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Gasification of Biomass Residuals – Industrial Perspective and Long-Term Practice

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An insight into long term operation of an industrial feather gasification facility is presented. The paper discusses the energy balance of the system and its efficiency, the main operational problems encountered during four years of operation of the plant and proposed solutions. The analysis of plant's long term performance showed that the overall efficiency of the system is 68 % while the efficiency of gasification process solely accounts for approximately 96 %. Further analysis showed that increasing plant's overall efficiency is possible through further dewatering of the fuel and investing in a more efficient recovery boiler. The most vital operational problems encountered during plant's operation involve boiler slagging and high emission of nitrogen oxides. It is shown that most of the problems occurring during operation of the plant are associated to the composition of the fuel, which contains high amounts of nitrogen, sulphur, chlorine, alkali metals and alkaline earth metals in comparison to popular woody biomass.

1. Introduction

Poultry feathers produced in industrial slaughterhouses are a moist and troublesome waste produced in large quantities (Kwiatkowski et al. 2013a). Growing demand and consumption of poultry meat observed worldwide in recent years led to rapid increase of the waste stream. All the biggest world producers of chicken and turkey meat, i.e., United States, China, Brazil and European Union, have increased their production by more than 9% over the last three years (USDA, 2013). Ecologically and economically feasible management of waste feathers is a growing issue, especially in the context of recent outbreak of avian influenza which led to restrictions in bone meal production.

Since the waste is moist and has a very low calorific value, it is not suitable for authothermal incineration without addition of auxiliary fuels (Arena, 2012). Instead, over the past 4 years, industrial gasification has proven to be a reliable and feasible method of thermal conversion of waste feathers. The Olsztyn gasifier (Poland) is a 3.2 MWth feather-fired heating unit that works efficiently and meets environmental standards. The feathers are gasified in an updraft, counter-current, fixed-bed gasifier and the produced syngas is burned in the adjacent combustion chamber. The produced flue gas is directed into a subsequent energy recovery boiler and then into a flue gas cleaning system based on semi-dry desulphurisation and textile filters.

Over the years of operation the unit experienced several maintenance problems which were consecutively solved or are subject of continuing research. The problems that focus most of attention involve creation and deposition of slagged solid residuals in the recovery boiler and conversion of fuel-bound nitrogen into nitrogen oxides. In the present paper we present an insight into long-term operation of the feather gasification technology, especially in the context of energy conversion efficiency and encountered operation problems.

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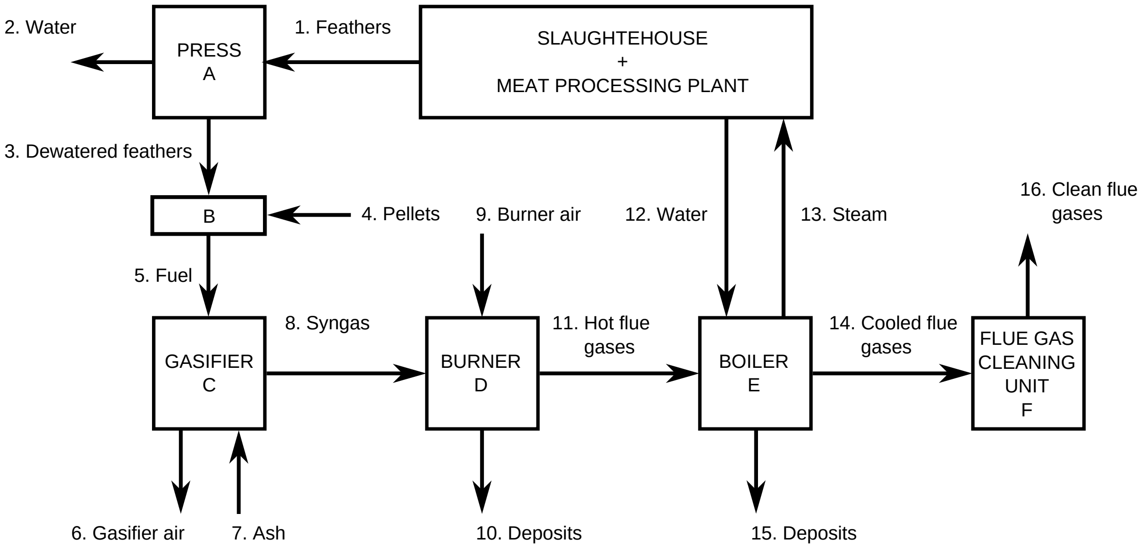

