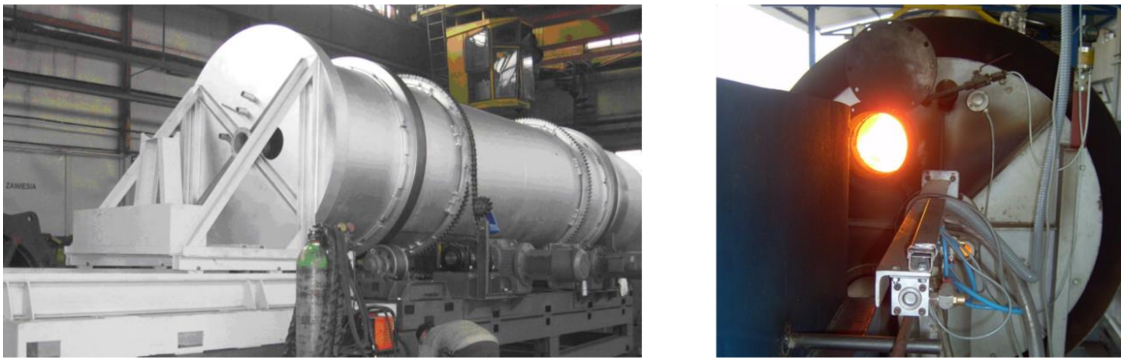

Fig. 3. Detailed view of the rotary pyrolysis chamber.

The presented technology system provides the complete combustion of animal meal and the elimination of combustible components from slag and the fly ash, as well as flammable gases from fumes. As confirmed by the measurements, the installation ensures the emissions of harmful substances below the permissible standards, including NO_x, SO_2, HCl and VOC. The implemented two-stage technology that use the rotary reactor for drying and degasifying waste fuel, and the fluidized bed chamber for separate combustion of pyrolysis gas and char, allows to control the individual stages of fuel combustion. These refer to the chemistry of a process, namely, the elementary composition of a reactive atmosphere, and to the thermal regime, i.e., the characteristic process temperature range.

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Fig. 4. Fluidized bed chamber.

The commonly used installations for waste incineration based on the grate-type boilers do not provide complete combustion and they generate a slag that contains substantial quantities of combustible components in form of char, exceeding mass percentage of 5%. It consists of carbon in nearly 100%. This slag is thus a waste, which has to be further disposed. In the case of studied prototype system for thermal conversion of waste, particularly the MBM, the remaining ash constitutes a valuable raw material for the production of phosphorous-, potassium- and calcium-magnesium-based fertilizers. The content of phosphates in ash reaches 25-28% and is about 5 times higher than typical contents in natural minerals. The obtained ash is a valuable resource, basically due to high levels of P_2O_5 and the trace levels of combustible parts which remain at 0.5% by weight.

In the case of examined prototype installation in Ostrowite, the amount of auxiliary (liquid) fuel ranges between 0.01 and 0.08 kilograms per 1 kg of a meal, depending on a moisture content in a target waste fuel. In any case, the system provides the positive thermal effect. The heat generated in a furnace is used in a heat recovery boiler that produces steam at the pressure

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of 4-6 bars and temperature of 250-300^{o}C, depending on the technological needs. At the start-up stage, namely at the stage needed to establish the temperature balance in the system, the light heating oil is used. When the assumed temperature in a rotary pyrolysis reactor is achieved, the ignition fuelling system is switched from heating oil to heated animal fat at a temperature of 80^{o}C. This type of kindling fuel is classified as an alternative fuel from renewable resources, and thereby the total thermal energy generated by the system is regarded as renewable energy. The installation provides high availability and reliability. The minimum quantity of meal required for operating the system amounts to 20% of a nominal capacity, whereas the maximum corresponds to the nominal capacity of 120%.

As aforementioned, the process of MBM utilization is of continuous-type, and the facility equipped with automatic monitoring and control system based on the prescribed control algorithms allows an on-line adjustment of operating settings so as to meet the required output parameters.

3.1. Meal supply system

Meat meal is fed into the hopper of a unit of external conveyors, which transfer the fuel into an interim bunker hopper. From there the meal is fed into a loading hopper of a rotary pyrolyzer. To avoid dust lift-off and the spread of odours, the fuel supply unit is hermetically sealed. Additionally, it is placed in a room with continuous exhaust system of contaminated air, which is further used for fuel combustion. The installation is also fitted with a grate to separate bones exceeding the dimension of 50 mm. The amount of supplied meal is regulated with the use of inverter setting the travelling speed of a feeder.

3.2. Drying and thermal decomposition

The processes of drying and devolatilization take place in a rotary kiln reactor with a diameter of 1200 mm. Its chamber is equipped with specially designed material lifters, which are distributed alternately in three sectors along the chamber length. The chamber rotates at 0.5-5 rpm and is inclined by 2-3^{o} towards an outlet. It is made from an uncooled pipe with a refractory lining inside and closed by a sealed faceplate from the front. In a faceplate there is installed an oil burner, equipped with the systems of ignition and flame control. There is also mounted the charging device of meal and sorbent. The quantity of liquid fuel to be combusted is automatically adjusted, so as the temperature inside the chamber remains within range between 850 and 1100^{o}C, according to the type of animal meal being utilized. The amount of air supplied to the rotary kiln pyrolyzer depends on a supplementary fuel quantity and is set to ensure the complete combustion and nearly zero content of oxygen in the drying and pyrolysis zones. The process is carried out in a reductive atmosphere to avoid burning and heat release. The rotary chamber is directly connected with a fluidized bed chamber via a swirling element for primary air, which is necessary to partially combust evolved pyrolysis gas.

3.3. Combustion

Pyrolysis products are burned in several stages in a fluidized bed boiler. The boiler chamber is made of tight wall tubes that constitute the evaporator unit. At the chamber wall in a fluidized bed zone there is installed a burner for igniting and stabilizing combustion. There is an orifice plate at the chamber bottom, which provokes fluidization. It is composed of several sections,

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inclined towards an ash discharge hopper. The post-pyrolysis char is combusted in a fluidized bed, whereas pyrolysis gas is burnt in the upper part of a chamber in its consecutive sections being supplied with primary, secondary and the third air, respectively. Temperature in a flame zone is within 1100 and 1300^{o}C, and an oxygen content in a flue gas amounts to 7-8%. Temperature inside a fluidized bed ranges between 700 and 950^{o}C and is being set according to ash softening characteristics. An excess-air ratio is within 1.1 and 1.25, whereas an oxygen content in a fluidizing gas is 6%. The residence time of pyrolysis gas in a fluidized bed chamber at the required temperature range of 1200-1300^{o}C is 4-6 seconds. The residence time of the solid pyrolysis residue in a fluidized bed is about 10 minutes. The exhaust gases leaving the chamber, being next treated when passing through the separation chamber, flow to the waste heat recovery boiler.

4. Test results of 12 MW facility

The meal blend used to analyze combustion in the prototype installation was sourced from the lot feed material that was available during the day of testing. The results of proximate and ultimate analysis of examined blend are presented in Table 1.

Table 1
Chemical composition and physical properties of examined MBM blend.

		Standard
Proximate analysis (% as received)		
Moisture	2.53	PN-G-04511:1980
Ash	21.26	PN-ISO-1171:2002
Volatile matter	67.82	
Fixed carbon	8.39	
Ultimate analysis (% daf)		
Carbon	36.3	PN-G-04571:1998
Hydrogen	5.07	
Nitrogen	7.3	
Sulphur	0.33	PN-83/C-04091
Oxygen	12.47	
HHV. MJ/kg	16.13	PN-ISO-1928:2002
Bulk density, kg/m^3	608	

4.1.Balance and efficiency measurements

During measurements the temperature in a rotary kiln pyrolyzer was set at 850^{o}C. Under obtained thermal equilibrium, the processes of feedstock drying and decomposition were autothermic, and thereby there was no need to apply any auxiliary fuel. Each heat load test

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lasted 3 hours. The readings were recorded every 15 minutes. These included the following parameters:

- meat meal feed rate B, kg/h,
- temperature inside the rotary pyrolyzer, ^oC (5 measurement points T_k. k=1…5, along the rotary axis),
- inlet/outlet negative pressure p_k in a reactor chamber, Pa,
- pyrolysis gas composition at the pyrolyzer outlet, %,
- temperature in the upper zone of fluidized bed chamber T_f, ^oC,
- flue gas temperature ($T_{ex,out}$, ^oC) and composition (%) at the outlet of flue pipe connector of heat recovery boiler,
- steam output D_s, kg/h,
- steam pressure p_s, bar,
- steam temperature T_s, ^oC,
- supply water temperature T_{cw} ^oC,
- supply water pressure p_{cw}, bar,
- combustible content in ash C_a, %.

The sensors for temperature measurement inside the rotary pyrolyzer were evenly spaced along the rotary axis every 1.5 m starting from the face plate. During the tests, the system was supplied with chemically treated boiler water. Its temperature T_{cw} was kept at 18-20^oC, whereas the pressure p_{cw} at 6 bars.

Experimental tests were performed for various thermal loads, corresponding to the meal feed rate (B) of 500, 1000, 1500, 2000 and 2650 kilograms per hour. The balance calculations were made based on the arithmetic means of the measurements. These average parameter values for investigated heat loads are summarized in Table 2. Thermal efficiency of the installation was determined by means of Direct Method. An outlet excess air was calculated based on the measured CO_2 content in a flue gas and its estimated maximum value that may result from biogas combustion (this amounts to CO_{2max} = 1.7%).

Figures 5 and 6 show changes in the outlet flue gas temperature and the thermal system efficiency, depending on a given thermal load. As the results show, the possibility of fine adjustment of supplied air in accordance with a demand allows to optimize the combustion process so as to minimize the losses of incomplete combustion. Maintaining relatively constant temperature of exiting flue gas (at about 145^oC on average) and an excess-air number (at $\lambda \sim 1.1$) enables to keep the system efficiency at the defined level, close to the optimum one.

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Table 2

Results of measurements and balance calculations for the facility.

		MBM feed rate. kg/h				
		500	**1000**	**1500**	**2000**	**2650**
Thermal load		18%	38%	56%	75%	100%
Thermal input*, kW	Q_d	2 240.3	4 480.6	6 720.8	8 961.1	11873.5
Steam parameters:						
Output, kg/h	D_s	2 310	4 815	7 025	9 390	12720
Pressure, bar	p_s	4.95	5.05	5	5.1	5.2
Temperature, ^{o}C	T_s	254	250	248	252	252
Enthalpy, kJ/kg	h_s	2 962	2 960	2 959	2 960	2960
Heat capacity, kW	Q_w	1 901	3 959	5 774	7 721	1046
Efficiency, %	η	84.86	88.36	85.91	86.16	88.08
Excess-air number	λ	1.19	1.1	1.15	1.12	1.13
Flue gas parameters:						
Outlet temperature, ^{o}C	T_{e_out}	148	136	158	143	142
Composition, %	O_2	6.74	5.83	6.15	5.48	5.30
	CO	0.18	0.35	0.12	0.15	0.17
	CO_2	9.86	10.63	10.16	10.48	10.50
	SO_2	$4.05\cdot10^{-3}$	$4.74\cdot10^{-3}$	$8.15\cdot10^{-3}$	$7.91\cdot10^{-3}$	$6.35\cdot10^{-3}$
	NO_x	$13.95\cdot10^{-3}$	$16.05\cdot10^{-3}$	$13.12\cdot10^{-3}$	$13.94\cdot10^{-3}$	$13.25\cdot10^{-3}$
Parameters in a rotary pyrolysis reactor:						
Temperature, ^{o}C	at 1.5 m	618	585	560	532	530
	at 3.0 m	842	815	794	771	753
	at 4.5 m	1064	1078	1112	1116	1135
	at 6.0 m	1080	1091	1124	1137	1156
	at 7.5 m	1085	1096	1125	1138	1187
Pressure, Pa	in	-39	-35	-28	-24	-22
	out	-65	-63	-54	-45	-40

