ENERGY BALANCE OF A STEAM BOILER FIRED WITH BIOMASS

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Abstract

The paper presents preliminary results of investigations of the energy balance of a steam boiler fired with wood wastes of different moisture content. The efficiency of the boiler was determined. There were shown actions required for making full and detailed analysis of boiler's operation. The need for the reliability (accuracy) analysis of calculations was indicated.

Key words: *steam boiler, biomass, Sankey diagram, algorithm of calculations, reliability analysis*

INTRODUCTION

A modern steam boiler was installed in a company processing wood and other plant based materials. The production processes of the company were characterized by high steam demand. The furnace of the boiler was equipped with a sloping grate in which waste products of high moisture content are burned. The wastes are further called as biomass. The furnace chamber was additionally equipped a burner for combustion of small particles after grinding. The moisture content of the particles was low. The particles are further called as dust. The same burner was combusting natural gas during starting the installation or during emergency cases.

Shortly after installing the boiler the question was put on the effectiveness of the system. It was decided to make the energy balance and determine the efficiency of the system. The atypical solutions of some elements of the boiler as well as the control system forced to use an atypical algorithm of balance calculations.

METHODS

In order to make an energy balance it is required to determine or distinguish an investigated system and to close it with an energy balance boundary. Next step consists of constructing balance equations of the system and determining parameters of individual media, i.e. air and combustion gasses, water and steam, fuel, moisture content and heat. In order to ensure solvability of the system of equations the number of unknowns in the system has to be equal to the number of the equations. In some cases additional relations between the properties of the system have to be found, i.e. additional equations are defined. Also supplementary measurements can be done to increase the system of input data. After defining and solving the system of equations the algorithm of calculations is defined and the numerical analysis is made.

During starting the investigations of the boiler some measuring systems were not working and some values were registered in a monthly cycle. Therefore, the balance was made for mean values of a given month.

The detailed description of the boiler as well as the way of constructing equations and solving their system was given by Pawlak (2008). The algorithm of the balance calculations was constructed presented in the study.

INPUT DATA

The following values measured by the control and measuring system were used for performing the calculations.

- temperature of feed water: t_w = 105 ± 5°C
- water pressure: p_w = 4.9 ± 0.1 MPa
- mass flow rate of water: $\dot{M}_w$ = (7.6 ± 0.1)·10^6 kg/month
- heat flow rate of superheated steam: $\dot{Q}_D$ = (24.5 ± 0.1)·10^9 kJ/month
- ambient air temperature: t_{pz} = 2.6 ± 1°C
- ambient air relative humidity: φ_z = 0.68 ± 0.02
- temperature of air surrounding the boiler: t_{pw} = 46 ± 2°C
- relative humidity of air surrounding the boiler: φ_w = 0.13 ± 0.02
- volume flow rate of air used for combustion: $\dot{V}_{Npw}$ = (13.6 ± 0.2)·10^9 m^3/month
- outlet temperature of combustion gas: t_s = 210 ± 5°C
- mass flow rate of combusted dust: $\dot{B}_p$ = (1.0 ± 0.1)·10^6 kg/month
- mass flow rate of combusted biomass: $\dot{B}_b$ = (1.9 ± 0.1)·10^6 kg/month
- volume flow rate of combusted gas: $\dot{V}_{Ng}$ = (30.5 ± 0.1)·10^3 m_N^3/month
- hydrogen mass fraction in dust: h_p = 0.055 ± 0.001 kg/kg
- hydrogen mass fraction in biomass: h_b = 0.052 ± 0.001 kg/kg
- moisture mass fraction in dust: w_p = 0.05 ± 0.01 kg/kg
- moisture mass fraction in biomass: w_b = 0.34 ± 0.01 kg/kg
- ash mass fraction in dust: u_p = 0.035 ± 0.001 kg/kg
- ash mass fraction in biomass: u_b = 0.029 ± 0.001 kg/kg
- net calorific value of dust: Q_{ip} = (17.8 ±1.0)·10^3 kJ/kg
- net calorific value of biomass: Q_{ib} = (11.8 ±1.0)·10^3 kJ/kg

The listed above values are the mean values determined for a month in which measurements were done. The values of errors (uncertainty) of measurements were estimated on the basis of information on methods and conditions of the measurements.

The calculations require also data on other values which are present in the formulas and equations of the balance. The majority of the data are constants taken from the literature (Guzenda and Olek 2002):

- heat of evaporation of water: r = 2501 ± 0.8 kJ/kg
- enthalpy of feed water:
  - for t_w = 105°C and p_w = 4.9 MPa: h_w = 441.8± 0.1 kJ/kg
- heat capacity of steam: c_D = 1.86 ± 0.005 kJ/(kg·K)
- molecular mass of steam: M_D = 18.01 ± 0.005 kg/kmol
- saturation pressure of steam in air:
  - at temperature t_{pz}: p_{nz} = 0.000739 ± 0.000001 MPa
  - at temperature t_{pw}: p_{nw} = 0.0103 ± 0.0001 MPa
- ratio of gas constants of air and steam: R_{ps}/R_D = 0.622 ± 0.001
- heat capacity of dry air and dry combustion gas: c_{ps} = 1.01 ± 0.01 kJ/(kg·K)
- molecular mass of dry air: M_{ps} = 28.96 ± 0.005 kg/kmol
- barometric pressure: p_b = 0.1 ± 0.002 MPa
- volume of 1 kilomol of gas in the normal conditions: $\overline{v}_N$ = 22.7 ± 0.01 m^3/kmol
- molecular mass of methane: M_m = 16.04 ± 0.005 kg/kmol
- hydrogen mass fraction in natural gas: h_g = 0.25 ± 0.01 kg/kg
- moisture mass fraction in natural gas: w_g = 0 + 0.01 kg/kg
- ash mass fraction in natural gas u_g = 0 + 0.001 kg/kg
- heat capacity of natural gas: Q_{ig} = (38.1 ±0.1)·10^3 kJ/m^3

The presented above sets of input data were selected in such a way that they enabled calculations according to the algorithm presented below.

ALGORITHM OF CALCULATIONS AND RESULTS

The calculations were made according to the algorithm presented below and the input data given in the previous section. The scope of calculations was limited to determine elements of the heat balance as the most important factors applied for the estimation of the efficiency of the installation. The course of the calculations was as follows:

- absolute humidity of air used for combustion (air surrounding the boiler):

$$X_{pw} = \frac{R_{ps}}{R_D} \cdot \frac{\varphi_w \cdot p_{nw}}{p_b - \varphi_w \cdot p_{nw}} = ... = 0.00844 \text{ kg/kg} \quad (1)$$

- enthalpy of air for combustion:

$$h_{pw} = c_{ps} \cdot t_{pw} + X_{pw} \cdot (r + c_D \cdot t_{pw}) = \dots = 68.30 \text{ kJ/kg} \quad (2)$$

- absolute humidity of ambient air:

$$X_{pz} = \frac{R_{ps}}{R_D} \cdot \frac{\varphi_z \cdot p_{nz}}{p_b - \varphi_z \cdot p_{nz}} = ... = 0.003141 \text{ kg/kg} \quad (3)$$

- enthalpy of ambient air:

$$h_{pz} = c_{ps} \cdot t_{pz} + X_{pz} \cdot (r + c_D \cdot t_{pz}) = \dots = 10.50 \text{ kJ/kg} \quad (4)$$

- mass flow rate of moist air used for combustion:

$$\dot{M}_{pw} = \frac{\dot{V}_{Npw}}{\overline{v}_N} \cdot \frac{(1 + X_{pw}) \cdot M_{ps} \cdot M_D}{X_{pw} \cdot M_{ps} + M_D} = ... = 17.26 \cdot 10^6 \text{ kg/month} \quad (5)$$

- mass flow rate of moisture included in air used for combustion:

$$\dot{M}_{wp} = \frac{\dot{V}_{Npw}}{\overline{v}_N} \cdot \frac{X_{pw} \cdot M_{ps} \cdot M_D}{X_{pw} \cdot M_{ps} + M_D} = ... = 0.1445 \cdot 10^6 \text{ kg/month} \quad (6)$$

- mass flow rate of combusted gas:

$$\dot{B}_g = \frac{\dot{V}_{Ng} \cdot M_m}{\overline{v}_N} = ... = 0.02155 \cdot 10^6 \text{ kg/month} \quad (7)$$

