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Original Research

Experimental Study of the Lower Heating Value of Medical Waste

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Abstract

This paper presents an experimental study of the heating value of medical waste using an input-output method. The study was carried out at the Oncological Hospital in Bydgoszcz, Poland, over a period of three months. The installation for thermal treatment consisted of a loading unit, a combustion chamber, and a discharge chamber (thermoreactor). The medical waste constituted the primary fuel, and high-methane natural gas acted as the secondary fuel. With regard to the high heating value and low humidity of medical waste, the thermal processing in the combustion chamber fulfilled the criterion of stable combustion (autothermal combustion). The average temperature in the combustion chamber was 665.5ºC during the testing period. The study showed that the heating value of the waste varied considerably. The amount of incinerated waste varied between $\dot{m}_{mw}$=70 kg/h and 140 kg/h during the testing period. The calorific value of the medical waste fluctuated between 8.5 MJ/kg and 41.2 MJ/kg, with a mean value of q_{mw}=19.1 MJ/kg.

Keywords: combustion, incinerator, lower heating value, medical wastes

Introduction

When the prices of crude oil and natural gas are high, as is currently the case, medical waste can be utilized as an alternative fuel for thermal and electrical energy production. The thermal conversion of medical waste into energy is recognized as a recycling process.

More often than not, medical waste is heterogeneous, consisting of plastics, plastic wrappings, paper, medicine, organic waste, metal, and dressings. For this reason, the properties of the fuel (waste) undergo significant changes in terms of the fuel heating value. Subsequently, changes in combustion velocity can lead to temperature and pressure variations in the combustion chamber, which consequently disrupts the combustion process. Research into this phenomenon has been carried out by several investigators. Kuo [1] developed a combustion control algorithm for plant operators in order to attain stable combustion with various fuel parameters by regulating air supply and fuel feed rate. The combustion control model was based on the mass and thermal energy balances of the incinerator. Accurate determination of the fuel burning rate and its heating value were essential for obtaining realistic results from the simulation model. In practice, the optimum combustion control algorithm was introduced by weighing excess oxygen and flame temperature data, as well as CO emissions [2].

Fuel burning rate and optimum excess air ratio are also influenced by furnace design and operating conditions, such as heat demand and fuel properties. Other investigators, e.g. Chen et al. [3], Yang et al. [4], and Ryu et al. [5], have carried out thermal-physical and chemical analyses to simulate combustion processes in moving grate furnaces. Kodres [6], in turn, described a mathematical model to predict the temperature of the system, steaming rate, and energy recovery efficiency for a solid waste incinerator. The facility consisted of a primary chamber for burning solid

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residues and a secondary chamber for complete gaseous product combustion. Furthermore, Feindler [7] developed the input-output method to determine the solid residue heating value, thermal efficiency of the incineration system, and specific steaming rate of two-stage municipal solid residue combustors with multiple furnaces. Kuo et al. [8] estimated the heating value of solid residue, steaming rate, and energy recovery efficiency based on the energy balance analysis for the boiler-furnace system.

Solid residue heating value estimation can provide insight into the quantity of fuel needed to burn and the amount of energy that could be recovered [9-11]. The insight into the amount of recovered energy, in turn, enables one to apply suitable solutions and technologies needed for its management. Holmgren [12] analyzed a municipal district-heating (DH) system that uses waste heat from industries and waste incineration as base suppliers of heat and is currently investing in a natural-gas-fired combined heat-and-power (CHP) plant. That study showed that there is room in the DH system for all three energy carriers: heat from industries, waste incineration, and CHP plants. Mori et al. [13] presented a model for heat energy from river water and treated sewage water, and a system using waste-heat energy from municipal solid-waste incineration plants was built and applied to the Tokyo urban area in Japan, considering the spatial and time-related distribution of demands and supplies, the shapes of buildings in the demand area, and life-cycle analysis. The utilization of waste heat in the industrial area has also been described by Meneghetti et al. [14]. That work illustrated a waste-to-energy plant to be used for the industrial waste of the district of Friuli Venezia Giulia. It described how the expense for woodworking-waste disposal can become an advantage for the firms of the district owing to the incineration of this waste in a plant unique for the type of waste treated.

Fig. 1. Waste handling system at the Oncological Hospital in Bydgoszcz.

As mentioned above, medical waste is comprised of heterogeneous components in various quantities. Therefore, it is difficult to separate a representative sample to determine its heating value in a calorimetric bomb or with chemical analysis. This paper presents an experimental study on estimating the heating value of medical waste using the input-output method that considers the energy flux balance. The tests lasted for three months and were conducted in a hospital. The results can be useful at the design stage of the incineration facilities for medical waste, e.g. when sizing a combustion chamber or a thermoreactor. Knowledge of the waste heating value also permits the estimation of the quantity of secondary fuel or the determination of the energy efficiency of an incinerator that incorporates a heat recovery boiler.

Energy Balance, Mass Balance, and the Heating Value of Medical Waste

Technology Description

The technology primarily consists of a system for full-time (24-hour) multi-zone combustion of medical waste in a 380/21+LASH incinerator (Fig. 1) with a capacity of 120 kg/h (Australian company ENTECH). The process of thermal treatment takes place in the combustion chamber at a temperature of approximately 650-850ºC. The entire operation is controlled by a system of temperature sensors and by an oxygen-level sensor. Flue gases, slag, and ash are the end products. The process of slag and ash disposal is automatic (deashing device). The gases that occur as a result of combustion are introduced into the thermoreactor chamber, which has a minimum dwell time of 2 minutes at a minimum temperature of 1,100ºC. Two burners in the chamber, which engage automatically when the chamber temperature decreases, continuously control the entire process.

Energy Balance of the System

The energy and mass flows in the incinerator are shown in Fig. 2.

The equation for the energy flux balance of the waste handling system can be written as follows:

$$\dot{E}_{mw}+\dot{E}_{ng}+\dot{E}_{amw}+\dot{E}_{ang} = \dot{E}_{as-pe}+ \dot{E}_{as-che}+\dot{E}_{es-cch}+\dot{E}_{es-dch}+\dot{E}_{fg-pe}+\dot{E}_{fg-che} \qquad (1)$$

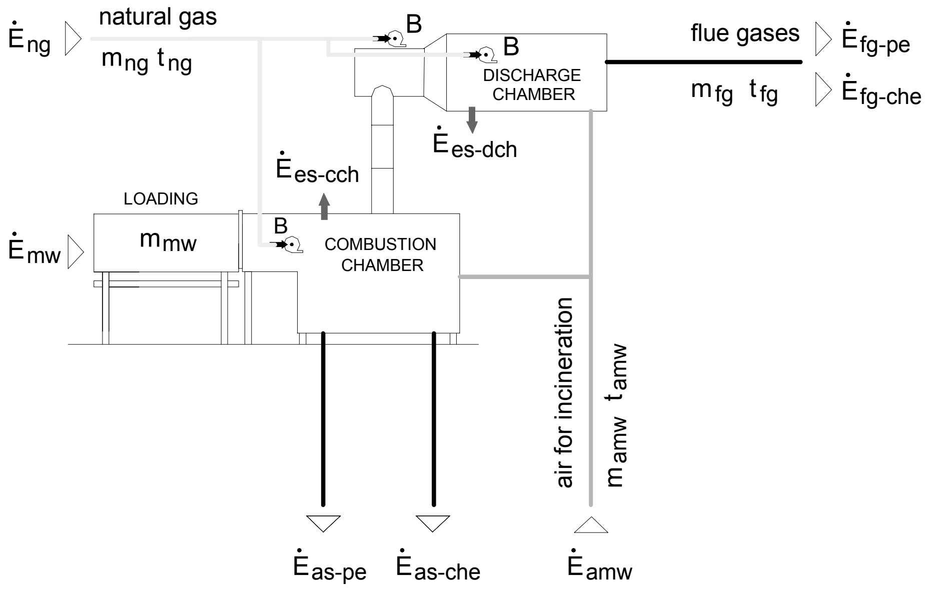

Fig. 2. Energy and mass flows of the incinerator.

...where the components of energy flux supplied to the system are on the left side of the equation (1), and the components of energy flux lost or carried away from the installation are on the right side.

After introducing the subsequent equations:

$$\dot{E}_{ng} = \dot{E}_{ng-cch} + \dot{E}_{ng-dch} \tag{2}$$

$$\dot{E}_{amw} = \dot{E}_{amw-cch} + \dot{E}_{amw-dch} \tag{3}$$

$$\dot{E}_{ang} = \dot{E}_{ang-cch} + \dot{E}_{ang-dch} \tag{4}$$

...equation (1) has the following form:

$$\begin{gathered}\dot{E}_{mw} + \dot{E}_{ng-cch} + \dot{E}_{ng-dch} + \dot{E}_{amw-cch} + \dot{E}_{amw-dch} + \\ \dot{E}_{ang-cch} + \dot{E}_{ang-dch} = \dot{E}_{as-pe} + \dot{E}_{as-che} + \dot{E}_{es-cch} + \\ \dot{E}_{es-dch} + \dot{E}_{fg-pe} + \dot{E}_{fg-che}\end{gathered} \tag{5}$$

Mass Balance of the System

The equation for the mass balance of the waste handling system can be written as follows:

$$\dot{m}_{mw} + \dot{m}_{ng} + \dot{m}_{amw} + \dot{m}_{ang} = \dot{m}_{as} + \dot{m}_{fg} \tag{6}$$

...where the components representing mass supplied to the system are on the left side of the equation (6), and the components carried away from the installation are on the right side.

After introducing the subsequent equations:

$$\dot{m}_{ng} = \dot{m}_{ng-cch} + \dot{m}_{ng-dch} \tag{7}$$

$$\dot{m}_{amw} = \dot{m}_{amw-cch} + \dot{m}_{amw-dch} \tag{8}$$

$$\dot{m}_{ang} = \dot{m}_{ang-cch} + \dot{m}_{ang-dch} \tag{9}$$

...equation (6) has the following form:

$$\begin{gathered}\dot{m}_{mw} + \dot{m}_{ng-cch} + \dot{m}_{ng-dch} + \dot{m}_{amw-cch} + \\ \dot{m}_{amw-dch} + \dot{m}_{ang-cch} + \dot{m}_{ang-dch} = \dot{m}_{as} + \dot{m}_{fg}\end{gathered} \tag{10}$$

Heating Value of Medical Waste

The heating value of medical waste was determined based on the energy and mass balances (5) according to the following formula:

$$q_{mw} = \frac{\begin{gathered}\dot{E}_{as-pe} + \dot{E}_{as-che} + \dot{E}_{es-cch} + \dot{E}_{es-dch} + \dot{E}_{fg-pe} + \dot{E}_{fg-che} - \\ \dot{E}_{ng-cch} - \dot{E}_{ng-dch} - \dot{E}_{amw-cch} - \dot{E}_{amw-dch} - \dot{E}_{ang-cch} - \dot{E}_{ang-dch}\end{gathered}}{\dot{m}_{mw}} \tag{11}$$

...where:

$$\dot{E}_{mw} = \dot{m}_{mw} \cdot q_{mw} \tag{12}$$

$$\begin{gathered}\dot{m}_{mw} = \dot{m}_{as} + \dot{m}_{fg} - \dot{m}_{ng-cch} - \dot{m}_{ng-dch} - \\ \dot{m}_{amw-cch} - \dot{m}_{amw-dch} - \dot{m}_{ang-cch} - \dot{m}_{ang-dch}\end{gathered} \tag{13}$$

Description of the Measurement System

The measurement system consists of two basic units: (a) a measurement unit of system energy fluxes, and (b) a system for the continuous control of flue gases.

a) The measurement unit (Fig. 3) of energy fluxes supplied to and carried away from the investigated system assesses the following:

- the chemical enthalpy flux in the secondary fuel supplied to the combustion chamber is measured with a Vortex flowmeter with a precision of 1.25% (GM1),
- the chemical enthalpy flux of the secondary fuel supplied to the discharge chamber, measured as the difference between GM and GM1,
- the physical enthalpy flux of air used for burning fuel wastes in the combustion chamber, measured by a Vortex flowmeter with a precision of 1.25% (AM1),
- the physical enthalpy flux of air used for after-burning of flue gases in the discharge chamber, measured by a Vortex flowmeter with a precision of 1.25% (AM2).

The enthalpy fluxes of air used for the burning of natural gas in the combustion chamber ($\dot{E}_{ang-cch}$) and the discharge chamber ($\dot{E}_{ang-dch}$) were determined with the assumption that the burner worked with a constant amount of excess air. Thus, before the tests, both burners were adjusted in such a way that in the full range of thermal power, the coefficient of excess air used for secondary fuel combustion was constant. As the quantity of gas consumption in the individual chambers was known, we also knew the quantity of air used for secondary fuel combustion. The temperature of the air for natural gas combustion was measured with a temperature sensor (t_i). Moreover, the quantity of slag was also measured. The calorific value of waste treated in the incinerator was determined from equation (11) of the energy flux balance.

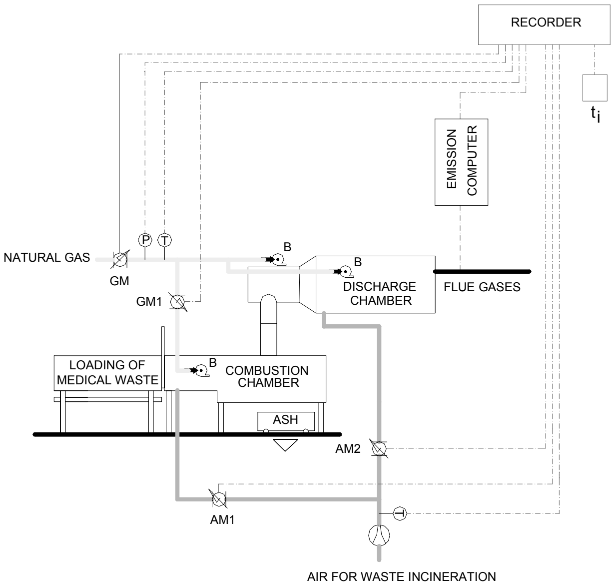

Fig. 3. Measurement system of energy fluxes supplied to the investigated installation.

b) The system for the continuous control of flue gases consists of:

- a gas sampling system,
- a system for flue gas measurement, dustiness, and reference parameters (static pressure, temperature, flue gases velocity), which is indispensable for calculations, with a precision of 2%,
- a measurement box complete with flue gas analyzers (Fig. 4),
- concentrators of measurement data that convert analog data into digital data as it is transmitted via analyzers into detectors (Fig. 4),
- an emission computer for activation, archiving, verification, and presentation of measurement data, as well as for creating graphs and reports (Fig. 4).

Results and Analysis

Characteristics of Flue Gases Exiting the Recovery Boiler, Natural Gas Used for Combustion, and Medical Waste

Table 1 shows the flue gas composition with variable parameters after the recovery boiler. This variation is caused by the heterogeneous composition of the incinerated waste.

Fig. 4. Gas sampling system (measurements of flue gas fluxes and dustiness).

Table 1. Flue gas composition after the recovery boiler.

Type of measured parameter	Min	Max
CO_2 [kg/h]	211.0	317.5
O_2 [kg/h]	385.6	572.5
H_2O [kg/h]	134.6	351.1
Other compounds [kg/h] (CO, NO_x, SO_2, HCl, HF, volatile dust)	1.7	9.9

Table 2. Chemical composition of natural gas.

Methane [%]	97.51
Ethane [%]	1.06
Propane [%]	0.37
CO_2 [%]	0.05
Nitrogen [%]	0.81
Others [%]	0.20

The natural gas used for incinerating the medical waste was comprised of 97.5% methane, and its calorific value was 36.2 MJ/N·m^3. A detailed description of the natural gas composition is shown in Table 2.

It was difficult to determine the elementary composition of the medical waste because of its heterogeneity. Hospital documentation revealed that plastics were the main components of the medical waste. The plastics composed 55-70% of the total waste mass, and other components included paper, medicines, organic wastes, metal, lint, and cotton.

Energy Flux Supplied to the Incinerator

The energy flux was supplied to the incinerator as medical waste, natural gas, and air used for their combustion. As seen in Fig. 5, the greatest energy flux represents the waste. The values of the flux varied from 80.9 kW to 1,119.8 kW. The mean value of the chemical enthalpy flux as medical waste was $\dot{E}_{mw}$=600.2 kW. The energy flux as natural gas (secondary fuel), in turn, fluctuated from 126.5 kW to 811.0 kW, reaching an average value of $\dot{E}_{ng}$=415.7 kW during the investigation. Because of the high heating value and low humidity of medical waste, the thermal treatment process in the combustion chamber fulfilled the criterion of stable combustion (autothermal combustion). The average temperature in the combustion chamber was 665.5ºC during the testing period. At the standard conditions of the incinerator operation there was no gas consumption in the combustion chamber. The gas burners supporting the chamber activated only during the installation start-up.

The temperature of air used for the medical waste combustion oscillated between t_{amw}=93.7ºC and 127.5ºC, and the enthalpy flux in air was between $\dot{E}_{amw}$=5.2 kW and 95.2 kW. The air used for natural gas combustion was taken directly from the surroundings (incineration room). The temperature of the air fluctuated between t_i=t_{ang}=25.2ºC and 29.5ºC. The enthalpy flux in this air did not exceed $\dot{E}_{ang}$=3.2 kW.

Energy Flux Lost or Carried Away from the System

The physical and chemical enthalpy fluxes of the flue gases were removed from the incineration system after the discharge chamber. The temperature of the flue gases oscillated between t_{fg}=1,102.7ºC and 1,167.5ºC. As seen in Fig. 6, the energy flux of flue gases removed from the incinerator varied considerably and fluctuated between 202.3 kW and 1,530.1 kW. The average value of the energy flux obtained in the testing period was $\dot{E}_{fg}$=1,012.9 kW. Because there was only a trace amount of carbon monoxide in the flue gases (0.1-1.1 kg/h), the energy flux carried away as chemical enthalpy was negligible.

Heat flux is lost from the incinerator to the environment through the external surfaces of the combustion and discharge chambers, as well as from the physical and chemical enthalpy fluxes of the exiting slag and ash. Fig. 7 shows that the energy flux lost through the external surfaces of the incinerator had an approximately constant value. The mean value of the heat flux lost due to heat transfer through the combustion chamber was $\dot{E}_{es\text{-}cch}$=26.4 kW, and that through

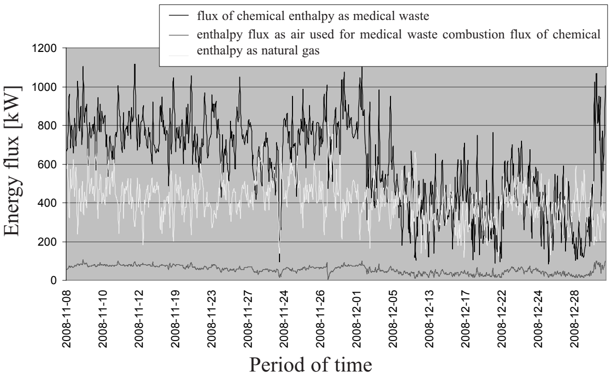

Fig. 5. Energy flux supplied to the incinerator.

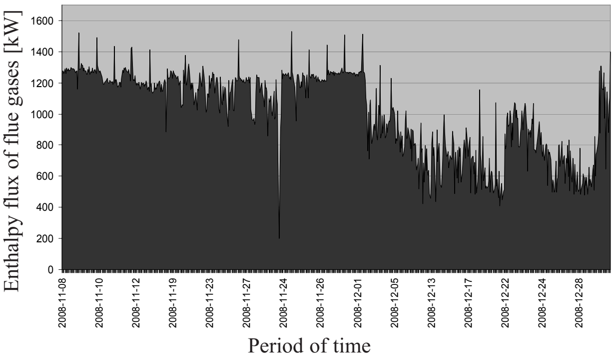

Fig. 6. Physical and chemical enthalpy flux of flue gases exiting the discharge chamber.

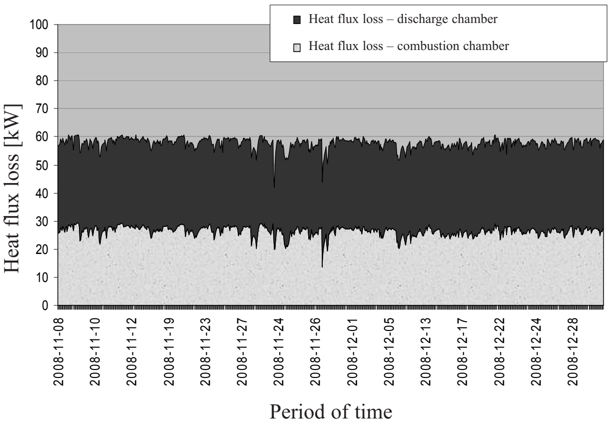

Fig. 7. Heat flux lost to the atmosphere through the external surfaces of the combustion and discharge chambers.

the discharge chamber was $\dot{E}_{es\text{-}dch}$=31.5 kW. The energy flux losses due to deslagging and deashing were not significant. Neither the physical enthalpy flux nor the chemical enthalpy flux exceeded 3 kW in each case.

Heating Value of Medical Waste

The tests showed (Fig. 6) that the heating value of medical waste is highly variable. It should be noted that the amount of burned waste fluctuated in the range from $\dot{m}_{mw}$=70 kg/h to 140 kg/h over the entire investigation period. The heating value of medical waste during the tests ranged from 8.5 MJ/kg to 41.2 MJ/kg, with a mean value of q_{mw}=19.1 MJ/kg. The calorific value of the medical waste was determined by Eq. 11. The measurements were carried out at a steady state, excluding start-ups and damping periods.

Accuracy of the Measurement Analysis

The measurement uncertainties of the lower heating value were determined by the total differential method. The maximum and probable measurement uncertainties for the calorific value of medical waste were determined using formulas (14) and (15):

$$\frac{u_{(q_{mw})\max}}{q_{mw}} = \pm \left[\sum_{i=1}^{n} \frac{u_{(x_i)}}{x_i} \right] \tag{14}$$

$$\frac{u_{(q_{mw})\,prob}}{q_{mw}} = \sqrt{\sum_{i=1}^{n} \left(\frac{u_{(x_i)}}{x_i} \right)^2} \tag{15}$$

The results of formulas (14) and (15) are shown in Table 3.

Table 3. Measurement uncertainty of the lower heating value of medical waste determined for a mean heating value.

Probable measured deviation of the lower heating value (MJ/kg)	19.1±0.89
Maximum measured deviation of the lower heating value (MJ/kg)	19.1±0.48

Validation of Experimental Studies

The validation process of the experimental studies involved the verification of the system mass balance. The flux of the flue gases obtained via measurements was compared with the value determined by the balance calculations.

The amounts of waste, secondary fuel, air used for combustion, slag, and ash were measured during the investigation. The mean calculated flux of the flue gases, which was equal to the total amount of medical waste, secondary fuel, and air for combustion (without slag and ash), was compared with the results obtained by the flue gas continuous control panel. The maximal difference between the mean flux and the measured flux was 4.6%.

Conclusions

This work describes experimental studies on the heating value of medical waste using the input-output method. The incineration system consisted of a loading unit, a combustion chamber, and a thermoreactor. The tests were carried out in the Oncological Hospital in Bydgoszcz. Medical wastes were supplied as primary fuel, and high-methane natural gas fed the system as secondary fuel. The investigation lasted for three months.

The study showed that the medical waste was characterized by a high calorific value and low humidity; hence, the thermal treatment process was steady (autothermal). The mean temperature in the combustion chamber was 665.5ºC. When the incinerator worked at standard conditions, there was no gas consumption in the combustion chamber. The gas burners in the primary chamber switched on only during the system start-up. The tests revealed that the heating value of the burned wastes was highly variable. The amount of incinerated wastes varied between $\dot{m}_{mw}$=70 kg/h and 140 kg/h during the testing period. The heating value of medical

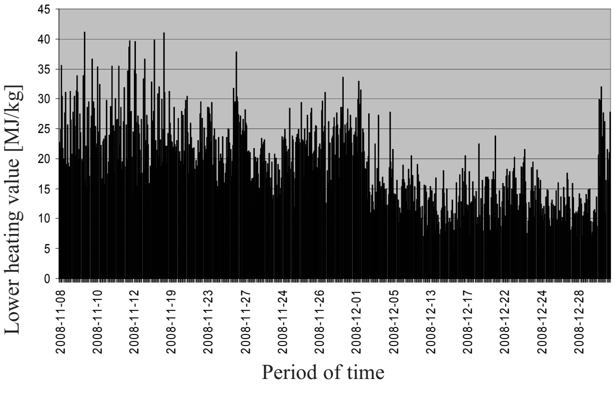

Fig. 8. Lower heating value of medical waste.

wastes fluctuated between 8.5 MJ/kg and 41.2 MJ/kg, reaching the average rate of q_{mw}=19.1 MJ/kg. The measurements were carried out at steady state, disregarding the start-up periods and damping periods of the furnace.

The obtained results can be helpful at the design stage of incinerators, for example, to calculate specifications for combustion chambers or discharge chambers (thermoreactors). The knowledge of waste heating values permits the calculation of the amount of secondary fuel or the determination of the energy efficiency of the incinerator together with the heat recovery boiler.

Nomenclature

$\dot{E}_{ang}$ – enthalpy flux with air used for natural gas combustion (kW)
$\dot{E}_{ang-cch}$ – enthalpy flux with air used for natural gas combustion in the combustion chamber (kW)
$\dot{E}_{ang-dch}$ – enthalpy flux with air used for natural gas combustion in the discharge chamber (kW)
$\dot{E}_{amw}$ – enthalpy flux with air used for medical waste incineration (kW)
$\dot{E}_{amw-cch}$ – enthalpy flux with air used for waste incineration in the combustion chamber (kW)
$\dot{E}_{amw-dch}$ – enthalpy flux with air used for after-burning gases in the discharge chamber (kW)
$\dot{E}_{as-che}$ – chemical enthalpy flux of hot ash in the combustion chamber (kW)
$\dot{E}_{as-pe}$ – physical enthalpy flux of hot ash in the combustion chamber (kW)
$\dot{E}_{es-cch}$ – heat flux lost to the environment through the external surface of the combustion chamber (kW)
$\dot{E}_{es-dch}$ – heat flux lost to the environment through the external surface of the discharge chamber (kW)
$\dot{E}_{fg}$ – enthalpy flux of flue gases (kW)
$\dot{E}_{fg-che}$ – chemical enthalpy flux of flue gases (kW)
$\dot{E}_{fg-pe}$ – physical enthalpy flux of flue gases (kW)
$\dot{E}_{mw}$ – flux of chemical enthalpy supplied as medical waste (kW)
$\dot{E}_{ng}$ – flux of chemical enthalpy as natural gas supplied to the incinerator (kW)
$\dot{E}_{ng-cch}$ – flux of chemical enthalpy as natural gas supplied to the combustion chamber (kW)
$\dot{E}_{ng-dch}$ – flux of chemical enthalpy as natural gas supplied to the discharge chamber (kW)
$\dot{m}_{as}$ – flux of ash mass (kg/h)
$\dot{m}_{amw}$ – flux of air mass used for medical waste combustion (kg/h)
$\dot{m}_{amw-cch}$ – flux of air mass used for medical waste combustion in the combustion chamber (kg/h)
$\dot{m}_{amw-dch}$ – flux of air mass used for medical waste combustion in the discharge chamber (kg/h)
$\dot{m}_{ang}$ – flux of air mass used for natural gas combustion (kg/h)
$\dot{m}_{ang-cch}$ – flux of air mass used for natural gas combustion in the combustion chamber (kg/h)
$\dot{m}_{ang-dch}$ – flux of air mass used for natural gas combustion in the discharge chamber (kg/h)
$\dot{m}_{fg}$ – flux of flue gas mass (kg/h)
$\dot{m}_{mw}$ – flux of medical waste mass (kg/h)
$\dot{m}_{ng}$ – flux of natural gas mass (kg/h)
$\dot{m}_{ng-cch}$ – flux of natural gas mass supplied to the combustion chamber (kg/h)
$\dot{m}_{ng-dch}$ – flux of natural gas mass supplied to the discharge chamber (kg/h)
t_{ang} – air temperature used for natural gas combustion (ºC)
t_{amw} – air temperature used for medical waste incineration (ºC)
t_{fg} – temperature of flue gases (ºC)
t_i – indoor air temperature (ºC)
t_{ng} – temperature of natural gas (ºC)
q_{mw} – low heating value of medical waste (MJ/kg)

Subscripts

AM1 – air meter (air used for medical waste incineration – combustion chamber)
AM2 – air meter (air used for after-burning gases – discharge chamber)
B – natural gas-fired burner
GM – total gas meter
GM1 – gas meter – combustion chamber

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