*) Calculated based on the determined HHV (see Table 1)

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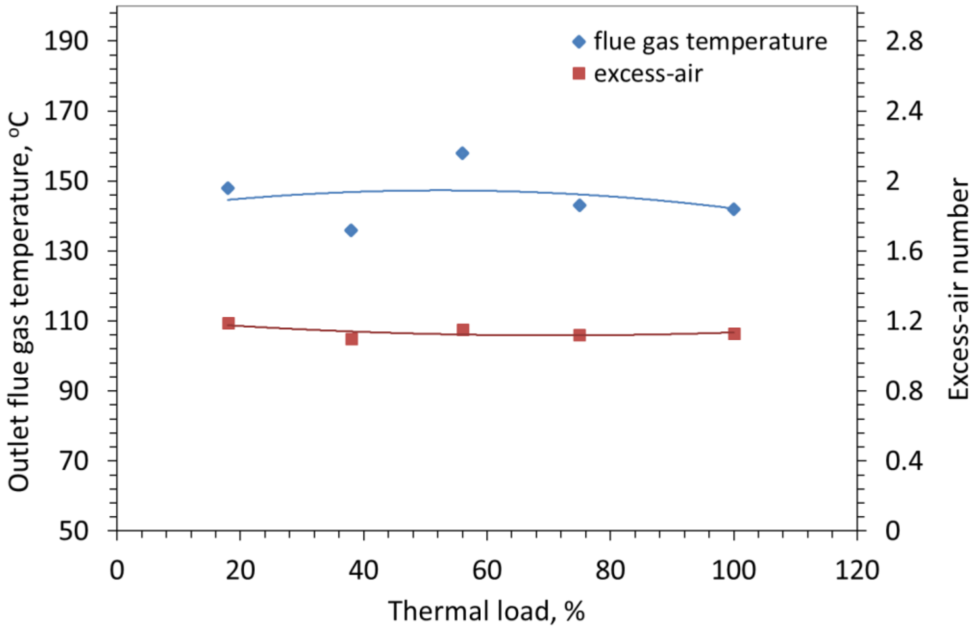

Fig. 5. Outlet flue gas temperature and the excess-air ratio vs. thermal load of the facility.

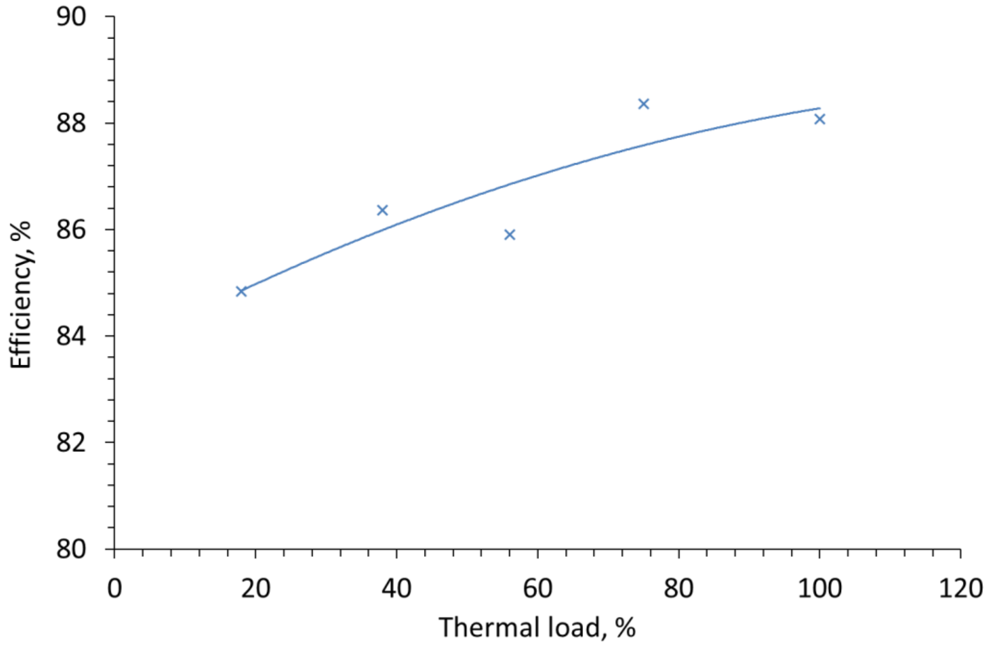

Fig. 6. Thermal efficiency of the installation depending on the thermal load of the facility.

Obtained results on emissions of CO, CO_2, SO_2 and NO_x expressed at 6%O_2 content in flue gas are presented in Fig. 7. The control capabilities of the installation offered the possibility to maintain the stable operating parameters during thermal utilization at any tested heat load. Stabilized oxygen content in flue gas allowed to provide the conditions to burn meat meal with a minimum incomplete combustion loss. This was represented by low emission of CO being at an average level of approximately 24 mg/Nm^3. The emission level of SO_2 is quite high, from 116 to 233 mg/Nm^3, and requires further steps to be taken to meet current limits [53]. One

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option to decrease the SO_2 concentrations, as suggested in [27], is to carry out the process in a strongly oxidizing atmosphere (i.e. 12-17% O_2). Another possibility is to further optimize the process with a support of three-dimensional CFD simulations, allowing to predict temperature distribution, evolution and diffusion of particular compounds, pressure and velocity fields [54, 55].

The study revealed that an increase in a facility load did not significantly affect NO_x concentration, which remained at the level between 270 and 330 mg/Nm^3. This was due to nearly constant temperature regardless of the variations in a thermal load, as well as to the small fluctuations in an excess-air number. The obtained NO_x emission may be considered satisfactory compared to those reported elsewhere [26].

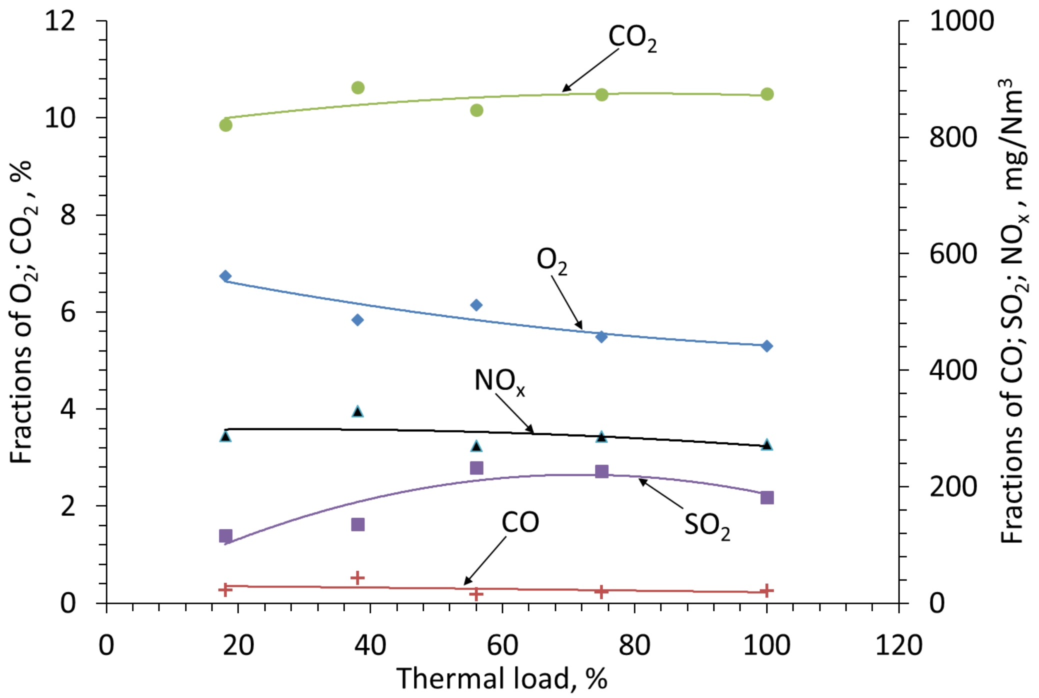

Fig. 7. Flue gas composition vs. thermal load of the facility.