Figure 1: Schematic diagram of the Olsztyn gasification plant. Source: Kwiatkowski et al, 2013

2. Materials and methods

2.1 Gasification unit

Gasification is a process of thermal conversion of solid organic matter into a flammable gas consisting of mostly hydrogen, carbon oxide, methane and carbon dioxide. The principles of the gasification process well accurately described by Cuoci et al., 2009.

The analysed gasification plant is located in Olsztyn, north-east Poland. The system is integrated with an industrial slaughterhouse and transforms approximately 10 kt/y of wet poultry feathers into heat. Before commissioning of the analysed gasification unit, the slaughterhouse was supplied with heat produced in a conventional hard coal boiler and paid a specialised waste management company to utilise the feathers. The boiler was replaced by the waste gasification plant in 2009, allowing the slaughterhouse to recover energy from the waste produced in the process. The new gasification plant produces a stable stream of process steam, while the peak requirements of the slaughterhouse are satisfied by an additional natural gas boiler.

Figure 1 contains a schematic diagram of the material flow between the slaughterhouse and elements of the gasification plant. The entire gasification system consists of: a hydraulic lift necessary for unloading the fuel from containers, a press (A), an air-tight loading system (B), an updraft gasification reactor supplied with air (C), a syngas combustion chamber (D), a heat recovery boiler (E), a flue gas conditioning system including semi-dry desulphurisation and textile filters (F), and a chimney (for explanation of symbols see Figure 1).

The gasifier is an updraft fixed-bed cylindrical reactor (Dudyński, 2000) equipped with a complex multi-layer and multi-point hot air injection system (Dudyński, 2008), which allows for precise control over the process stability and enhances its efficiency. The air supply system prevents the unburned material from mixing with the ash and the fluids from condensing at the bottom of the gasifier. For more details on the design of the gasifier see Dudyński et al., 2012. The reactor is followed by a combustion chamber, where air and syngas are supplied separately. The chamber is a vertical cylinder with a system of swirl-enhancing air inlets installed in the top surface and a flue gas outlet located near the bottom of the cylindrical side wall. After leaving the combustion chamber the hot flue gas with an average temperature of 850 °C is directed into a recovery boiler.

2.2 Fuel

The fuel consists of turkey and chicken feathers mixed with additional meat processing remains (approximately 10 %wt), such as entrails, bones, beaks, claws, carcasses and some amount of stones from stomachs. The material is challenging for further processing, mainly due to its entangling ability and high initial water content of approximately 70 %. The average calorific value of such a fuel is only 5.77 MJ/kg, which is not sufficient enough for the gasification process to self-sustain and therefore before

Table 1: Composition of feathers from the Olsztyn slaughterhouse compared to the composition of wood chips

	Turkey feathers	Wood chips
Proximate analysis [wt%, as delivered]		
Moisture	51.6	10.0
Volatiles	42.7	69.5
Fixed carbon	5.0	20.0
Ash	0.7	0.5
Ultimate analysis [wt%, moisture free]		
C	61.77	51.4
H	5.68	6.1
O	11.86	41.6
N	18.53	0.9
S	2.13	0.0
Cl	0.12	0.0
Na	0.06	nd
K	0.04	nd
Ca	0.21	nd
Calorific value [MJ/kg, as received]		
HHV	7.90	18.4
LHV	5.31	17.0

introducing the fuel into the reactor its moisture content has to be reduced to approximately 50 %. The waste contains high amount of nitrogen (18.53 % dry mass) and relatively high amount of sulphur (2.13 % d. m.), chlorine (0.12 % d. m.) and sodium (0.06 % d. m.) in comparison to popular woody biomass. For detailed composition of the fuel see Table 1. As it will be shown later, most of the problems occurring during operation of the plant are associated to the fuel composition.

2.3 Material flow and energy balance

Mass, component and energy balance calculations were performed for the system basing on the data collected at the plant and the chemical composition of analysed samples of fuel, bottom ash, fireside deposits, flue gas cleaning waste and flue gas.

The mass and energy calculations were performed on the basis of data obtained for 1 week of continuous and representative operation of the plant, namely 1-7 March 2011. Detailed assumptions and method for performing the calculations were described in Kwiatkowski et al., 2013a. The material flow data is visualised in a form of a Sankey graph in Figure 2.

2.4 XRF analysis

In order to determine the mechanism of creation and deposition of slagged solid residuals in the combustion chamber and the recovery boiler, the fuel and the deposits were analysed using standard analytic methods. The analysis of fuels was performed in accordance with current Polish and ISO technical standards. Moisture, ash and volatile contents were determined by means of thermogravimetric analysis, while the ultimate analysis was performed using infrared spectroscopy. Calorific values were determined using bomb calorimeters.

The samples of fireside deposits were milled and then pressed into pellets (47 mm in diameter) with addition of a wax binder (1:9). The pellets were analyzed using a WD-XRF spectrometer equipped with a rhodium tube and both proportional and scintillation counters. The linear intensity range was over 10 million cps. All analyses were conducted at maximum 50 keV and 50 mA. A non-standard analysis was used to determine the concentrations of the measured elements.

2.5 CFD modelling

During the initial period of operation of the gasification unit, the emission levels of nitrogen oxides were very close to the limit values set out by the European Commission, while the consumption of the urea solution used in the Selective Non Catalytic Reduction process was very high (20 dm^3/h of 30% solution) and generated significant costs. In order to determine the mechanism of formation of nitrogen oxides we have performed numerical simulations of the flow occurring in the combustion chamber and changed the position of the urea dosing system.

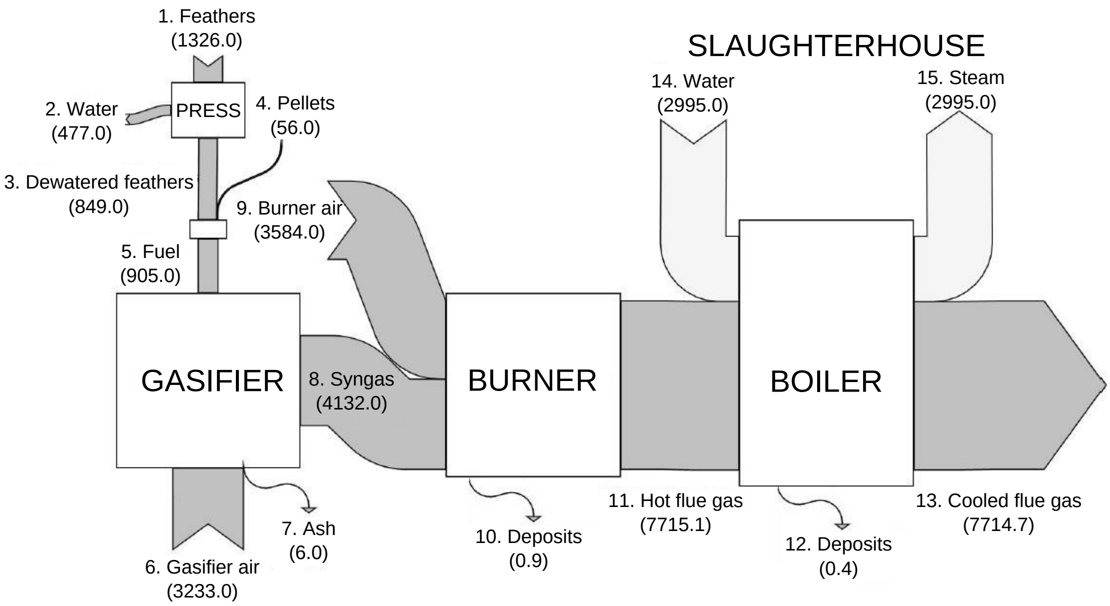

Figure 2 Sankey graph for the analysed gasification unit [kg/h]. Source: Kwiatkowski et al, 2013a

Three-dimensional Unsteady RANS simulations were performed using the commercial CFD code ANSYS Fluent 13.0. Turbulence was modelled with standard *k* –ε closure. During simulations the following were simultaneously computed: turbulent flow, energy transfer, radiation and non-premixed combustion. In the post-processing stage the pollutants emission was calculated. Detailed description of the model is provided in Kwiatkowski et al., 2013b.

3. Results

3.1 Performance

The results of the mass and energy balance calculations are summarised in Table 2 and discussed in detail by Kwiatkowski et al, 2013a. The overall efficiency of the system during the analysed week, when the ambient temperature was on average 0 °C, equalled to 68 %. In the moderate climate of Poland the higher monthly average temperatures oscillate around 15 °C and in that case the efficiency of the system equals to approximately 70 %. The efficiency of energy conversion in the gasifier solely accounts for 96 % on average. Analysis of the heat losses of the system shows that further improvement in the overall process efficiency can be achieved primarily by improving the heat exchange in the recovery boiler and further dewatering of the fuel. However, given the costs of such improvements, further investments aiming at increasing system's overall efficiency are not economically justified.

The quality of the produced syngas is rather low. Detailed data concerning the composition and calorific value of the feathers syngas is presented in Table 3 and compared to the properties of syngas produced from woodchips. The feathers syngas has a significantly lower calorific value than the gas produced from wood chips (1.8 MJ/kg and 4.5 MJ/kg respectively).

The system fulfils all legal requirements concerning emission levels from waste treatment facilities thanks to employed emission reduction equipment. The average emission of pollutants from the plant equals to (oxygen content: 11% of the flue gas): 1.5 mgPM10/Nm^{3}16.2 mgSO$_2$/Nm^3, 2.6 mgHCl/Nm^3, 91.7 mgNO$_X$/Nm^3, 38.5 mgCO/Nm^3, 0.5 mgTOC/Nm^3 and 0.6 mgHF/Nm^3. The use of reagents is 7 l/h of 30% urea solution and 38 kg/h of calcium hydroxide.

3.2 Causes of operational problems

The analysis proved that the operational problems encountered in the Olsztyn gasifier that included slagging occurring in the boiler and high emission of nitrogen oxides, are primarily caused by the specific composition of feathers.

The samples of fireside deposits were collected from 5 parts of the system, namely: the combustion chamber, the channel connecting the combustion chamber to the boiler and three parts of the boiler

Table 2: Mass and energy balance of the Olsztyn gasification system – stream properties (Kwiatkowski et al, 2013).

No	Description	T [°C]	m [kg/h]	H [MJ/kg]	h [MJ/h]
1	Wet feathers	0	1 326	7.90	10 467
2	Water	0	477	0	0
3	Dewatered feathers	0	849	12.30	10 467
4	Pellets	0	56	18.44	1 045
5	Fuel	0	905	12.72	11 512
6	Gasifier air	0	3 233	0	0
7	Ash	0	6	0	0
8	Syngas	850	4 132	2.68	11 065
9	Burner air	0	3 584	0	0
10	Deposits	0	0.9	0	0
11	Hot flue gas	998	7 715	1.40	10 772
12	Deposits	0	0.4	0	0
13	Cooled flue gas	139	7 715	0.37	2 817
14	Water	40	2 995	0.17	503
15	Steam	173	2 995	2.77	8 299

Table 3: Composition and calorific value of feathers syngas compared to syngas produced from wood chips (Kwiatkowski et al., 2013b).

Type of syngas	N_2 [%]	CO_2 [%]	CO [%]	CH_4 [%]	O_2 [%]	H_2 [%]	LHV [MJ/kg]
Feathers syngas	59.9	29.9	6.8	1.5	1.4	0.3	1.8
Wood chips syngas	58.0	12.0	28.0	1.2	0.0	0.6	4.5

(entrance, middle part and exit). The samples differed a lot in colour and structure - the ones collected at the initial part of the boiler were white and very hard, whereas the ones collected at the end part were black and soft.

The mechanisms of deposit formation reported in the literature (Miles et al., 1996) include inertial impactation of molten or partially molten particles, condensation of vapours and chemical reaction with the scale. In terms of chemistry, the fireside deposits found in biomass combustion and gasification facilities consist of water-soluble compounds of alkali and alkaline earth metals, such as sulphates, carbonates, fuel and local temperature. The analysis of Olsztyn deposits showed that, with exception of the sample collected from the combustion chamber, they were composed of mostly oxygen (39.30 – 41.33 %wt), calcium (5.35 – 25.51 %wt), potassium (1.94 – 25.79 %wt), sulphur (13.81 – 17.79 %wt) and sodium (2.44-10.4 chlorides and reduced sulphur compounds. The exact composition of the deposits depends on the type of %wt). The samples collected from the combustion chamber consisted of mostly oxygen (40.81 %wt), calcium (25.51 %wt) and phosphorus (13.69 %wt) and contained almost no sulphur (0.44 %wt).

A probable set of chemical compounds forming the deposits was calculated basing on the results of the XRF analysis and on the assumption that the deposits consist of sulphates and oxides (see Table 3 for the results). The melting temperatures of resulting compounds and possible eutectic systems were analysed.

The results clearly indicate presence of the 50 $CaSO_4$ – 30 K_2SO_4 – 20 Na_2SO_4 eutectic system in the flue gas channel connecting the combustion chamber to the boiler and at the entrance to the boiler. The eutectic temperature is 1126 K, which corresponds precisely to the average temperature of flue gas leaving the combustion chamber. Such eutectic system was described, among others, by Du, 2000. The sample collected from the entrance part of the boiler contained 31.41 %wt $CaSO_4$, 19.21 %wt K_2SO_4, 12.82 %wt Na_2SO_4 and 36.56 %wt of various oxides. The relative share of the $CaSO_4$, K2SO$_4$ and Na_2SO_4 compounds is 49.52 %wt Ca_2SO_4, 30.28 %wt K_2SO_4 and 20.20 %wt Na_2SO_4, which indicates that the deposits were formed due to occurrence of this eutectic system and inertial impactation of fly ash mixed with molten sulphates. Analysis of XRF results for samples collected from the middle part of the boiler and from its exit lead to a conclusion that there occurs a different eutectic system of 30 K_2SO_4 – 40 Na_2SO_4 – 30 $ZnSO_4$ at the temperature of 657 K.

Such results indicate that these deposits were formed in a process of inhibition of chlorine corrosion with sulphur dioxide. Mixtures of alkali metal sulphates, which were formed in this process formed eutectic systems with each other and with heavy metals present in the system, and deposited on the walls.

Nitrogen oxides can be formed through three mechanisms: thermal oxidation of atmospheric nitrogen, oxidation of fuel-bound nitrogen and prompt mechanism occurring due to reaction of the atmospheric nitrogen with highly reactive radicals occurring in the flue gases.
The results of the numerical simulations performed for the system and described in detail in Kwiatkowski et al., 2013b, clearly indicate that the two mechanisms involving oxidation of atmospheric nitrogen are negligible and therefore changing the operational conditions in the plant, such as lowering the temperature in the combustion chamber, would not influence the amount of produced nitrogen oxides. The NO_x form due to oxidation of the relatively large amount of nitrogen bound in the fuel. Hence, the only way of reducing the emissions is the use of secondary measures such as SNCR or SCR. By analysing the dynamics of the combustion chamber we were able to change the position of the urea dosing valve in such a way that the solution is now better distributed thought the combustion chamber.

4. Conclusions

Gasification of feathers is technologically sound and efficient. The overall energy conversion efficiency of the facility is up to 70 %. The efficiency can by further increased only by means of more efficient removal of water from the feathers or better energy recovery from the flue gas. Both methods of increasing the efficiency are technically challenging and economically unreasonable.
The Olsztyn gasifier has been significantly modified and improved over its 4 years of operation. The problem of deposition of solid residues on the surfaces of the combustion chamber and the boiler remain unsolved, even though the mechanism of deposition was determined. The simplest method of dealing with the problem is to change the type of the recovery boiler from shale and tube to plate. However, this solution is economically unreasonable. Described operational problems arise from the specific composition of the fuel which is characterised by high content of nitrogen, sulphur, chlorine, calcium, sodium and potassium.
The results of performed numerical simulations clearly indicate that the main mechanism of NO_x formation is oxidation of nitrogen bound in the fuel. It was concluded that changing the operational conditions in the plant, such as lowering the temperature in the combustion chamber, would not influence the amount of produced nitrogen oxides. As a result of performed CFD modelling of the combustion chamber the urea dosing SNCR system was relocated and the NO_x emissions were reduced to an acceptable level.

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