

1 Thermal utilization of meat-and-bone meal using the rotary kiln pyrolyzer 2 and the fluidized bed boiler – the performance of pilot-scale installation

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17
18 **Abstract:** Thermal utilization of meat-and-bone meal (MBM) is subject to stringent
19 regulations that are meant to provide elimination of any potential pathogens. Incineration as
20 well as other possible routes for thermal conversion of MBM are still at the research state. The
21 universal technology was developed that allows to combust various types of waste organic
22 materials, including animal waste, municipal solid waste and sludge, mixed at any ratio with
23 different types of biomass. It provides the possibility to utilize the waste-and-biomass fuel
24 blends of up to 90% wt of moisture content, while maintaining the allowable pollutant emissions
25 and soil contamination. This regards mainly NO_x, SO₂, HCl and VOC. Contrary to the typical
26 large scale grate boilers used for waste burning, the developed operating pilot-scale plant with
27 a capacity of 12MW offers the complete combustion of MBM, resulting in a flue gas which is
28 proved to be free of flammable gaseous components and sooty particles in slag and fly ash. The
29 thermal decomposition and combustion of waste using this technology ensures thermal
30 conversion of chemical energy contained in waste and biomass. The efficiency of the prototype
31 installation varied between 84.8 and 88.4% depending on the facility load.

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

33 1. Introduction

34 The worldwide trends to move towards reducing carbon footprint and to promote
35 sustainable development has led to an increased focus on biomass as an alternative energy
36 source [1]. Apart from commonly used woody biomass [2], of interest is also waste biomass of
37 different kind, including large variety of organic by-products from industry and agriculture, as
38 well as municipal solid waste or sewage sludge. Biomass is the subject of extensive studies in
39 terms of various conversion technologies. Even though the direct combustion still remains the
40 basic one [3], other processes allowing to transform organic materials into useful gaseous and
41 liquid calorific products has also been considered, including pyrolysis [4-6] and gasification [6-
42 10]. Another possible pathway for environmentally beneficial and economically justified
43 utilization of organic wastes that may contribute to meet the target of increased share of biomass
44 in energy supply, is the anaerobic digestion [11,12], which consists in breaking the feedstock
45 down to biogas that can be directly used in combined heat and power systems.

46 The efficiency of conversion process and system operation safety however appear to be a
47 technical challenge. This stems from the variety of composition and structure of biomass that
48 largely determine the course of physicochemical processes [13,14]. Therefore, numerous
49 research are carried out on the pretreatment processes to enhance the biomass properties
50 [15,16], and thereby to improve its suitability for further use in energy generation [3,17]. This
51 also applies to a large extent to sewage sludge, which needs special treatment due to high
52 moisture and ash contents, the presence of pathogens and organic contaminants [18].

53 Considerable proportion of alternative fuels in the energy sector nowadays is a group of
54 waste from meat industry. Constantly increasing worldwide production of meat translates into
55 the increased amounts of animal waste that require management. This refers to meat-and-bone
56 meal (MBM) [19], poultry litter [20] and feathers [21]. The major attention and analyses has
57 been dedicated to MBM, as due to the risk of the Bovine Spongiform Encephalopathy (BSE)
58 that arised in 1980s and 1990s this type of waste started being considered as hazardous [19,22-
59 24]. Since then, implemented regulations, restricted its use as an additive to cattle feed and
60 direct disposal in landfilling as natural fertilizer [25,26]. Addressing the need for
61 environmentally safe destruction of this type of waste, the efforts have been undertaken to
62 develop efficient thermochemical technologies that would allow its energy utilization with low
63 emissions [19,27-30]. Since MBM is classified as harmful to environment and human health,
64 its thermal utilization requires special processing conditions to ensure destruction of any
65 pathogens, namely, the relatively high temperatures (above 800°C) and the appropriate
66 residence time. Therefore it used to be incinerated in cement kilns that are able to meet these
67 requirements [31-34]. The rotary kiln technology for the on-site burning of animal waste in the
68 meat-processing plant has also been implemented [35]. MBM is also considered as an
69 alternative fuel in combustion and co-combustion with other solid fuels. This include the
70 combustion in grate boilers [36], as well as in fluidized bed combustors [22,26,31,37,38], which
71 offer high process temperatures, long residence times and flexibility in dealing with fuels of
72 various nature [26,39-41]. Clearly, the composition of MBM differs depending on the origin of
73 raw material, however it has appeared to feature good calorific value as compared to
74 conventional fuels. The gross calorific value of MBM has been reported to range typically
75 between about 14.2 and 19.2 MJ/kg [6,26,33,42,43], thereby giving an average level of about
76 16.6 MJ/kg. Other study shows even the value of 30 MJ/kg [31]. On the other hand, the
77 problems may arise during MBM combustion due to its chemical composition, characterized
78 of relatively high contents of minerals, including nitrogen, phosphorous, sulphur, calcium and
79 potassium, as well as trace metals. This may specifically lead to boiler operation problems
80 related with fouling and corrosion [42,44], bed agglomeration [28] and to an increase in
81 nitrogen oxides emissions [42]. In this context, particularly the fluidized bed combustion has
82 been considered to be beneficial as providing low NO_x emissions and giving the possibility to
83 combust fuel with high efficiency [37].