4.2. Ash characterization

Composition of ash remained after the meal incineration is shown in Table 3. It should be noted that the ash analysis refers to an average sample taken from the discharge hopper of a fluidized bed boiler. As can be seen, the derived ash is rich in macronutrients, such as P_2O_5 (15.7%) and CaO (22.01%). It includes less percentages of other valuable compounds in form of oxides, i.e., K_2O, Na_2O, MgO etc.

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Table 3
Ultimate analysis of MBM-derived ash.

Ash (%*db*)	22.04
Composition (%*ash*, *db*)	
SiO_2	2.81
Al_2O_3	1.54
Fe_2O_3	0.50
CaO	22.01
$5CaO_3Al_2O_3$	6.44
K_2SO_4	13.02
$CaSO_4O_5H_2O$	22.37
MgO	2.09
Na_2O	0.36
K_2O	1.68
$CaSO_4$	11.48
P_2O_5	15.70

The contents of particulate matter in the bottom and fly ashes are shown in Fig 8. The fraction of combustible solids in a bottom ash discharged from the fluidized bed was very low and did not exceed the level of 0.025% within the examined range of installation load. It thus may be assumed that the problem with unburnt carbon in this case does not exist. The content of unburnt char particles in fly ash ranged between 1.0 and 1.5%. A significant increase in unburnt carbon percentage in fly ash is to a large extent related to the physical structure of ash particulates. They are characterized by low apparent density, varying within the range between 0.2 and 0.3 g/m^3 [47], and by highly developed structure similar to that of a soot. These parameters greatly contribute to driving considerable amounts of char particles out of the fluidized bed chamber.

It shall be noted that the vast advantage of the facility, alongside the good operation parameters and satisfactory emission levels, is its relatively large capacity. To date, besides the trials of co-combustion of MBM with coal or natural gas in large–scale units (of thermal outputs of 0.5 MW and more) [31,37], the thermal utilization of animal waste involves rather small- and medium-scale systems. These include the pilot-scale fluidized bed combustors of ~50 kW capacity (i.e. several kilograms of a fuel per hour), as those reported by Gulyurtlu et al. [26] (up to 16.5 kg/h) and Lopes et al. [28] (15-16 kg/h). Similar fuel feed rate (18 kg/h) was applied to convert MBM into bio-oil in a pilot scale pyrolysis fluidized bed [22]. Dedicated full technical scale facilities are still under development. Bujak [35] demonstrated the installation with rotary kiln of capacity 700 kg/h for continuous waste treatment, however limited to 70%wt maximum humidity of a feedstock. The industrial scale installation for two-stage combustion of animal and post-slaughter waste with the loading capacity of 1000 kg/h was shown by Poskrobko [27]. The presented installation, operated at the feed rate up to ~3000 kg/h fuel with the maximum moisture content of 90%wt, thus offers the possibility to treat large streams of more difficult

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alternative fuels. The implemented technology has thereby proved its potential in supporting effective waste management and renewable energy sector.

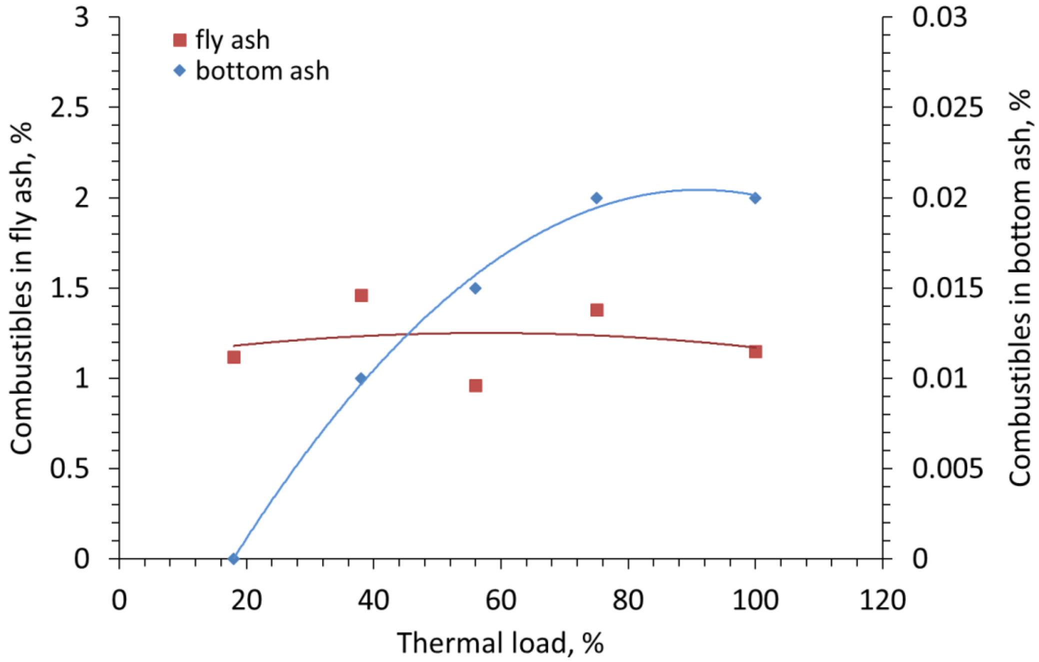

Fig. 8. Contents of combustibles in fly and bottom ashes vs. thermal load of the facility.

5. Conclusions

Process stabilization of thermal destruction of biofuels, particularly those of high ash contents, is a key issue in reducing environmentally harmful emissions. In the paper we presented the two-stage technology for waste utilization, including in a first place the meat-and-bone meal, which offers the fuel incineration with a maximum available thermal efficiency and the minimum levels of contaminants, including emitted gaseous components and unburned carbon in fly ash. The study provides an analysis of the process of animal meal utilization in a pilot-scale installation with an output of 12MW. The facility performance was tested under four various thermal inputs. The carried out measurements fully confirmed that the developed technology is universal, allowing to incinerate any waste, as well as any mixtures of waste and biomass. Simultaneously, the thermal decomposition and combustion of waste using the method provide the conversion of chemical energy into useful heat and electricity with an optimum thermodynamic efficiency of a system. This varied between 84.8 and 88.4%, depending on a thermal input.

Stable oxygen content in a flue gas has supported the animal meal incineration with a minimum level of an incomplete combustion loss, evidenced by low CO emission of approximately 24 mg/Nm^3. The emission of SO_2 was at the level of 116÷233 mg/Nm^3 and requires additional steps to be taken to meet the current emission limits. It is vital that despite the change in a system load, a constant level of temperature in a combustion zone of a fluidized bed chamber was achieved. Owing to this and, additionally, to a consistent excess-air number, an increase in a quantity of utilized waste did not affect the NO_x emissions allowing to maintain its constant level ranged from 270 to 330 mg/Nm^3. It may also be stated that the technology is

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promising in terms of combustible content in the bottom and fly ashes. The content of unburned combustibles is very low, particularly in the case of a bottom ash discharged from a fluidized bed chamber, which appeared to be independent on a facility load and remained below 0.025%. In the case of fly ash this content fluctuated between 1.0 and 1.5 %.

Another aspect is the numerical modeling of ash deposition on the boiler walls, corrosion and the variation in the system efficiency. The presented installation operates continuously and complies with the requirements without significant loss of efficiency. However, further research is on the horizon, involving the numerical calculations based on the mass and thermal-FSI modeling, which will start from modeling the single-particle phenomena [56,57] through incorporate fouling phenomenon, deterioration of heat transfer and loss of boiler service life [58]. Similar computations are currently carried out for pulverized fuel boilers [59], and fluidized bed boilers [60].

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