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Fuel consumption in the thermal treatment of low-calorific industrial food processing waste

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HIGHLIGHTS

- Effect of an oxygen concentration in flue gases on the consumption of additional fuel was analysed.
- Increasing oxygen concentration caused non-linear increasing consumption of extra fuel.
- Above the 13.4% O2 concentration, the extra fuel consumption increases to infinity.

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ABSTRACT

Animal waste resulting from food production represents a potential sanitary risk. For this reason, it is necessary to apply an effective and ecologically safe procedure for eliminating this danger. In this process, one of the numerous legal obligations is maintaining a flue gas temperature of 850 °C. Animal waste has a relatively low calorific value and a high moisture content, so it requires a certain amount of auxiliary fuel to incinerate. The purpose of this paper is the minimization or elimination of auxiliary fuel consumption during the incineration of low-calorific waste.

This article presents an analysis of two factors that determine the consumption of additional fuel, the waste mass flow and the oxygen concentration in the flue gas. The analysis was based on a comparison of the energy supplied and demanded for the incineration of pork bones under various operating conditions. The analysis and tests show three working categories of the system: additional fuel is not needed, additional fuel is needed, and a flue gas temperature of 850 °C is not achievable regardless of the quantity of additional fuel used.

The research shows that thermal treatment of low-calorific waste units can work without or with a minimal amount of additional fuel. However, there is an area where the required temperature of 850 °C is not reached despite increasing the amount of burned auxiliary fuel.

1. Introduction

The animal waste resulting from food production represents a potential sanitary risk. For this reason, it is necessary to apply an effective and ecologically safe procedure to eliminate this danger. Requirements for such procedures are specified in the legislation of the European Union [1]. A basic method of altering animal waste to a form recognized as safe is thermal treatment [2–5]. In the case of thermal treatment of animal waste, there is a legal obligation to maintain a flue gas temperature of 850 °C in the afterburner chamber with a 2-s retention time at this temperature. Other specified legal regulations apply to the permissible concentrations of hazardous substances in flue gases [6,7] and adequate slag levels and bottom ash treatment. However, there are economic and energy efficiency requirements that are defined by investors. Additionally, technical and operating limitations result from the strength parameters of the applied materials and must also be considered.

These complex issues were analysed in a number of papers focusing on the multi-criterial optimization procedures of thermal treatment processes [8,9]. The abovementioned conditions and limitations, as well as the complexity and multidimensionality of the process of incineration, which is carried out for various types of waste, require the utilization of advanced simulation and calculation tools [10–13]. Individual models highlight the most important factors of the described processes in a given technical, economic, organizational or legal environment. Paper [14] presents a technical and economic model of the

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thermal treatment of poultry litter with a capacity of 1500 kg/h. This plant produces biochar, and heat or electric energy is recovered. This analytical work considered the legal and economic conditions that exist in Northern Ireland and Great Britain. In paper [15], a general model of the combustion process that particularly considered the variability of the thermo-chemical parameters of the waste stream was presented. This model worked out the optimum parameters of the thermal waste conversion plant according to the assumed criterion (energy efficiency improvement). Computational models dedicated to combustion plants using rotary combustion chambers are found in [16,17]. These analyses include, among other things, the design parameters (dimensions) of the rotary combustion chamber. In this case, the models were designed to optimize the process for different waste stream quantities and different excess oxygen quantities in the exhaust gases. The results of these studies are guidelines for plant builders as they are defined in the design and rebuilding of combustion systems. The mathematical model of the municipal waste incineration process has been presented in the literature [18]. The finite element method (FEM) was used in the computational structure of this model. The aim of this analysis was to select the most advantageous design solutions (dimensions) for the combustion chamber. In turn, article [19] presents an analysis of the combustion of biomass, which is a material with a high humidity and a variable elemental composition. The model included calculations using computational fluid mechanics (CFD) laws for individual biomass particles. The purpose of these calculations was to determine the optimal temperature parameters for this process. Few studies include an analysis of the incineration of low calorific value waste requiring auxiliary fuel [20,21]. This issue is considered marginally as only one of many elements in the combustion analysis.

This paper presents an analysis of additional fuel consumption (to provide the required exhaust temperature of 850 °C) in the incineration process as a function of the chemical composition, the installation load and the excess oxygen in the exhaust gas (in this paper, excess oxygen is defined by the ratio of the oxygen volume to the total volume flue gas as a percentage). An analysis was also carried out to determine the flue gas temperature distribution as a function of the unit consumption of auxiliary fuel and the excess oxygen in the exhaust gas. The analytical models that were obtained can be effective tools for optimizing the waste incineration processes leading to the minimization or elimination of auxiliary fuel consumption. The implementation of the appropriate corrective measures based on these models significantly reduces the cost of thermal treatment plants and reduces negative environmental impacts by decreasing the combustion of fossil fuels. The results of this study are presented with the example of animal waste and were verified on an industrial scale. These analyses can be used in all existing and planned waste thermal treatment plants.

