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JANUSZ BUJAK*

WASTE UTILIZATION SYSTEM WITH HEAT RECUPERATION AND AIR PREHEATING – EFFICIENCY ANALYSIS

The article rises an issue of animal by-products management in Polish meat factories. The aim of this study is to illustrate new possibilities of systems for waste thermal utilization with heat recovery installed in meat works. A particular attention has been focused on improving the efficiency of heat production to satisfy the factory own needs.

The waste recovery system described in this paper is regarded as a device for saturated steam production, and the animal remains – as primary fuel. Additionally, the system is equipped with the air preheating facilities used for incinerating the remains. The analysis has been carried out, taking account of energy, ecology and economy. Calculations have been made by means of a mathematical model.

NOMENCLATURE

A_{cd} – external surface of the flue concrete duct, m^2,

A_{ch1} – external surface of the combustion chamber (primary chamber), m^2,

A_{ch2} – external surface of the discharge chamber (secondary chamber) , m^2,

c – concentration of salt or silica in feed water of recovery boiler, mg/m^3,

$c_{c/a}$ – mass content of carbon in ash, kg/kg,

$c_{co/fg}$ – mass content of carbon monoxide in flue gases, kg/kg,

c_{fg} – specific heat of flue gases after the recovery boiler, kJ/kgK,

$c_{\max}$ – maximum concentration of salt or silica in feed water of recovery boiler, mg/m^3,

$\dot{E}_{l-ash}$ – physical enthalpy flux lost due to hot ash removal from the combustion chamber (physical loss of solid combustion products), kW,

$\dot{E}_{l-bd}$ – enthalpy flux lost due to the recovery boiler blow-down, kW,

$\dot{E}_{l-bo}$ – enthalpy flux lost due to recovery boiler blow-off, kW,

$\dot{E}_{l-cd-es}$ – heat flux lost through the external surface of the concrete duct connecting thermal chamber to the recovery boiler, kW,

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* Polish Association of Sanitary Engineers, Bydgoszcz Division, Rumińskiego 6, 85-950 Bydgoszcz, Poland.

PPM PROMONT, ul. Jagiellońska 35, 85-950 Bydgoszcz, Poland. E-mail: dn@promont.com, mobile phone 0501 541 185.

$\dot{E}_{l-ch-es}$ – heat flux lost through the external surface of the utilization system to the environment (primary chamber + secondary chamber), kW,

$\dot{E}_{l-ch1-es}$ – heat flux lost trough the external surface of the combustion chamber, kW,

$\dot{E}_{l-ch2-es}$ – heat flux lost trough the external surface of the discharge chamber, kW,

$\dot{E}_{l-chd}$ – chemical enthalpy lost due to the content of flammable gases in flue gases (incomplete combustion loss), kW,

$\dot{E}_{l-fg}$ – physical enthalpy flux lost in gases discharged into the environment (chimney loss), kW,

$\dot{E}_{l-fg-ch2}$ – physical enthalpy flux lost in flue gases emitted into the environment from the thermal reactor chamber, kW,

$\dot{E}_{l-icp}$ – chemical enthalpy flux lost due to the content of flammable components in solid combustion products (incomplete combustion loss of products), kW,

$\dot{E}_{l-rb-es}$ – heat flux lost through the external surface of the recovery boiler to the environment, kW,

$\dot{E}_{o-h}$ – output heat flux as saturated steam produced by the system, kW,

$\dot{E}_{o-uh}$ – usable heat flux as saturated steam carried away from the system, kW,

$\dot{E}_{s-af}$ – chemical enthalpy flux supplied as additional fuel to assist combustion process, kW,

$\dot{E}_{s-af-ch1}$ – chemical energy flux supplied to the combustion chamber in the form of additional fuel facilitating the process of combustion, kW,

$\dot{E}_{s-af-ch2}$ – chemical energy flux supplied to the thermal reactor chamber in the form of additional fuel facilitating the process of combustion, kW,

$\dot{E}_{s-air}$ – enthalpy flux supplied as air for the combustion process (primary and secondary chambers), kW,

$\dot{E}_{s-air1-ch1}$ – enthalpy flux in the form of air used for incinerating animal waste in the combustion chamber, kW,

$\dot{E}_{s-air1-ch2}$ – enthalpy flux supplied as air used for gas aftercombustion in the thermal reactor chamber, kW,

$\dot{E}_{s-air2-ch1}$ – enthalpy flux supplied as air used for burning additional fuel in the combustion chamber, kW,

$\dot{E}_{s-air2-ch2}$ – enthalpy flux supplied as air used for burning additional fuel in the thermal reactor chamber, kW,

$\dot{E}_{s-fw}$ – enthalpy flux supplied to the recovery boiler as feed water, kW,

$\dot{E}_{s-th}$ – total heat flux supplied to the system, kW,

$\dot{E}_{s-waste}$ – heat flux supplied as wastes, kW,

h_{ash} – enthalpy of hot ash in the combustion chamber, kJ/kg,

h_{bd} – water enthalpy carried away from the steam boiler due to its blow-down, kJ/kg,

h_{bo} – water enthalpy carried away from the steam boiler due to its blow-off, kJ/kg,