84 The key aspect in combustion of a waste fuel such as MBM is to ensure the process
85 stability, which allows to keep the emission levels of SO₂, NO_x, HCl and CO possibly low
86 [27,45]. The analyses of co-combustion of MBM with other solid fuels indicate that the levels
87 of SO₂, CO and NO_x depend on the fraction of MBM in a combusted fuel blend. Research on
88 combustion of MBM with brown coal in a pilot-scale fluidized bed furnace has shown the
89 reduction in emissions of SO₂ and NO_x with an increase in MBM amounts in a blend [26]. The

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

104 Additional issue is that MBM ashes poses valuable properties. Being free from potentially
105 harmful pathogens and, primarily, rich with macronutrients such as phosphorous, calcium,
106 magnesium and potassium compounds [28,42,43], they may serve as a natural fertilizer,
107 allowing to substitute the synthetic one. This seems to be advantageous noting in particular the
108 increasing agricultural production that involves an increasing demand for phosphate fertilizers
109 [46]. In this way, the combustion of MBM as the save disposal method, contributes to the idea
110 of sustainable development and to the reduction of pollutant emissions.

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

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

126 2. The system details

127
128 The described herein technology [51,52] provides the possibility to incinerate not only the
129 animal waste, but also other types of organic waste such as sewage sludge, municipal solid
130 waste and biomass of different kind. It allows to utilize the biodegradable waste of the overall
131 moisture content up to 90%wt and whilst preserving the maximum permitted levels of the
132 atmosphere and soil contamination.

133 The energy recycling of hazardous and non-hazardous waste implementing the two-stage
134 technology that use the rotary reactor to pyrolyze the feedstock and the fluidized bed chamber
135 to combust the pyrolysis gas and the remaining char, ensures thermal conversion of waste with
136 flue gases free from any environmentally harmful dioxins and furans. The combustion process
137 is supplemented with the liquid or gas fuel, which is added in an amount ranging from 0.015 to
138 0.070 kg per kilogram of a feedstock, depending on its moisture content. The physical structure
139 of waste to be utilized may be solid, as well as in form of a pulp or a dense slurry. In each case,
140 the technology provides the optimum thermal effect. In view of this, the presented
141 waste/biomass-to-energy technology allows to obtain the maximum levels of thermal efficiency
142 and protection to the environment and human health and, additionally, the optimum economical
143 effect.

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

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

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

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

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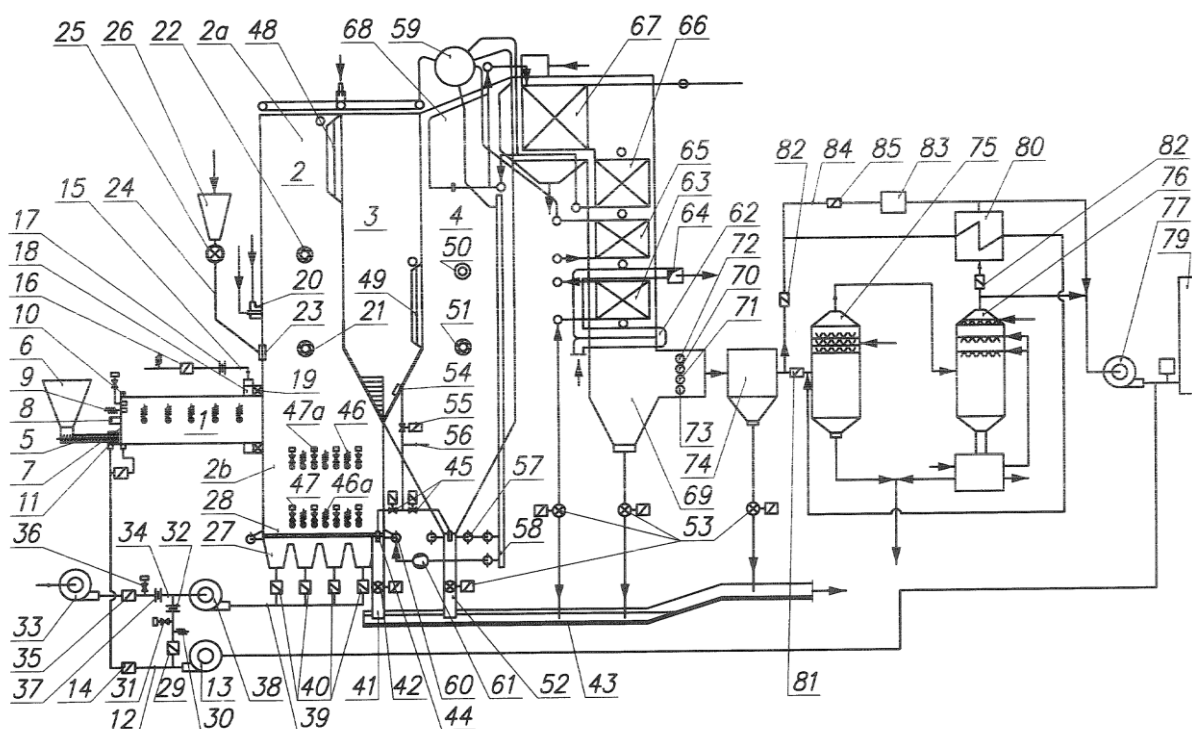


Fig. 1. The schematic of the installation for thermal utilization of meat-and-bone meal.

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°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

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

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

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

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

232 As aforementioned, a fluidized bed is generated in a chamber hopper as a result of a
233 fluidizing gas flow i.e., the air/flue gas mixtures with the volumetric ratios ranging from
234 10%/90% to 90%/10%, through the inert bed material. This is composed of a mixture of silica
235 sand and properly grinded slag, which is blended with limestone in its mass fraction ranging
236 from 2 to 80 %, depending on the sulphur, chlorine and the fixed carbon contents in a fuel. The
237 material is fed into the fluidized bed chamber periodically through the inlet window (23) from
238 the storage tank (26) and through the duct (24) with a rotary feeder (25).

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

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

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

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

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

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

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

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306 **3. Pilot-scale installation of 12 MW capacity**

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



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Fig. 2. General view of the installation.



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

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



Fig. 4. Fluidized bed chamber.

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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

353 of 4-6 bars and temperature of 250-300°C, depending on the technological needs. At the start-
354 up stage, namely at the stage needed to establish the temperature balance in the system, the light
355 heating oil is used. When the assumed temperature in a rotary pyrolysis reactor is achieved, the
356 ignition fuelling system is switched from heating oil to heated animal fat at a temperature of
357 80°C. This type of kindling fuel is classified as an alternative fuel from renewable resources,
358 and thereby the total thermal energy generated by the system is regarded as renewable energy.
359 The installation provides high availability and reliability. The minimum quantity of meal
360 required for operating the system amounts to 20% of a nominal capacity, whereas the maximum
361 corresponds to the nominal capacity of 120%.

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

366 ***3.1. Meal supply system***

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

374 ***3.2. Drying and thermal decomposition***

375 The processes of drying and devolatilization take place in a rotary kiln reactor with a
376 diameter of 1200 mm. Its chamber is equipped with specially designed material lifters, which
377 are distributed alternately in three sectors along the chamber length. The chamber rotates at 0.5-
378 5 rpm and is inclined by 2-3° towards an outlet. It is made from an uncooled pipe with a
379 refractory lining inside and closed by a sealed faceplate from the front. In a faceplate there is
380 installed an oil burner, equipped with the systems of ignition and flame control. There is also
381 mounted the charging device of meal and sorbent. The quantity of liquid fuel to be combusted
382 is automatically adjusted, so as the temperature inside the chamber remains within range
383 between 850 and 1100°C, according to the type of animal meal being utilized. The amount of
384 air supplied to the rotary kiln pyrolyzer depends on a supplementary fuel quantity and is set to
385 ensure the complete combustion and nearly zero content of oxygen in the drying and pyrolysis
386 zones. The process is carried out in a reductive atmosphere to avoid burning and heat release.
387 The rotary chamber is directly connected with a fluidized bed chamber via a swirling element
388 for primary air, which is necessary to partially combust evolved pyrolysis gas.