- mass flow rate of combusted fuel:

$$\dot{B} = \dot{B}_p + \dot{B}_b + \dot{B}_g = ... = 2.922 \cdot 10^6 \text{ kg/month} \quad (8)$$

- mass flow rate of ash in fuel:

$$\dot{P} = u_p \cdot \dot{B}_p + u_b \cdot \dot{B}_b + u_g \cdot \dot{B}_g = ... = 0.0901 \cdot 10^6 \text{ kg/month} \quad (9)$$

- mass flow rate of moisture in fuel:

$$\dot{M}_{wB} = \dot{B}_p \cdot \left(9 \cdot h_p + w_p\right) + \dot{B}_b \cdot \left(9 \cdot h_b + w_b\right) + \dot{B}_g \cdot \left(9 \cdot h_g + w_g\right) = ... = 2.129 \cdot 10^6 \text{ kg/month} \quad (10)$$

- mass flow rate of moisture in combustion gas:

$$\dot{M}_{ws} = \dot{M}_{wB} + \dot{M}_{wp} = ... = 2.274 \cdot 10^6 \text{ kg/month} \quad (11)$$

- mass flow rate of moist combustion gas:

$$\dot{M}_{sw} = \dot{B} - \dot{P} + \dot{M}_{pw} = ... = 20.09 \cdot 10^6 \text{ kg/month} \quad (12)$$

- absolute humidity of combustion gas:

$$X_s = \frac{\dot{M}_{ws}}{\dot{M}_{sw} - \dot{M}_{ws}} = ... = 0.1276 \text{ kg/kg} \quad (13)$$

- enthalpy of moist combustion gas at outlet:

$$h_{sw} = c_{ps} \cdot t_s + X_s \cdot (r + c_D \cdot t_s) = \ldots = 581.1 \text{ kJ/kg} \quad (14)$$

- heat flow rate of feed water:

$$\dot{Q}_w = \dot{M}_w \cdot h_w = ... = 3.358 \cdot 10^9 \text{ kJ/month} \quad (15)$$

- heat flow rate of air used for combustion:

$$\dot{Q}_{pw} = \dot{M}_{pw} \cdot h_{pw} = ... = 1.179 \cdot 10^9 \text{ kJ/month} \quad (16)$$

- heat flow rate of combusted dust:

$$\dot{Q}_p = \dot{B}_p \cdot Q_{ip} = ... = 17.8 \cdot 10^9 \text{ kJ/month} \quad (17)$$

- heat flow rate of combusted biomass:

$$\dot{Q}_b = \dot{B}_b \cdot Q_{ib} = ... = 22.42 \cdot 10^9 \text{ kJ/month} \quad (18)$$

- heat flow rate of combusted gas:

$$\dot{Q}_g = \dot{V}_{Ng} \cdot Q_{ig} = ... = 1.162 \cdot 10^9 \text{ kJ/month} \quad (19)$$

- heat flow rate of combusted fuel:

$$\dot{Q}_B = \dot{Q}_p + \dot{Q}_b + \dot{Q}_g = ... = 41.38 \cdot 10^9 \text{ kJ/month} \quad (20)$$

- heat flow rate lost with combustion gas at outlet:

$$\dot{Q}_{sw} = \dot{M}_{sw} \cdot h_{sw} = ... = 11.67 \cdot 10^9 \text{ kJ/month} \quad (21)$$

- heat flow rate lost to air surrounding the boiler:

$$\dot{Q}_{s1} = \dot{M}_{pw} \cdot \left(h_{pw} - h_{pz}\right) = ... = 0.9976 \cdot 10^9 \text{ kJ/month} \quad (22)$$

- heat flow rate lost due to incomplete and imperfect combustion:

$$\dot{Q}_{s2} = \dot{Q}_{pw} + \dot{Q}_B + \dot{Q}_w - \dot{Q}_D - \dot{Q}_{sw} - \dot{Q}_{s1} = ... = 8.749 \cdot 10^9 \text{ kJ/month} \quad (23)$$

- boiler efficiency:

$$\eta_k = \frac{\dot{Q}_D}{\dot{Q}_B} = ... = 0.592 \quad (24)$$

DISCUSSION

The results of the energy balance of the investigated boiler are presented in Figure 1 in the form of Sankey diagram.

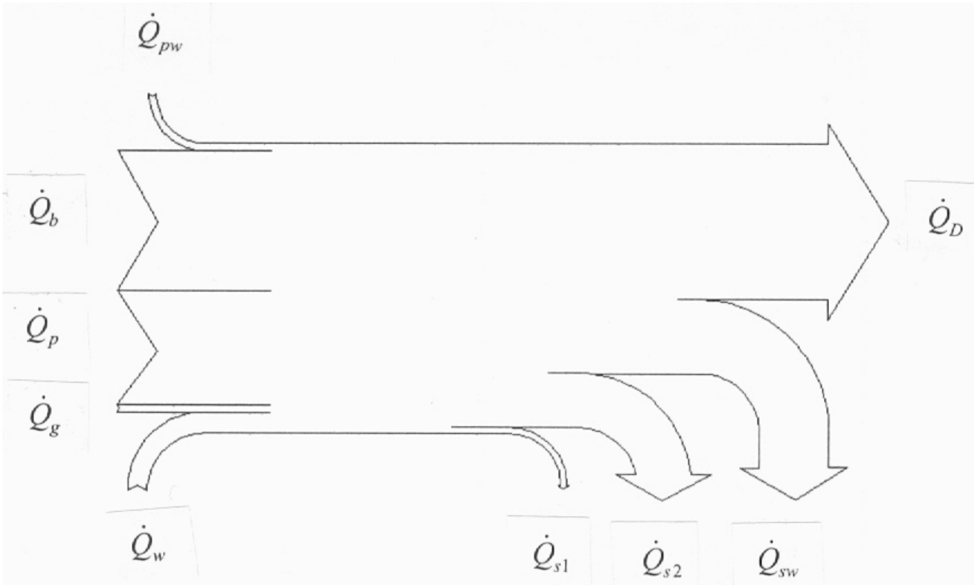

Figure 1 Energy balance of the boiler – Sankey diagram

Contents of individual heat flow rates are as follows:

- supplied heat: $\dot{Q}_{pw}$ = 2.6%, $\dot{Q}_b$ =48.8%, $\dot{Q}_p$ = 38.8%, $\dot{Q}_g$ = 2.5%, $\dot{Q}_w$ = 7.3%;
- outlet heat: $\dot{Q}_D$ = 53.4%, $\dot{Q}_{sw}$ = 25.4%, $\dot{Q}_{s1}$ = 2.2%, $\dot{Q}_{s2}$ = 19.0%.

The boiler was fired almost only by biomass and dust and heat obtained from gas combustion amounted to as little as 2.5% of heat supplied with fuel.

The highest flow rate of lost heat was the flow rate of heat carried out with combustion gas (25.4% although the significant portion of the heat was used in the steam superheater and water preheater). In fact the efficiency of combustion gas utilization is higher because the gas is used in drying processes carried out in the company. Such utilization of combustion gas is justified from the thermodynamic point of view (Longauer and Świgoń 1996). The estimation of that effectiveness requires to perform investigations of energy balance of dryers.

The efficiency of the boiler depends on its rating. Therefore, in order to perform full estimation of a boiler it is required to provide information on rating factor, time of boiler's operation during a day as well as range of rating changes. The variable conditions of boiler's operation cause increase of fuel consumption (Wróblewski et al. 1993). Such extended analysis will be possible when investigations of energy balance will be done for shorter time periods, i.e. shorter than a month and comparable to stabilized operation of the boiler.

It is justified to analyze the applied algorithm of balance calculations in order to estimate reliability of the obtained results of the numerical analysis.

CONCLUSIONS

1. The applied algorithm may be used for making energy balances of boilers. However, the reliability of results of calculations has to be analyzed.
2. The boiler efficiency was equal to 59.2% in a monthly cycle. The additional utilization of outlet combustion gas in drying processes increases the energetic efficiency of the company.
3. Full and detailed estimation of the boiler operation requires investigations performed in shorter time periods which can be compared to stabilized operation of the boiler.

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