K_{fc} – coefficient of flow capacity of the blow-down valve, m^3/h,

m_{ash} – ash mass flux removed from the combustion chamber, kg/s,

m_{bd} – water mass flux carried away from the boiler due to its blow-down, kg/s,

m_{fg} – mass flux of flue gases, kg/s,

m_{fg-ch2} – mass flux of flue gases after the discharge chamber, kg/s,

m_{ss} – saturated steam mass flux produced by the recovery boiler, kg/s,

m_{waste} – mass flux of incinerated animal waste, kg/s,

Q_{u-rb} – usable power of the recovery boiler, kW,

t_a – ambient temperature, °C,

t_{cd} – flue gas temperature inside the concrete duct, °C,

t_{ch1} – flue gas temperature inside the combustion chamber, °C,

t_{ch2} – flue gas temperature inside the discharge chamber, °C,

t_{fg} – flue gas temperature behind the recovery boiler, °C,

t_{fg-ch2} – flue gas temperature behind the discharge chamber, °C,
U_{cd} – coefficient of heat transmission through the external wall of the concrete duct, W/m^2K,
U_{ch1} – coefficient of heat transmission through the external wall of the combustion chamber, W/m^2K,
U_{ch2} – coefficient of heat transmission through the external wall of the discharge chamber, W/m^2K,
W_c – calorific value of amorphous carbon element, kJ/kg,
W_{co} – calorific value of carbon monoxide, kJ/kg,
W_{waste} – calorific value of animal waste, kJ/kg.

GREEK SYMBOLS

Δp – differential pressure between the inlet and outlet of the blow-down valve, bar,
ε_{th} – coefficient of thermal performance,
φ – incinerator load, %,
ρ_{bd} – blow-down water density, kg/m^3,
$\Sigma(E_{l-th})$ – total heat flux losses of the overall system, kW.

1. INTRODUCTION

The only purpose of waste combustion systems is to process this waste into safe material while maintaining required legal conditions, e.g. flue gas temperature at the discharge chamber outlet shall be at a minimum 850 °C for animal remains. Therefore, economic issues and efficiency, though significant, are of a secondary importance. It is worth designing and building systems whose role is not only to dispose of waste, but also to have high thermal efficiency [1]. The ecological aspect cannot be neglected here. Burning animal remains for production of heat energy is ‘climatically neutral’ [2] because of their life cycle. Energy generated in such a system reduces fossil fuel consumption, and consequently the emission of greenhouse gases into the environment.

The process of waste disposal in Poland is conducted in big regional specialized plants. The plants collect meat remains from smaller meat factories and transport them to their own place, where the remains are mainly processed into meat-and-bone meal. Nevertheless, the European Union Law prohibits using the meat as animal feeding stuff nowadays. Therefore, it is used in agriculture or as fuel for heat production. This process involves subsequent meat transportations to fields or heating stations which are prepared for meat-and-bone meal incineration. Despite those procedures, presently the meat-and-bone meat is utilized to a considerably lesser degree compared with the output of plants processing them. Thus, the stocks of meal in the European Union and Poland are constantly growing.

One of the solutions to this problem is to utilize the meat remains for energy in those individual meat factories without transporting and deposing them in another common place. Each of such plants needs heat sources for technology, ventilation, heating and domestic hot water. Heat consumption in such factories is almost unchangeable during the whole year as its participation in central heating is not remarkable. Therefore, the heat generated due to waste thermal utilization can totally be used for the meat factory needs during the year. This allows us to reduce considerably the consumption of fuel needed to generate heat in a specific factory. Moreover, an individual private installation for waste utilization contributes to financial savings connected with the waste transportation to other utilization places. Consequently, we also reduce the amount of diesel oil for transporting the remains and meat-and-bone meal. There are also a lot of benefits from reducing the production of meat as this process requires big quantities of energy and heat inputs.

The aim of this paper is to study, with the use of a mathematical model, the waste utilization system equipped with heat recuperation facilities, i.e. a steam boiler placed in a meat factory. However, a particular attention was focused on improving the efficiency of heat production and the analysis was carried out based on the three following aspects:

- energy – reduction of fossil fuel consumption,
- ecology – environment protection,
- economy – capital savings.

In this paper, the waste recovery system is regarded as a device for saturated steam production, and remains are considered as primary fuel. The primary energy [3], [4] is defined as energy used directly by the end-user decreased by losses due to its production and transfer.

Currently, based on the hereby analysis, the first waste utilization system equipped with a recovery boiler is being built in Poland (in a 'Unimięs' meat factory, Chrzanów). The overall installation operates as a technological unit designed for saturated steam production. The factory shall not receive any wastes from the outside.

The waste recovery systems consist of two basic elements:

- set of devices for waste incineration,
- set of devices for heat recovery.

Characterization of municipal solid waste combustion in a grate furnace has been presented by FREY et al. [5]. In that article, the combustion of municipal solid waste in a grate furnace was evaluated both experimentally and numerically by using the data of a reference experiment with over-stoichiometric primary air supply. Similarly, in paper [6] a mathematical model for the combustion of municipal solid waste in a novel two-stage reciprocating grate furnace was presented. Numerical simulations were performed to predict the temperature, the flow, and the species distributions in the furnace with practical operational conditions taken into account.

The primary unit of the heat recovery system is a steam boiler, whose thermal efficiency considerably influences the amount of the saturated steam produced. One of the most important processes influencing thermal efficiency of this boiler is the efficiency of heat exchange in the steam boiler furnaces. HUANG [7] has presented a fire-tube boiler model in terms of its thermal efficiency. The model shows the heat exchange between flue gases and boiling water as well as between the boiler external surface and the environment. Applying this type of model we can simulate boiler efficiency (efficiency) at different heat loads. GÜRÜZ [8] has described a mathematical model of heat exchange in the furnace taking into account its soot deposit. Also BUETERS [9], RICHTER and PAYNE [10] have presented mathematical models for furnaces and studied their thermal efficiency. BUJAK and BAŁDYGA [11], in turn, have described a mathematical model examining the influence of the steam boiler blow-off on its thermal efficiency in the function of heat load and at different salinity of feed water. The analysis [11] has been carried out using two methods. The first method involved fire-tube shell boilers generating saturated steam, the second one – superheated steam. Finally, RUSINOWSKI and STANEK [12] have presented a neural modelling of steam boilers. The neural modelling enables the analysis of the influence of heat loss (as flue gases, unburned combustibles in both slag and flue dust, or through the external boiler surface to the environment) on the thermal efficiency of the boiler.

The modelling presented in this paper allows us to calculate the saturated steam flux produced, particular individual heat losses, the coefficient of thermal efficiency of the overall system, and the amount of additional fuel indispensable for the total operation of waste recovery system. The calculations are made for various calorific values and different quantities of wastes, after determining the initial air preheating for waste combustion. Using the mathematical model we can also determine the amount of the fossil fuel saved and estimate the effect of emission elimination.

2. HEAT BALANCE AND COEFFICIENT OF THERMAL EFFICIENCY OF ANIMAL WASTE UTILIZATION SYSTEM WITH HEAT RECOVERY (STEAM BOILER WITH AIR PREHEATING)

2.1. DESCRIPTION OF THE SYSTEM

The remains of animal products come from both carcass and processed meat as well as its by-products. Therefore, the incineration process should conform to the Regulation of the European Parliament [13] and the Council Directive [14].

The animal waste recovery system [15], [16] (figure 1) consists of the following elements:

A. The set of devices for preparing and loading the waste – the container with the remains is automatically weighed and recorded in the computer system, then lifted to the edge of the charging hopper of the crusher and emptied.

B. A rotary combustion chamber at the inclination of 2–4% towards the afterburning chamber – here the animal by-products are incinerated with additional fuel. The time of combustion depends on their calorific value and humidity. The waste humidity cannot be higher than 70%, and its density should range from 200 to 1000 kg/m^3. The primary chamber in the shape of a rotary kiln (with an internal furnace lining resistant to high temperatures) operates in a steady mode and with a variable quantity of incinerated waste (due to automatic loading and the ash removal system). To initiate the incineration process in the combustion chamber (at a temperature of about 650 °C), it is necessary to apply an external source of energy. This task is accomplished by using gaseous or liquid fuel-fired burners.

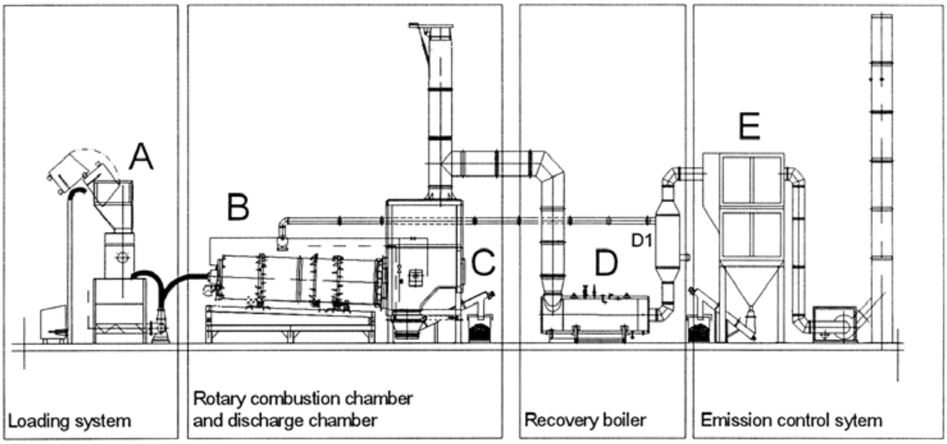

Fig. 1. Schematic diagram of waste utilization system with heat recovery and air preheating

C. Discharge chamber (thermoreactor) – gases, which might have arisen in the combustion chamber, are burned once again. This process takes place at temperatures from 850 °C to 900 °C, and the minimum dwell time of burning gases should be at least 2 seconds. The temperature from 850 °C to 900 °C in secondary chamber is controlled by means of additional burners fed with natural gas NG-50 or heating oil. In the case of waste with a high calorific content, the temperature of flue gases at the outlet can reach the values higher than 1000 °C.

D. Steam boiler (recovery boiler) – flue gases at a temperature from 850 °C to 900 °C leave the thermoreactor and heat up the recovery boiler which generates saturated steam. The temperature of flue gases after leaving the boiler fluctuates between 220 and 280 °C, depending on the saturated steam pressure and the boiler heat load. The gases are then directed to the air preheating system (figure 1, D1).

E. Emission control system – it is a complex bag filter for removing dust.

2.2. HEAT BALANCE OF THE SYSTEM

The system for thermal utilization of animal by-products equipped with the heat recovery unit and other fittings and connected to other installations can be treated as an open thermodynamic system exchanging mass, energy and heat with the environment. The equation of heat balance of this system can be written as follows:

$$\dot{E}_{s-waste} + \dot{E}_{s-af} + \dot{E}_{s-fw} + \dot{E}_{s-air}$$
$$= \dot{E}_{o-h} + \dot{E}_{l-ch-es} + \dot{E}_{l-icp} + \dot{E}_{l-ash} + \dot{E}_{l-cd-es} + \dot{E}_{l-fg} + \dot{E}_{l-chd} + \dot{E}_{l-bd} + \dot{E}_{l-bo} + \dot{E}_{l-rb-es}, \quad (1)$$

where the components referring to heat flux supplied to the system are placed on the left-hand side of the equation, and the components concerning heat flux carried away or lost from the installation are on the right-hand side.

After transposing the component of enthalpy flux in feed water into the right-hand side of the equation (1) and assuming that usable heat flux carried away from the system constitutes the following difference:

$$\dot{E}_{o-uh} = \dot{E}_{o-h} - \dot{E}_{s-fw} \quad (2)$$

we can write formula (1) in this way:

$$\dot{E}_{s-waste} + \dot{E}_{s-af} + \dot{E}_{s-air}$$
$$= \dot{E}_{o-uh} + \dot{E}_{l-ch-es} + \dot{E}_{l-icp} + \dot{E}_{l-ash} + \dot{E}_{l-cd-es} + \dot{E}_{l-fg} + \dot{E}_{l-chd} + \dot{E}_{l-bd} + \dot{E}_{l-bo} + \dot{E}_{l-rb-es}. \quad (3)$$

Taking into account that the right-hand side of formula (3) can be written as follows:

$$\Sigma(\dot{E}_{l-th}) = \dot{E}_{l-ch-es} + \dot{E}_{l-icp} + \dot{E}_{l-ash} + \dot{E}_{l-cd-es} + \dot{E}_{l-fg} + \dot{E}_{l-chd} + \dot{E}_{l-bd} + \dot{E}_{l-bo} + \dot{E}_{l-rb-es}, \quad (4)$$

equation (1) of heat balance is given by

$$\dot{E}_{s-\mathrm{waste}} + \dot{E}_{s-af} + \dot{E}_{s-air} = \dot{E}_{o-uh} + \Sigma(\dot{E}_{l-th}). \quad (5)$$

2.3. HEAT FLUX LOSSES OF THE SYSTEM

The subsequent components of heat balance, according to formula (4), can be determined in the following way:

A. Heat flux lost through the external surface of the waste utilization system to the environment:

- through the combustion chamber:

$$\dot{E}_{l-ch1-es} = U_{ch1} \cdot A_{ch1} \cdot (t_{ch1} - t_a), \quad (6)$$

- through the discharge chamber:

$$\dot{E}_{l-ch2-es} = U_{ch2} \cdot A_{ch2} \cdot (t_{ch2} - t_a) \quad (7)$$

whose total heat flux loss to the environment is:

$$\dot{E}_{l-ch-es} = \dot{E}_{l-ch1-es} + \dot{E}_{l-ch2-es}. \quad (8)$$

B. Chemical enthalpy flux lost due to the content of combustible elements in solid combustion products (incomplete combustion loss):

$$\dot{E}_{l-icp} = \dot{m}_{ash} \cdot W_c \cdot c_{c/a} . \tag{9}$$

C. Physical enthalpy flux lost due to hot ash removal from the combustion chamber (physical loss of solid combustion products):

$$\dot{E}_{l-ash} = \dot{m}_{ash} \cdot h_{ash} . \tag{10}$$

D. Heat flux lost to the environment through the external surface of the concrete duct joining the thermal system to the recovery boiler:

$$\dot{E}_{l-cd-es} = U_{cd} \cdot A_{cd} \cdot (t_{cd} - t_a) . \tag{11}$$

E. Physical enthalpy flux lost as flue gases escaping into the environment (chimney loss, physical discharge loss) from the recovery boiler:

$$\dot{E}_{l-fg} = \dot{m}_{fg} \cdot c_{fg} \cdot t_{fg} . \tag{12}$$

F. Chemical enthalpy flux lost due to the content of flammable gases in flue gases (chemical discharge loss, incomplete combustion loss):

$$\dot{E}_{l-chd} = \dot{m}_{fg} \cdot c_{co/fg} \cdot W_{co} . \tag{13}$$

G. Enthalpy flux lost due to the recovery boiler blow-down [17]:

$$\dot{E}_{l-bd} = \dot{m}_{bd} \cdot h_{bd} . \tag{14}$$

Knowing the value K_{fc} of the blow-down valve and its opening time, the above formula can be rewritten as:

$$\dot{E}_{l-bd} = \frac{K_{fc} \cdot \sqrt{\Delta p} \cdot \rho_{bd} \cdot h_{bd}}{3600^2} . \tag{15}$$

H. Enthalpy flux lost due to recovery boiler blow-off:

$$\dot{E}_{l-bo} = \frac{\dot{m}_{ss} \cdot c \ \cdot h_{bo}}{c_{\max} - c} . \tag{16}$$

The procedure determining the admissible concentration (maximum) of silica and salt in boiler water was accepted according to the European Standard [18].

I. Heat flux lost through the external surface of the recovery boiler to the environment [19]:

$$\dot{E}_{l-rb-es} = 0.0072 \cdot Q_{u-rb}^{0.6} . \tag{17}$$

2.4. COEFFICIENT OF THERMAL EFFICIENCY

The coefficient of thermal efficiency can be defined as follows [20]:

$$\varepsilon_{th} = \frac{\dot{E}_{o-uh}}{\dot{E}_{s-th}}. \tag{18}$$

Because the total heat supplied to the system is the sum of the usable heat flux, carried away in the form of saturated steam, and the total heat flux losses of the overall system, the above formula can also take the following form:

$$\varepsilon_{th} = \frac{\dot{E}_{o-uh}}{\dot{E}_{o-uh} + \Sigma(\dot{E}_{l-th})}. \tag{19}$$

Taking into account formula (4), the coefficient of thermal efficiency (19) for the waste installation together with the recovery system can be determined as follows:

$$\varepsilon_{th} = \frac{\dot{E}_{o-uh}}{\dot{E}_{o-uh} + \dot{E}_{l-ch-es} + \dot{E}_{l-icp} + \dot{E}_{l-ash} + \dot{E}_{l-cd-es} + \dot{E}_{l-fg} + \dot{E}_{l-chd} + \dot{E}_{l-bd} + \dot{E}_{l-bo} + \dot{E}_{l-rb-es}}. \tag{20}$$

3. ENERGY ASPECT – REDUCTION OF FOSSIL FUEL CONSUMPTION

3.1. DESCRIPTION OF THE SYSTEM AND PROCESS AS WELL AS ANIMAL REMAINS

The study of the coefficient of thermal efficiency for the waste utilization installation with the recovery system and air preheating used for combustion process is conducted for the system with the capacity of 500 kg/h. The analysis was carried out in the full range of the heat load for rotary kilns.

The remains for combustion come from meat factories dealing with processing and slaughtering. Table 1 shows the quantity of wastes and table 2 – their chemical constitution. Calorific value of the waste being presented is 11.7 MJ/kg.

Table 1

Qualitative characteristic (mass content) of animal remains

Type of waste	Quantity (% w/w)
Bones	45.0
Blood	5.0
Stomach contents	14.0
Mixed waste	36.0

Natural gas NG-50 aids the process of thermal utilization. It is assumed that the process proceeds under steady conditions. The installation works continuously without breaks and standstills. Saturated steam generated in the recovery boiler is integrally used for the technological needs of the meat factory. The heat load of the installation was defined as the amount of waste supplied to the utilization system. Table 3 shows the fluxes of primary and auxiliary energy supplied to the system in the form of a flux of incinerated waste.

Table 2

Chemical analysis

Chemical analysis	Quantity (% w/w)
Carbon	24.0
Hydrogen	7.0
Oxygen	3.0
Nitrogen	1.0
Ash	5.0
Water	60.0

Table 3

Fluxes of primary and auxiliary energy supplied to the system

Incinerator load		100	200	300	400	500
		(kg/h)				
Flux of primary energy from incinerated waste supplied to the system	(kW)	326.1	652.2	978.4	1304.5	1630.6
Flux of additional fuel supplied to the system as natural gas	(Nm^3/h)	21.6	14.1	7.1	0.0	0.0
Flux of auxiliary energy supplied to the system as natural gas	(kW)	216.0	141.0	71.0	0.0	0.0

3.2. ENERGY BALANCE

Figure 2 shows the energy balance in the animal waste thermal treatment system (without a heat recovery system) at a nominal (100%) load of the incinerator. The total loss of the system energy fluxes is 1765.0 kW.

The loss of the flux of physical enthalpy for flue gases carried away from the thermal reactor chamber always reaches the highest value among all losses, i.e. $\dot{E}_{l\text{–}fg\text{–}ch2}$ = 1586.3 kW which amounts to 89.9% of energy losses. It is therefore concluded that building similar systems without recovering energy contained in waste gas leaving the discharge chamber results in obtaining the systems with zero energy efficiency. Heat flux loss through the external surface of the combustion chamber $\dot{E}_{l-ch1-es}$ equals 89.1 kW (accounting for 5.0% of energy losses), and the loss through the external surface of the thermal reactor chamber $\dot{E}_{l-ch2-es}$ reaches 80.2 kW (4.6%). The fluxes of chemical enthalpy lost due to the presence of combustible components in slag and flue gas leaving the thermal reactor chamber and the fluxes of physical enthalpy of hot ash are very low. Their total value is 9.4 kW, which accounts for 0.5% of total energy losses.

The main energy flux $\dot{E}_{s-waste}$ is supplied to the system in the form of a chemical enthalpy flux in animal waste. It equals 1630.6 kW which constitutes 92.4% of the value of all energy fluxes supplied to the system. The process of incineration in the combustion chamber and thermal reactor is stable (autothermical) and does not require any additional fuel.

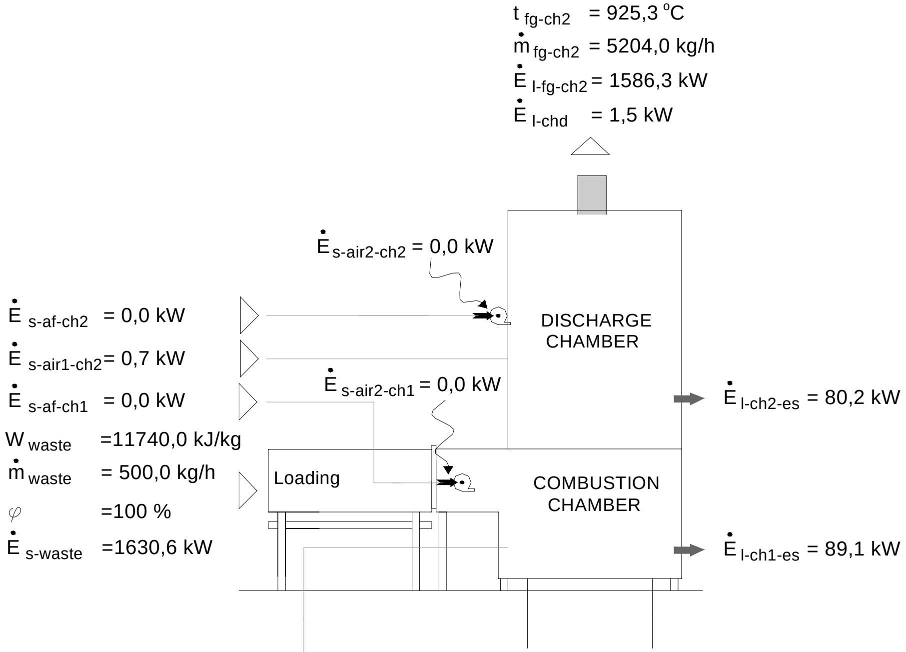

Fig. 2. Energy balance in animal waste thermal treatment system without a heat recovering part at a nominal load (500 kg/h)

Figure 3 shows the energy balance for the heat recovery system only. The balance is also achieved at a nominal (100%) load of the system. The total loss of energy fluxes reaches 461.8 kW, whereas the loss of the physical enthalpy flux $\dot{E}_{l-fg}$ of flue gas leaving the recovery boiler is the highest. In the example being presented, it amounted to 357.2 kW (77.3% of all energy losses).

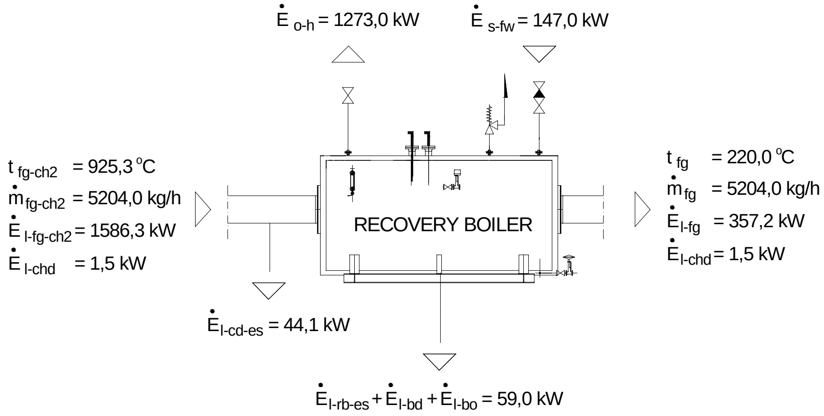

Fig. 3. Energy balance for a part of heat recovery system with a nominal (500 kg/h) load of the system

Other substantial losses are the heat flux losses to the environment from the external surface of the recovery boiler and the losses of water enthalpy fluxes resulting from the boiler blow-down and blow-off. The total losses $\dot{E}_{l-rb-es} + \dot{E}_{l-bd} + \dot{E}_{l-bo}$ amount to 59.0 kW (12.8% of all energy losses). The loss of a heat flux emitted into the environment through the external surface of the concrete duct connecting the thermal reactor chamber to the recovery boiler $\dot{E}_{l-cd-es}$ is 44.1 kW (9.6%). The loss of the chemical enthalpy flux in the form of combustible gases contained in flue gases after the recovery boiler is very low, i.e. below 0.3% of all energy losses.

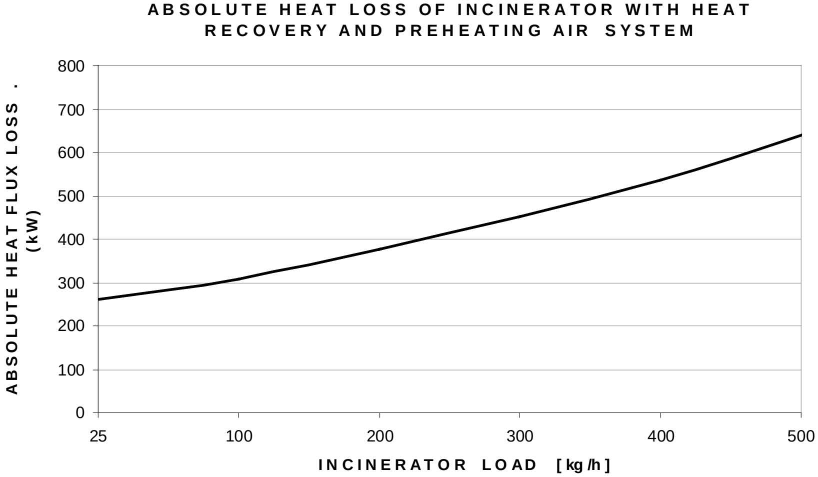

Fig. 4. Total heat flux losses of the thermal system for waste utilization with the recovery boiler and preheating air unit depending on the incinerator load

Figure 4 shows the total heat flux losses of the waste recovery system in the function of the amount of animal remains intended for incineration, defined as the incinerator load. While the heat load of the system increases, the heat losses also increase, reaching the value of 639.1 kW at the highest efficiency (100%). In the range of low heat load (from 25 to 100 kg/h), the rate of heat loss does not change considerably and fluctuates between 262 kW and 308 kW. This is due to a high proportion of steady heat flux losses (independent of the incinerator load) in the total heat loss.

3.3. THE COEFFICIENT OF THERMAL EFFICIENCY

Figure 5 shows the coefficient of thermal efficiency for the waste utilization system equipped with the recovery boiler and air preheating facility in the quantitative function of the incinerated animal remains. As can be seen, the coefficient of thermal efficiency reaches the highest values at the high heat load of the system. In the range from 300 to 500 kg/h, the coefficient rate takes the value from 60 to 64%. While the incinerator load drops below 300 kg/h, the coefficient rate dramatically drops. When the heat load equals less than 25 kg/h, the coefficient takes the values below 30%.

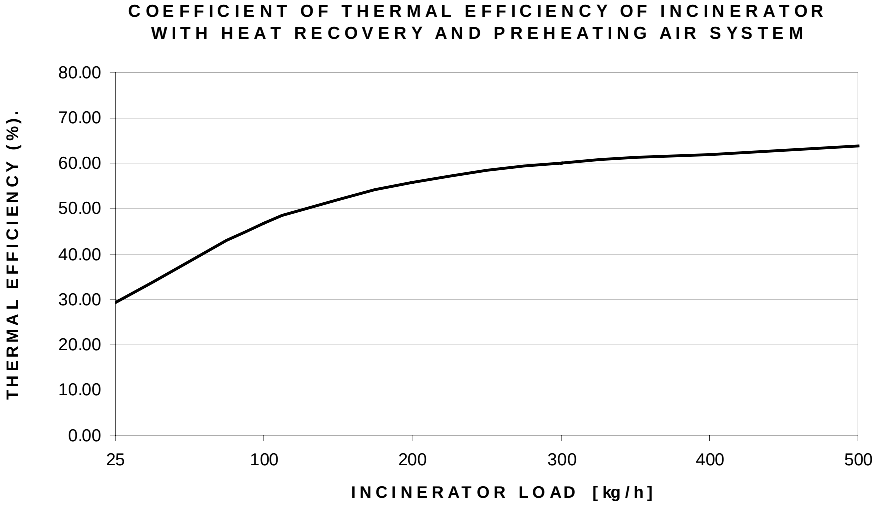

Fig. 5. Coefficient of thermal efficiency for the waste utilization system with the recovery boiler and air preheating depending on the incinerator load

3.4. REDUCTION OF FOSSIL FUEL CONSUMPTION

Analysing figure 6 we can observe that the maximum amount of usable heat emerges at the full load of the incinerator. Incinerating 500 kg/h of slaughterhouse offal we can obtain 1689 kg/h of saturated steam with a pressure of p = 10 bar. However, it should be remembered that the production of usable heat decreases dramatically when the quantity of utilized waste is diminished. For instance, at the load of 40% the heat production reaches the value of 714 kg/h.

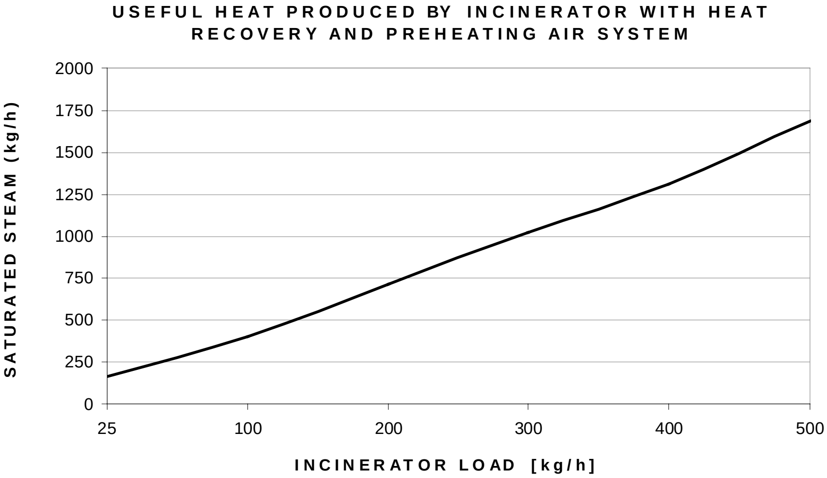

Fig. 6. The quantity of usable heat as saturated steam generated by the waste recovery system depending on the incinerator load

Because the usable heat in the form of saturated steam is utilized exclusively for the factory needs (e.g. technology, ventilation, central heating, and domestic hot water), the heating oil consumption for heat production in the boiler room is also reduced. Table 4 shows the amounts of natural gas NG-50 savings due to the application of the heat recovery system with air preheating at the incinerator heat load. The recovered flux of usable energy in the recovery boiler allows lower consumption of fossil fuels (natural gas) in the meat processing plant boiler room. At a full incinerator

Table 4

Reduction of natural gas consumption in the plant boiler room

Incinerator load		100	200	300	400	500
		(kg/h)				
Flux of usable energy – recovered from the system	(kW)	269.5	476.1	679.5	875.6	1125.7
Volume flux of natural gas required to generate the above flux of usable energy – reduction of gas consumption in the boiler room	(Nm^3/h)	35	61	87	112	144

load the reduction of the gas flux in the boiler room reaches the value of 144 Nm^3/h. When calculating the reduction of natural gas usage, its consumption as additional fuel was not taken into account. This results from the fact that additional fuel is necessary for waste treatment regardless of whether or not the system is equipped with a heat recovery system.

4. ECOLOGICAL ASPECT – ENVIRONMENTAL PROTECTION

The term *biomass* [21] is used to describe all substances containing organic carbon and derived from animal and vegetable products [22]. Biomass also refers to biological by-products from the living organisms, both plants and animals. Animal by-products from meat processing are ranked among biomass of animal origin. In this regard, we benefit from burning animal remains and recovering heat in two ways:

- minimizing emission effect – we reduce consumption of fossil fuels,
- emission of insignificant amount of CO_2, which in this case is environmentally neutral.

Table 5 shows the effect of reducing the emission of carbon dioxide into the atmosphere, depending on the system efficiency as far as the thermal waste treatment is concerned.

Table 5

Effect of avoided emission in the case of natural gas combustion

Incinerator load		100	200	300	400	500
		(kg/h)				
Reduction of gas consumption in the plant boiler room	(Nm^3/h)	35	61	87	112	144
Reduction of CO_2	(kg/h)	70	122	174	224	288

We assume that the plant boiler room is natural gas-fired. The recovered flux of usable energy in the recovery boiler enables the boiler room to use less fossil fuels (natural gas). Lower consumption of natural gas means lower emission of CO_2 into the atmosphere. If the plant boiler room was powered by other fuels than natural gas, e.g. fuel oil or hard coal, the effect of emission reduction would be even greater. The emission of sulphur dioxide and dust could occur.

Thermal animal waste treatment systems with heat recovery have an added advantage of eliminating the transport of waste to external (regional) waste treatment plants. Therefore, substantial amounts of diesel oil or petrol used by vehicles can be saved. The extra effect of emission avoided in this way (transport) and the effect of using in the plant boiler room the fuels worse than natural gas were not taken into account when calculating the values of the parameters given in table 5.

5. ECONOMICAL ASPECT – INVESTMENT PROFITABILITY

Based on the present mathematical model for investigating thermal efficiency of the incinerator with the recovery system and air preheating we can carry out the economical analysis of this installation. The reference point for this analysis profitability is the cost of waste disposal offered by other specialised services. The average cost of utilising 1 ton of slaughterhouse offal in Poland currently comes to 150 USD.

Table 6

The economical analysis of the plant construction project

Description	Animal by-products (11.7 MJ/kg)
Original state – utilization with the aid of external company	
Utilisation cost of 1 ton of waste carried out by external services, (USD)	150
Amount of waste produced annually, (ton/year)	3 960
Waste utilization cost carried out by external services, (USD/year)	540 000
After modernization – meat factory with its own recovery system	
Coefficient of usable saturated steam	0.90
Amount of saturated steam produced by the recovery boiler including the coefficient of usable saturated steam, (ton/year)	12 046
Value of saturated steam produced by the recovery unit, (USD/year)	438 000
Operating and utilization costs including additional fuel (USD/year)	114 500
Cost of the installation for waste thermal utilization at a capacity of 1000 kg/h with the recovery system, (USD)	1 500 000
Repayment for the recovery system, (years)	1.7

The analysis was conducted for the waste described in tables 1 and 2. It was assumed. that not all saturated steam generated from the recovery process was used for technological purposes and that

- the coefficient of usable saturated steam is 0.9,
- the installation for waste thermal utilization is equipped with a rotary kiln operating continuously at a capacity of 500 kg/h,
- the mean calorific value of animal remains is 11.7 MJ/kg,
- the analysis is based on average prices which are currently valid in Poland.

The results of calculations are presented in table 6. The economical analysis shows that this kind of a waste utilization system with heat recovery is really profitable while in use and, as seen, the time of repayment is slightly shorter than 2 years.

6. CONCLUSION

It has been shown that meat and animal remains form biomass which can constitute the fuel of a good quality and a valuable source of heat. It is possible to utilize such remains in the place where they are produced, i.e. in a meat factory with the incineration unit equipped with the recovery system.

The paper has presented the components, construction and operating rules of the utilization system with the heat recovery in a steam boiler. The author has calculated a heat balance of this system, described the mathematical components of heat losses in the system, and defined its coefficient of thermal efficiency. The study of the system thermal efficiency has shown that the installation is absolutely profitable in terms of energy, mostly at high and boundary heat loads of the incinerator. Moreover, remarkable savings are done in the usage of fossil fuels (e.g. natural gas).

The analysis carried out from the environmental point of view has proved that the animal by-products combustion in this kind of system is environmentally friendly. Reduction of fossil fuel usage contributes to a remarkable reduction of pollutant emission into the atmosphere, mostly at high and boundary heat loads of the incinerator. We avoid the emission effect, and CO_2 is emitted in small quantities, neutral to the environment.

The economical analysis of this installation has shown that the payback period on investment for the system construction, compared with the waste utilization cost offered by other services, is slightly shorter than 2 years. Therefore, the solution presented in this paper is absolutely effective since in economy the investments realized even for 7 years are considered to be profitable.

The high efficiency of the utilization system has been described in three crucial aspects: energy, ecology, economy. This fact should draw attention of potential producers and encourage them to apply this waste disposal method with heat recovery in meat factories.

Although the above analyses have been carried out under current Polish conditions (including prices), their qualitative results are also very encouraging for other countries and regions. This conclusion is drawn from remarkable economical savings, energy savings and ecological benefits coming from the application of the new system in Polish meat factories.

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