389 ***3.3. Combustion***

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

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

405 **4. Test results of 12 MW facility**

406 The meal blend used to analyze combustion in the prototype installation was sourced from
 407 the lot feed material that was available during the day of testing. The results of proximate and
 408 ultimate analysis of examined blend are presented in Table 1.
 409

410 **Table 1**

411 Chemical composition and physical properties of examined MBM blend.

	Standard	
<i>Proximate analysis (% as received)</i>		
Moisture	2.53	PN-G-04511:1980
Ash	21.26	PN-ISO-1171:2002
Volatile matter	67.82	
Fixed carbon	8.39	
<i>Ultimate analysis (% daf)</i>		
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	

412 **4.1. Balance and efficiency measurements**

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



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

- 418 ➤ meat meal feed rate B , kg/h,
- 419 ➤ temperature inside the rotary pyrolyzer, °C (5 measurement points T_k , $k=1 \dots 5$, along the
420 rotary axis),
- 421 ➤ inlet/outlet negative pressure p_k in a reactor chamber, Pa,
- 422 ➤ pyrolysis gas composition at the pyrolyzer outlet, %,
- 423 ➤ temperature in the upper zone of fluidized bed chamber T_f , °C,
- 424 ➤ flue gas temperature ($T_{ex,out}$, °C) and composition (%) at the outlet of flue pipe connector
425 of heat recovery boiler,
- 426 ➤ steam output D_s , kg/h,
- 427 ➤ steam pressure p_s , bar,
- 428 ➤ steam temperature T_s , °C,
- 429 ➤ supply water temperature T_{cw} °C,
- 430 ➤ supply water pressure p_{cw} , bar,
- 431 ➤ combustible content in ash C_a , %.

432

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

437 Experimental tests were performed for various thermal loads, corresponding to the meal
438 feed rate (B) of 500, 1000, 1500, 2000 and 2650 kilograms per hour. The balance calculations
439 were made based on the arithmetic means of the measurements. These average parameter values
440 for investigated heat loads are summarized in Table 2. Thermal efficiency of the installation
441 was determined by means of Direct Method. An outlet excess air was calculated based on the
442 measured CO₂ content in a flue gas and its estimated maximum value that may result from
443 biogas combustion (this amounts to CO_{2max} = 1.7%).

444

445 Figures 5 and 6 show changes in the outlet flue gas temperature and the thermal system
446 efficiency, depending on a given thermal load. As the results show, the possibility of fine
447 adjustment of supplied air in accordance with a demand allows to optimize the combustion
448 process so as to minimize the losses of incomplete combustion. Maintaining relatively constant
449 temperature of exiting flue gas (at about 145°C on average) and an excess-air number (at
450 $\lambda \sim 1.1$) enables to keep the system efficiency at the defined level, close to the optimum one.

451

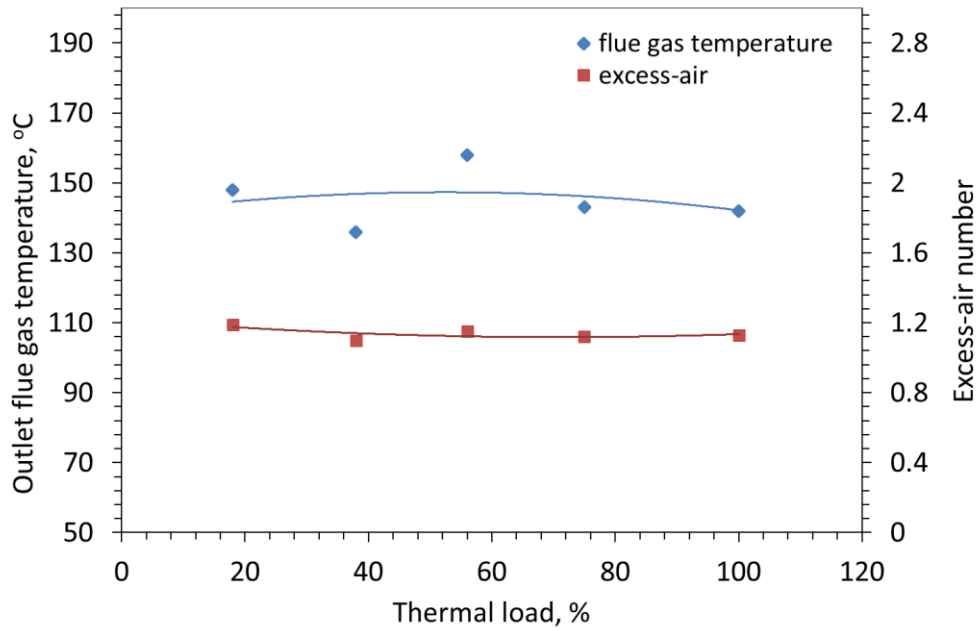
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Table 2