2. Theoretical basis

2.1. Balance of input and output energy fluxes

The waste combustion system (the equipment components in combination with other auxiliary systems) is as an open thermodynamic system (Fig. 1), exchanging mass and energy with the environment. The following fluxes are input into the system:

$\dot{E}_{i\text{-}w}$	chemical energy flux of waste (kW),
$\dot{E}_{i\text{-}af(rk)}$	chemical energy flux of additional fuel dosed to the combustion chamber (kW),
$\dot{E}_{i\text{-}af(ach)}$	chemical energy flux of additional fuel dosed to the afterburner chamber (kW),
$\dot{E}_{i\text{-}a(rk)}$	physical enthalpy flux of air supplied to burn waste and additional fuel in the rotary kiln (kW),
$\dot{E}_{i\text{-}a(ach)}$	physical enthalpy flux of air supplied to combust afterburning gases and additional fuel in the afterburner chamber (kW).

The following fluxes are output from the system:

$\dot{E}_{o\text{-}fg}$	physical and chemical enthalpy flux of flue gases (potential usable energy flux) (kW),
$\dot{E}_{o\text{-}es(rk)}$	heat flux lost to the environment through the rotary kiln external surface (kW),
$\dot{E}_{o\text{-}es(ach)}$	heat flux lost to the environment through the afterburner chamber external surface (kW),
$\dot{E}_{o\text{-}bash(rk)}$	physical and chemical enthalpy flux of the ash (kW).

The energy balance equation for the system may be written as

$$\dot{E}_{i-w} + \dot{E}_{i-af(rk)} + \dot{E}_{i-af(ach)} + \dot{E}_{i-a(rk)} + \dot{E}_{i-a(ach)} = \dot{E}_{o-fg} + \dot{E}_{o-es(rk)} + \dot{E}_{o-es(ach)} + \dot{E}_{o-bash(rk)} \quad (1)$$

By introducing the equation for loss fluxes:

$$\sum (\dot{E}_{tl}) = \dot{E}_{o-es(rk)} + \dot{E}_{o-es(ach)} + \dot{E}_{o-bash(rk)}, \quad (2)$$

the energy fluxes Eq. (1) can be rewritten as follows:

$$\dot{E}_{i-w} + \dot{E}_{i-af(rk)} + \dot{E}_{i-af(ach)} + \dot{E}_{i-a(rk)} + \dot{E}_{i-a(ach)} = \dot{E}_{o-fg} + \sum (\dot{E}_{tl}), \quad (3)$$

where

$\Sigma(\dot{E}_{tl})$ total energy loss flux (kW), considering that

$$\dot{E}_{i-af} = \dot{E}_{i-af(rk)} + \dot{E}_{i-af(ach)}, \quad (4)$$

$$\dot{E}_{i-a} = \dot{E}_{i-a(rk)} + \dot{E}_{i-a(ach)}, \quad (5)$$

where

$\dot{E}_{i\text{-}af}$	total chemical energy flux of additional fuel supplied to the combustion chamber and afterburner chamber (kW).
$\dot{E}_{i\text{-}a}$	total physical enthalpy flux of air supplied to the combustion chamber and afterburner chamber (kW).

Eq. (4) takes the form:

$$\dot{E}_{i-w} + \dot{E}_{i-af} + \dot{E}_{i-a} = \dot{E}_{o-fg} + \sum (\dot{E}_{tl}) \quad (6)$$

Using the above formulas, a computational numerical model has been prepared. A detailed description of this algorithm is presented in work [17]. The basic input values in the calculation algorithm are as follows:

- the setpoints of the flux of incinerated waste: $m_{i\text{-}w}$ (kg/h),
- the setpoints of the unit of additional fuel consumption: $V_{i\text{-}af}/\dot{m}_{i\text{-}w}$ (–),
- the setpoints concentration of oxygen outside the combustion chamber: O_2 (%),
- The basic input constants in the calculation algorithm are:
- elemental composition of waste: C, H, O, N, S, Cl, Ash, H_2O (kg) or (%),
- elemental composition of additional fuel: C, H, O, N, S, Cl, Ash, H_2O (kg) or (%),
- temperature of the air used for combustion of waste and additional fuel: $T_{oa(ach)}$ (°C),
- heat transfer coefficient of the outer surfaces of the rotary kiln: $\alpha_{2(rk)}$ (W/m^2 K),
- heat transfer coefficient of the outer surfaces of the afterburner chamber: $\alpha_{2(ach)}$ (W/m^2 K),
- low calorific value of waste incinerated: $LCV_{i\text{-}w}$ (MJ/kg),
- low calorific value of additional fuel: $LCV_{i\text{-}af}$ (MJ/kg),
- The basic output values calculated by the simulation model were as follows:
- fuel flux delivered to the rotary kiln and the afterburner chamber: