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3D DIAGRAM OF HEAT BOILER EFFICIENCY FOR COMBUSTION OF FUELWOOD

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ABSTRACT

The paper analyses the influence of moisture content of fuelwood on the heat losses and the thermal efficiency of a boiler. The moisture content of fuelwood has a negative effect especially on the flue gas loss. There is presented the dependence of the thermal efficiency of a boiler for the boundary conditions: the moisture content of fuelwood $W^r = 10 \div 50\%$, range of temperatures of emitted flue gases from the boiler into the atmosphere $t_{fg} = 120 \div 200$ °C, nominal power 5−10 MW and the emissions meeting the emission standards: carbon monoxide $EL_{CO} = 250\ mg \cdot m^{-3}$ and fly ash $EL_{Cfa} = 50\ mg \cdot m^{-3}$. Dependence of the thermal efficiency of a boiler on the moisture content of fuelwood and temperature of flue gases is shown in the form of a 3D diagram.

Key words: boiler; fuelwood; combustion; thermal efficiency; 3D diagram.

INTRODUCTION

The efficiency of heat production from biofuels - fuelwood depends, according to the works (GOLONKOV *et al.* 1987, MARUTZKY, SEEGER 1999, DOMANSKI *et al.* 2007, MALAŤÁK, VACULÍK 2008, DZURENDA, JANDAČKA 2010, ŠOOŠ *et al.* 2012, DZURENDA, PŇAKOVIČ 2015, HRONCOVÁ *et al.* 2016, NOSEK *et al.* 2016), as much on the design of the heat generator as on the energy properties of fuelwood and the actual operation of the heat generator. The energy properties of fuelwood are crucially dependent on its moisture content, which adversely affects not only the basic energy properties, namely: higher heating value Q_s and lower heating value Q_n, but also the process of combustion in the furnace: flame temperature, generated amount of flue gases, the dew point of flue gases and emission production. The design of the exchanger of the heat generator influences the use of the heat content of flue gases - the process of cooling off before their emission into the atmosphere and thus the flue gas loss, as well. Currently, boilers of medium power using fuelwood reach the thermal efficiency of η_B= 75–85% and modern boiler units combusting homogenises biofuel - wood with guaranteed energy properties reach the efficiency of η_B = 92%. According to works (DZURENDA, JANDAČKA 2010, RAJNIAK *et al.* 1997, HOLOUBEK 2002), the standard boiler heat losses include: flue gas loss, loss in the form of volatile combustible and combustibles in solid residues, so called chemical and mechanical unburned carbon loss, loss by thermal radiation and convection of heat from the surface of the boiler.

The paper presents the analysis of the impact of moisture content fuelwood and temperature of flue gas on the thermal losses of the boiler. In a 3D coordinate system is presented the dependence of the thermal efficiency of the boiler at the moisture content of fuelwood for the boundary conditions: fuelwood moisture content $W^r = 10 \div 60$ %, temperature range of the flue gases emitted out of the boiler into the atmosphere $t_{fg} = 120 \div 200$ °C, nominal power 5–10 MW and of the emissions meeting the emission standards: carbon monoxide $EL_{CO} = 250$ mg·m^{-3} and fly ash $EL_{Cfa} = 50$ mg·m^{-3}.

EXPERIMENT

The thermal efficiency of the boiler is defined as the ratio of the heating capacity and power consumption of the boiler. One way to determine it is by using an indirect method, i.e. on the basis of standard heat losses of the boiler ξ_i. It is mathematically described by the equation:

$$\eta_B = \frac{Q_o}{Q_i} \cdot 100 = 100 - \sum \xi_i \ [\%] \tag{1}$$

Standard heat losses of the boiler producing heat by combusting fuelwood, according to the authors of (DZURENDA, JANDAČKA 2010, RAJNIAK *et al.* 1997, HOLOUBEK 2002), include the following heat losses:

$$\sum \xi_i = \xi_{fg} + \xi_{CO} + \xi_{Cfa} + \xi_{CA} + \xi_R \ [\%] \tag{2}$$

Flue gas loss (ξ_{fg}) the heat loss of the boiler caused by the abstraction of heat in flue gases out of the boiler into the atmosphere. It is defined as the difference between the enthalpy of flue gases emitted out of the boiler and the enthalpy of flue gases cooled down to the ambient temperature to the amount of heat produced by 1 kg of fuel. It can be determined by the following formula (RAJNIAK *et al.* 1997, DZURENDA, BANSKI 2015):

$$\xi_{fg} = \frac{V_{fg} \cdot c_p \cdot \left(t_{fg} - t_{fg\text{-}e}\right)}{Q_n} \cdot 100 \ [\%] \tag{3}$$

Heat loss caused by the combustible loss in flue gases - chemical unburned carbon loss ($\xi_{CO} + \xi_{fa}$) represents the loss due to incomplete combustion of volatile combustible matter of biofuel. It relates to the presence of: fly ash and soot C_{fa}, carbon monoxide CO, methane CH_4 or tars C_nH_m in flue gases emitted out of the boiler into the atmosphere. The most commonly occurring and measurable components of chemical unburned carbon loss from fuelwood combustion are these emissions: fly ash and soot C_{fa}, and carbon monoxide CO. The calculation of heat loss caused by the volatile combustible loss is described in the equations:

$$\xi_{CO} = \frac{10\ 200 \cdot X_{CO} \cdot V_{fg\text{-}d}}{Q_n} \cdot 100 \ [\%] \tag{4}$$

$$\xi_{C_{fa}} = \frac{32\ 600 \cdot X_{C_{fa}} \cdot V_{fg-d}}{Q_n} \cdot 100 \ [\%] \tag{5}$$

Heat loss caused by the combustible loss in solid residues - mechanical unburned carbon loss (ξ_C) occurs due to the overflow of solid combustible matter (charcoal) through the grate into the dustbin. It only occurs in grate furnaces while combusting solid fuel. The loss is presented in the formula:

$$\xi_{CA} = 32600 \cdot \frac{\frac{C_A}{100} \cdot \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right)}{Q_n} \cdot 100 \ [\%] \tag{6}$$

Heat loss caused by thermal radiation and convection of heat from the surface of the boiler into the ambient space (ξ_R) depends on the design of the heat generator, wall thickness, material, insulation and surface finish. To determine the heat loss caused by thermal radiation and convection of heat from the surface of the boiler into the ambient space, nomograms are used in practice, or the empirical formula:

$$\xi_R = \frac{4}{100 \cdot \sqrt[3]{P_m}} \cdot \frac{P_m}{P} \cdot 100 \; [\%] \tag{7}$$

The following equations describe the algorithm for calculating various parameters of heat losses dependent on the chemical composition of combustible matter C^{daf}, H^{daf}, O^{daf}, N^{daf}, ash content in the dry matter of fuelwood A^d, relative moisture content content of combusted fuelwood W^r and excess of combustion air λ:

The volume of wet flue gases from fuelwood combustion is described in equation (8). The calculation of flue gas volume does not reflect the negligible amount of water vapor present in the combustion air within the process of fuelwood combustion.

$$V_{fg} = \left[1{,}867 \cdot \frac{C^{daf}}{100} + 11{,}2 \cdot \frac{H^{daf}}{100} + 0{,}8 \cdot \frac{N^{daf}}{100} + V_{air} \cdot (\lambda - 0{,}21)\right] \cdot \left[1 - \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right) - \frac{W^r}{100}\right] + 1{,}24 \cdot \frac{W^r}{100} \quad [\mathrm{m_n^3 \cdot kg^{-1}}] \tag{8}$$

Stoichiometric air volume for the combustion of 1 kg of fuelwood:

$$V_{air} = \frac{1}{0.21} \cdot \left[1.87 \cdot \frac{C^{daf}}{100} + 5.6 \cdot \frac{H^{daf}}{100} + 0.8 \cdot \frac{N^{daf}}{100} - 0.7 \cdot \frac{O^{daf}}{100}\right] \quad [\mathrm{m_n^3 \cdot kg^{-1}}] \tag{9}$$

The volume of dry flue gases produced by the combustion of 1 kg of fuelwood:

$$\mathrm{V}_{fg-d} = \left[1{,}867 \cdot \frac{C^{daf}}{100} + 0{,}8 \cdot \frac{N^{daf}}{100} + 0{,}79 \cdot V_{air} + V_{air} \cdot (\lambda - 1)\right] \cdot \left[1 - \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right) - \frac{W^r}{100}\right] [\mathrm{m_n^3 \cdot kg^{-1}}] \tag{10}$$

The value of the mean specific heat capacity of 1 m_n^3 of flue gases at constant pressure is quantified by the equation:

$$c_p = c_{P\text{-}CO2} . X_{CO2} + c_{p\text{-}O2} . X_{O2} + c_{pN2} . X_{N2} + c_{p\text{-}H2O} . X_{H2O} \quad [\mathrm{kJ \cdot m_n^{-3} \cdot K^{-1}}] \tag{11}$$

The following equations describe the dependence of the specific heat capacity of 1 m_n^3 of various components of flue gases on temperature:

carbon dioxide $c_{p\text{-}CO2} = 0.0008 \cdot t + 1.6473$ [kJ·m_n^{-3}·K^{-1}] (12)
water vapor $c_{p\text{-}H2O} = 10^{-7} \cdot t^2 + 10^{-4} \cdot t + 1.4895$ [kJ·m_n^{-3}·K^{-1}] (13)
oxygen $c_{p\text{-}O2} = 5 \cdot 10^{-8} \cdot t^2 + 2 \cdot 10^{-4} \cdot t + 1.3036$ [kJ·m_n^{-3}·K^{-1}] (14)
nitrogen $c_{pN2} = 9 \cdot 10^{-8} . t^2 + 2.10^{-5} \cdot t + 1.3022$ [kJ·m_n^{-3}·K^{-1}] (15)

Tab. 1 Values of the mean specific heat capacity of 1 m_n^3 of flue gases at a constant pressure (RAJNIAK *et al.* 1997).

Temperature [°C]	$c_{p\text{-}i}$ - mean specific heat capacity of 1 m_n^3 of flue gases at constant pressure [kJ·m_n^{-3}·K^{-1}]			
	CO_2	O_2	N_2	H_2O
0	1.620	1.306	1.302	1.491
100	1.725	1.319	1.306	1.499
200	1.817	1.336	1.310	1.520
300	1.892	1.357	1.315	1.537
400	1.955	1.382	1.327	1.557
500	2.022	1.403	1.336	1.583
600	2.077	1.419	1.348	1.608

The volumetric proportions of the components of flue gases can be determined from the following equations:
Volumetric proportion of carbon dioxide in flue gases:

$$X_{CO_2} = \frac{1.867 \cdot \frac{C^{daf}}{100} \cdot \left[1 - \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right) - \frac{W^r}{100}\right]}{V_{fg}} \quad [-] \tag{16}$$

Volumetric proportion of nitrogen in flue gases:

$$X_{N_2} = \frac{\left(0.8 \cdot \frac{N^{daf}}{100} + 0.79 \cdot V_{air} \cdot \lambda\right) \cdot \left[1 - \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right) - \frac{W^r}{100}\right]}{V_{fg}} \quad [-] \tag{17}$$

Volumetric proportion of oxygen in flue gases:

$$X_{O_2} = \frac{0.21 \cdot V_{air} \cdot (\lambda - 1) \cdot \left[1 - \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right) - \frac{W^r}{100}\right]}{V_{fg}} \quad [-] \tag{18}$$

Volumetric proportion of water vapor in flue gases:

$$X_{H_2O} = \frac{11.2 \cdot \frac{H^{daf}}{100} \cdot \left[1 - \frac{A^d}{100}\left(1 - \frac{W^r}{100}\right) - \frac{W^r}{100}\right] + 1.24 \cdot \frac{W^r}{100}}{V_{fg}} \quad [-] \tag{19}$$

The heat value of biomass depending on its moisture content is described by the authors of (KOLLMANN 1951, JANDAČKA *et al.* 2007, SIMANOV 1995) as follows:

$$Q_n = 18840 - 21353 . \frac{W^r}{100} \quad [\mathrm{kJ \cdot kg^{-1}}] \tag{20}$$

In order to make the process of analysing the impact of fuelwood moisture content on the operational efficiency of the boiler more effective, a program in EXCEL has been developed - in the form of sheets where, on the basis of the following input data, the thermal efficiency of the boiler as well as its heat losses can be calculated: C^{daf}, H^{daf}, O^{daf}, N^{daf} - chemical composition of the combustible matter of fuelwood, W - relative moisture content of fuelwood, A^d - ash content of fuelwood, λ - excess of combustion air, t_e - temperature of the air in the atmosphere, t_{fg} - temperature of flue gases when emitted out of the boiler, X_{CA} - proportion of carbon in ash, X_{CO} - mass concentration of carbon monoxide (CO) and X_{Cfa} - mass concentration of soot and fly ash in dry flue gases.

RESULTS AND DISCUSSION

The given mathematical model of the impact of moisture content fuelwood on the heat loss and thermal efficiency of the boiler applies to fuelwood with the chemical composition of the combustible matter: $C^{daf} = 0.5 \pm 0.01$ [kg·kg^{-1}], $H^{daf} = 0.06 \pm 0.001$ [kg·kg^{-1}], $O^{daf} = 0.44 \pm 0.03$ [kg·kg^{-1}], and with the ash content $A^d = 0.01$[kg·kg^{-1}].

Table 2 presents the values of heat loss and the thermal efficiency of the boiler combusting fuelwood with the following moisture content values: $W^r = 10\%$, $W^r = 25\ \%$ a $W^r = 50\%$, at the excess of the combustion air $\lambda = 2.1$, the average temperature of the combustion air blown in the furnace of the boiler t_{air} = 10 °C, the temperature of the flue gases emitted out of the heat generator t_{fg} = 120 °C and t_{fg} = 200 °C, nominal power 7,5 MW and of the emissions meeting the emission standards: carbon monoxide EL_{CO} = 250 mg·m^{-3} and fly ash EL_{Cfa} = 50 mg·m^{-3}.

Tab. 2 Heat losses and the thermal efficiency of the boiler due to the moisture content of the combusted fuelwood W^r = 10%; W^r = 25 %; W^r = 50 % and the temperature of flue gases t_{fg} = 120 °C and t_{fg} = 120 °C.

Parameter	Heat loss of the boiler [%]					
Flue gas temperature t_{fg} [°C]	t_{fg} = 120 °C			t_{fg} = 200 °C		
Relative moisture content W^r [%]	10 %	25 %	50 %	10 %	25 %	50 %
Flue gas loss (ξ_{fg})	8.37	9.23	10.51	15.19	16.08	19.08
Heat loss caused by the volatile combustible loss in flue gases (ξ_{CO})	0.13	0.14	0.16	0.13	0.14	0.16
Heat loss caused by the involatile combustible loss in flue gases (ξ_{Cfa})	0.17	0.18	0.20	0.17	0.18	0.20
Heat loss caused by the involatile combustible loss in the ash (ξ_{CA})	0.18	0.19	0.21	0.18	0.19	0.21
Heat loss caused by thermal radiation and convection of heat from the surface of the boiler (ξ_R)	2.04	2.04	2.04	2.04	2.04	2.04
Thermal efficiency (η_K)	89.11	88.22	86.88	82.29	81.37	78.31

The analysis of the impact of fuelwood moisture content on heat loss has shown that the greatest heat loss of the boiler is the flue gas loss at both temperatures of flue gases t_{fg} = 120 °C and t_{fg} = 200 °C. Fuelwood moisture content causes increasing heat loss at the temperature of flue gases t_{fg} = 120 °C from $\xi_{B\text{-}w10\%}$ = 8.37 % to $\xi_{B\text{-}w50}$ = 10.51 % and at the temperature of flue gases t_{fg} = 200 °C from $\xi_{B\text{-}w10\%}$ = 15.19 % to $\xi_{B\text{-}w50\%}$ = 19.08. The other heat losses, such as volatile or involatile combustible loss in flue gases or mechanical unburned carbon loss, are in comparison with the flue gas loss much smaller and the impact of fuelwood moisture content does not exceed $\Delta\xi$ = 0,05%.

The analysis of the thermal efficiency and heat loss of the boiler combusting fuelwood has shown that the thermal efficiency of the boiler is largely dependent on the flue gas temperature and fuelwood moisture content. Based on the above, a visual aid has been created in order to promptly determine the thermal efficiency of a boiler dependent on the moisture content of fuelwood ranging between W^r = 10% and W^r = 50%, and the temperature of flue gases emitted out of a boiler into the atmosphere t_{fg} = 120 ÷ 200 °C in a 3D coordinate system (Fig. 1).

From the 3D diagram, the thermal efficiency of the boiler to the moisture content of the fuelwood and the temperature of the flue gas follows that, while the combustion of the fuelwood with a moisture content W=10%, temperature of exhaust gas emitted from the boiler to the atmosphere t_{fg} = 120°C the boiler reaches the thermal efficiency $\eta_{B\text{-}w10\%}$= 89% and under the same operating conditions, by burning firewood with moisture content w = 50% thermal efficiency of the boiler drops to $\eta_{B\text{-}w50\%}$ = 86,5%, i.e. by $_{\Delta}\eta_B$ = 2,5 %._With the increasing temperature of emitted flue gas, is stated even more significant decline of the boiler thermal efficiency. The combustion of fuelwood within the moisture content range W = 10 – 50%, at the temperature of emitted flue gas to the atmosphere t_{fg} = 200°C, is accompanied by a decrease of the boiler thermal efficiency in $_{\Delta}\eta_B$ = 5 %.

The average decrease in thermal efficiency of the boiler $_{\Delta}\eta_B$ = 0.8% at the increase in fuelwood moisture content by $_{\Delta}W^r$ = 10% is argument for reducing the moisture content of combusted fuelwood and using economically effective forms of pre-drying and drying fuelwood. The technologies suitable for these purposes are in Central Europe, as mentioned in works (JANDAČKA *et al.* 2007, DZURENDA *et al.* 2015, NOSEK, HOLUBCÍK 2016), natural drying of fuelwood in sheltered warehouses.

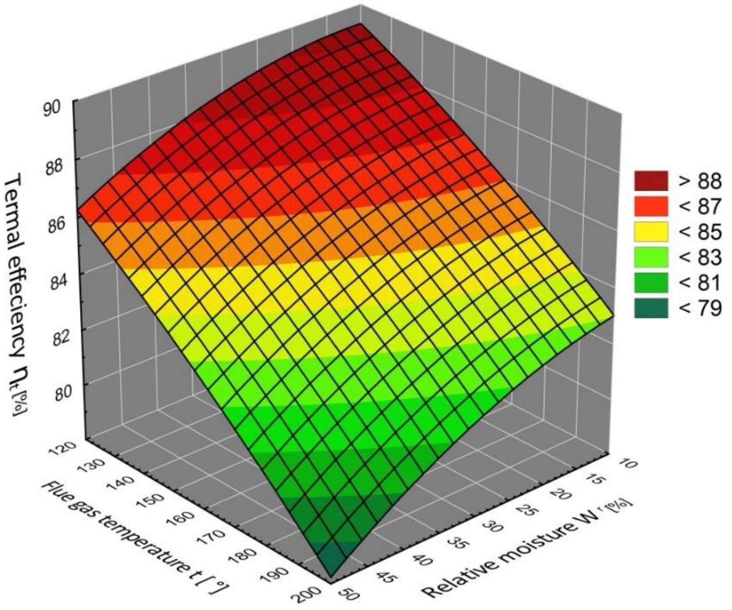

Fig. 1 Dependence of the impact of moisture content $W^r = 10 \div 50\%$ and flue gas temperature $t_{fg} = 120$ °C to $t_{fg} = 200$ °C on the thermal efficiency of a boiler combusting fuelwood.

Not only does the reduction of fuelwood moisture content before combustion increase the thermal efficiency and the effectiveness of heat production, but it also contributes to decreasing the heat load of the atmosphere by emitting heat in water vapor in flue gases (DZURENDA 2015).

CONCLUSION

Based on the analyses of standard heat loss of boilers, this paper in 3D diagram presents, dependence of the thermal efficiency of a boiler on moisture content fuelwood and temperature of flue gases emitted out of the boiler into the atmosphere. The boundary conditions are given by the relative moisture content of fuelwood: $W^r = 10 \div 50\%$, the temperature of flue gas emitted into the atmosphere: $t_{fg} = 120 \div 200$ °C, nominal power 5−10 MW and the emissions not exceeding the emission standards: carbon monoxide $EL_{CO} = 250$ mg·m^{-3} and fly ash EL_{Cfa} 50 mg·m^{-3}.

From the analysis and presentation depending on the moisture content of fuelwood boiler thermal efficiency in a 3D diagram shows that with increasing moisture content of fuelwood decreases thermal efficiency.

Until the combustion of the fuelwood with a moisture content W = 10%, temperature of exhaust gas emitted from the boiler to the atmosphere $t_{fg} = 120$ ° C the boiler reaches the thermal efficiency $\eta_{B\text{-}w10\%} = 89\%$ and under the same operating conditions, by burning firewood with moisture content w = 50% thermal efficiency of the boiler drops to $\eta_{B\text{-}w50\%} =$ 86,5%. With the increasing temperature of emitted flue gas, there is stated even more significant decline of the boiler thermal efficiency. The combustion of fuelwood within the moisture content range W = 10 – 50%, at the temperature of emitted flue gas to the atmosphere $t_{fg} = 200^{o}$C, is accompanied by a decrease in thermal efficiency of the boiler $\eta_{B\text{-}w10\%} = 83\%$ to $\eta_{B\text{-}w50\%} = 78\%$.

The average decrease in thermal efficiency of the boiler $_{\Delta}\eta_B = 0.8\%$ at the increase in fuelwood moisture content by $_{\Delta}W^r = 10\%$ is argument for reducing the moisture content of combusted fuelwood and using economically effective forms of pre-drying and drying fuelwood.

3D diagram the thermal efficiency of the boiler on the moisture content fuelwood and temperature flue gas emitted into the atmosphere can be helpful operators boilers for rapid determination of the effectiveness of heat from fuelwood through the thermal efficiency of the boiler.

Symbols:

A^d - proportional weight of ash in dry fuelwood, %
c_{pCO2} - mean specific heat capacity of carbon dioxide, kJ/m^3·K
c_{pH2O} - mean specific heat capacity of water wapor, kJ/m^3·K
c_{pO2} - mean specific heat capacity of oxygen, kJ/m^3·K
c_{pN2} - mean specific heat capacity of nitrogen, kJ/m^3·K
C^{daf} - proportional weight of carbon in the combustible matter of fuelwood, %
C_A - weight of carbon in the ash, n %
H^{daf} - proportional weight of hydrogen in the combustible matter of fuelwood, %
N^{daf} - proportional weight of nitrogen in the combustible matter of fuelwood, %
O^{daf} - proportional weight of oxygen in the combustible matter of fuelwood, %
t_{air} - combustion air temperature, °C
t_{fg} - flue gas temperature, °C
t_{fg-e} - temperature of flue gases cooled down to the combustion air temperature, °C
V_{air} - stoichiometric amount of dry combustion air, m^3/ kg
V_{fg} - volume of wet flue gases emitted by combusting 1 kg of fuelwood, m^3/kg
V_{fg-d} - volume of dry flue gases emitted by combusting 1 kg of fuelwood, m^3/kg
W^r - relative moisture content of fuelwood, %
Q_n - heat value of fuelwood, kJ/kg
Q_i - heat input of the boiler, MW
Q_o - heating capacity of the boiler, MW
X_{CO2} - volumetric proportion of carbon dioxide in flue gases, m^3/m^3
X_{CO} - mass concentration of carbon monoxide (CO) in dry flue gases, kg/m^3
X_{Cfa} - mass concentration of fly ash and soot in dry flue gases, kg/m^3
X_{H2O} - volumetric proportion of water vapor in flue gases, m^3/m^3
X_{O2} - volumetric proportion of oxygen in flue gases, m^3/m^3
X_{N2} - volumetric proportion of nitrogen in flue gases, m^3/m^3

Greek symbols

λ - coefficient of the excess of the combustion air, m^3/m^3
ξ_{fg} - flue gas heat loss, %
ξ_{CA} - heat loss caused by combustible loss in solid residues, %
ξ_{CO} - heat loss caused by carbon monoxide loss in flue gases, %
ξ_{Cfa} - heat loss caused by fly ash and soot loss in flue gases, %
ξ_R - loss caused by thermal radiation and convection of heat from the surface of the boiler into the ambient space, %
η_B - thermal efficiency of the boiler, %

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