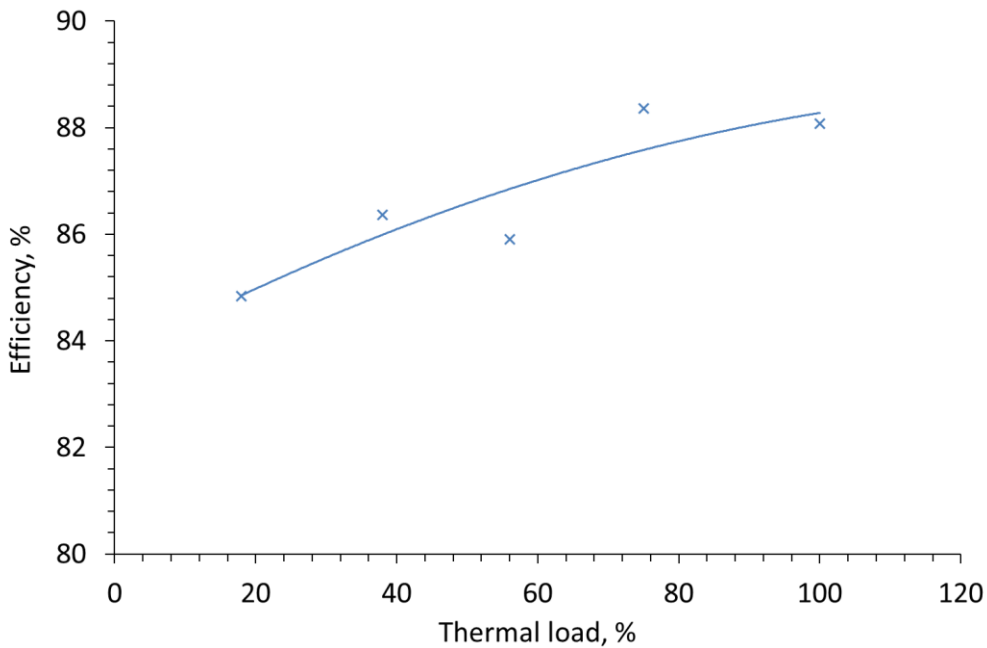
Results of measurements and balance calculations for the facility.

		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
<i>Steam parameters:</i>						
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, °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
<i>Flue gas parameters:</i>						
Outlet temperature, °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	$4.05 \cdot 10^{-3}$	$4.74 \cdot 10^{-3}$	$8.15 \cdot 10^{-3}$	$7.91 \cdot 10^{-3}$	$6.35 \cdot 10^{-3}$
	NO _x	$13.95 \cdot 10^{-3}$	$16.05 \cdot 10^{-3}$	$13.12 \cdot 10^{-3}$	$13.94 \cdot 10^{-3}$	$13.25 \cdot 10^{-3}$
<i>Parameters in a rotary pyrolysis reactor:</i>						
Temperature, °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

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



456
457
458 **Fig. 5.** Outlet flue gas temperature and the excess-air ratio vs. thermal load of the facility.
459



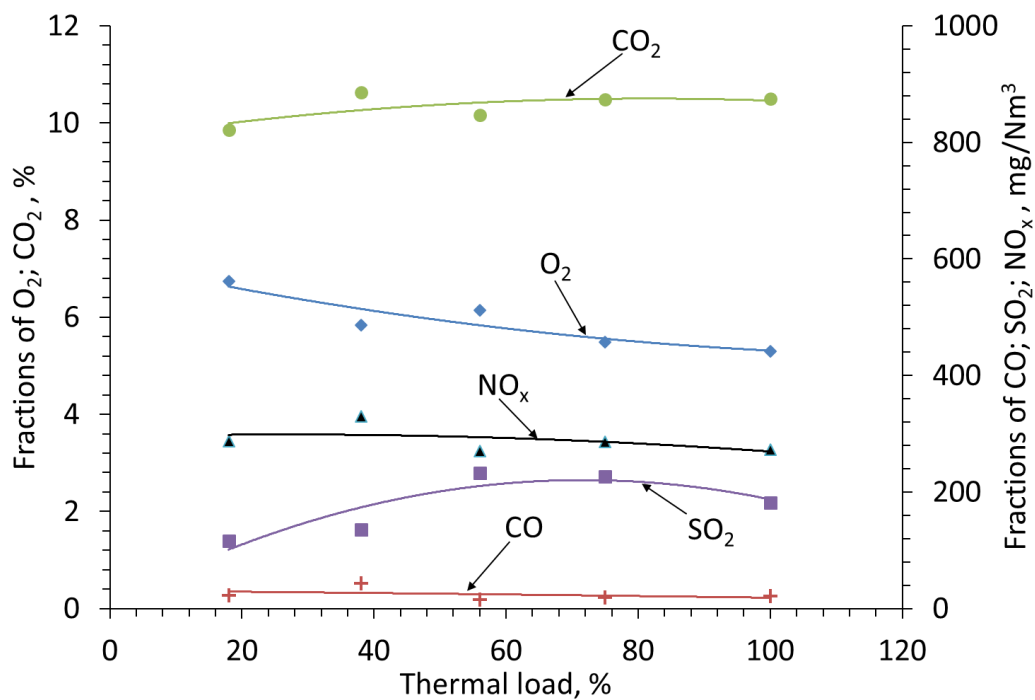
460
461
462 **Fig. 6.** Thermal efficiency of the installation depending on the thermal load of the facility.
463

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470
Obtained results on emissions of CO, CO₂, SO₂ and NO_x expressed at 6% O₂ 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/Nm³. The emission level of SO₂ is quite high, from 116 to 233 mg/Nm³, and requires further steps to be taken to meet current limits [53]. One

471 option to decrease the SO₂ concentrations, as suggested in [27], is to carry out the process in a
472 strongly oxidizing atmosphere (i.e. 12-17% O₂). Another possibility is to further optimize the
473 process with a support of three-dimensional CFD simulations, allowing to predict temperature
474 distribution, evolution and diffusion of particular compounds, pressure and velocity fields [54,
475 55].

476 The study revealed that an increase in a facility load did not significantly affect NO_x
477 concentration, which remained at the level between 270 and 330 mg/Nm³. This was due to
478 nearly constant temperature regardless of the variations in a thermal load, as well as to the small
479 fluctuations in an excess-air number. The obtained NO_x emission may be considered
480 satisfactory compared to those reported elsewhere [26].

481



482

483

484

485

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

486

4.2. Ash characterization

487 Composition of ash remained after the meal incineration is shown in Table 3. It should be noted
488 that the ash analysis refers to an average sample taken from the discharge hopper of a fluidized
489 bed boiler. As can be seen, the derived ash is rich in macronutrients, such as P₂O₅ (15.7%) and
490 CaO (22.01%). It includes less percentages of other valuable compounds in form of oxides, i.e.,
491 K₂O, Na₂O, MgO etc.

492

493

494 **Table 3**

495 Ultimate analysis of MBM-derived ash.

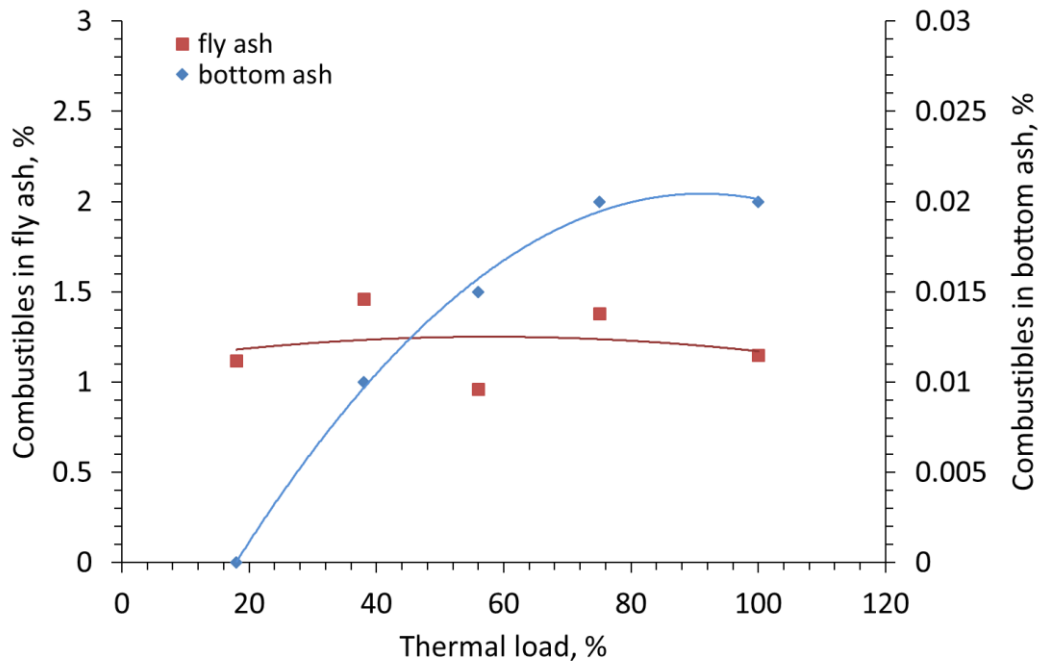
Ash (%db)	22.04
<i>Composition (%ash, db)</i>	
SiO ₂	2.81
Al ₂ O ₃	1.54
Fe ₂ O ₃	0.50
CaO	22.01
5CaO ₃ Al ₂ O ₃	6.44
K ₂ SO ₄	13.02
CaSO ₄ O ₅ H ₂ O	22.37
MgO	2.09
Na ₂ O	0.36
K ₂ O	1.68
CaSO ₄	11.48
P ₂ O ₅	15.70

496

497 The contents of particulate matter in the bottom and fly ashes are shown in Fig 8. The
 498 fraction of combustible solids in a bottom ash discharged from the fluidized bed was very low
 499 and did not exceed the level of 0.025% within the examined range of installation load. It thus
 500 may be assumed that the problem with unburnt carbon in this case does not exist. The content
 501 of unburnt char particles in fly ash ranged between 1.0 and 1.5%. A significant increase in
 502 unburnt carbon percentage in fly ash is to a large extent related to the physical structure of ash
 503 particulates. They are characterized by low apparent density, varying within the range between
 504 0.2 and 0.3 g/m³ [47], and by highly developed structure similar to that of a soot. These
 505 parameters greatly contribute to driving considerable amounts of char particles out of the
 506 fluidized bed chamber.

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

521 alternative fuels. The implemented technology has thereby proved its potential in supporting
522 effective waste management and renewable energy sector.
523



524
525 **Fig. 8.** Contents of combustibles in fly and bottom ashes vs. thermal load of the facility.
526

527 5. Conclusions

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

541 Stable oxygen content in a flue gas has supported the animal meal incineration with
542 a minimum level of an incomplete combustion loss, evidenced by low CO emission of
543 approximately 24 mg/Nm³. The emission of SO₂ was at the level of 116÷233 mg/Nm³ and
544 requires additional steps to be taken to meet the current emission limits. It is vital that despite
545 the change in a system load, a constant level of temperature in a combustion zone of a fluidized
546 bed chamber was achieved. Owing to this and, additionally, to a consistent excess-air number,
547 an increase in a quantity of utilized waste did not affect the NO_x emissions allowing to maintain
548 its constant level ranged from 270 to 330 mg/Nm³. It may also be stated that the technology is

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

553 Another aspect is the numerical modeling of ash deposition on the boiler walls, corrosion
554 and the variation in the system efficiency. The presented installation operates continuously and
555 complies with the requirements without significant loss of efficiency. However, further research
556 is on the horizon, involving the numerical calculations based on the mass and thermal-FSI
557 modeling, which will start from modeling the single-particle phenomena [56,57] through
558 incorporate fouling phenomenon, deterioration of heat transfer and loss of boiler service life
559 [58]. Similar computations are currently carried out for pulverized fuel boilers [59], and
560 fluidized bed boilers [60].

561

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