ESTIMATION OF THE ENERGY EFFICIENCY OF A BOILER FACILITY IN CELLULOSE PRODUCTION LINE

Lubka Atanasova, Ginka Baikusheva-Dimitrova

University “Prof. Dr. Asen Zlatarov”-Burgas, Prof. Yakimov str.1, Burgas 8010, Bulgaria

Abstract

The production of cellulose requires high amounts of heat. To assess the energy efficiency of a generator for production of saturated steam used in a cellulose production line, a modern method of analysis was used – the exergy analysis.

The present paper reports for the elaboration of material, heat and exergy balances of a steam generator for saturated steam with parameters P=1.8 MPa and T=210 ^{0}C. The calculations are carried out on the basis of production data. The exergy efficiency was calculated to be 41.71 %. It was found that an increase of the temperature of the air fed into the combustion chamber and an increase of the parameters of the steam obtained will give higher efficiency of the steam generator.

Key words: *exergy, exergy efficiency, cellulose production line, generator for production of saturated steam*

1. INTRODUCTION

The realization of technological processes in modern industry often requires significant amounts of water as cooling agent, heat carrier (hot water and steam) or working fluid. Larger factories usually have their own heat units. They comprise a complex of installations and tubes necessary for the production, transportation and consumption of heat energy. The most important part is the steam generator which produces the steam required by the technological processes.

The production of cellulose requires high amounts of heat. To assess the energy efficiency of a generator for production of saturated steam used in a cellulose production line, a modern method of analysis was used – the exergy analysis.

The exergy method of thermodynamic analysis is widely used for assessment of the energy efficiency of industrial facilities, including boilers for production of steam for technological purposes (Kotas, 1995; Szargut et al., 1988; Dincer and Rosen, 2007; Hirs, 2003,p. 1303; Goran, 2003; Silvio, 2012; Szargut, 2005; Dragan et al., 2011, Brodyanski, 1973; Arharov, 1986).

The aim of the present work is to estimate the energy efficiency of a boiler facility in cellulose production line.

2. DESCRIPTION OF THE TECHNOLOGICAL SCHEME

Every industrial enterprise has heat production unit comprising a complex of installations and tubes necessary for the production, transportation and consumption of heat energy. The core of the complex is the steam generator which produces the steam required by the technological processes.

Fresh water is pumped out of tubed wells and fed into the preparation installation where water is softened and decarbonized to obtain the so called chemically purified water (CPW). The condensates collected by the cellulose production are mixed with CPW and pumped to the deaeration unit. Deaeration is a process of removal of the gases dissolved in the water. Oxygen and carbon dioxide are removed by heating the water to its boiling point at certain pressure. A general requirement is that oxygen content in the water fed into high pressure boilers should be less than 0.03 mg/l. Mixing deaerators are the most widely used ones. The water to be deaerated is heated to 75-85 ^{0}C and fed at the top of the deaeration column. Heating steam with P=0.15 MPa is fed above the water and passes to column bottom. Non-condensed steam and gases removed are vented out at the top of the column

while gas-free water flows down to a reservoir. The deaerated water with T=100°C is then drawn by boiler pumps and passed to water heaters (economizers). Water is heated to boiling point at the corresponding pressure (138-165°C) at the expense of chimney gases and fed into the boiler.

In the boiler, centrifugal air ventilators draw the combustion air and increase its pressure before feeding it to the radiation part of the boiler. Fuel combustion generates chimney gases the heat of which is used for heating and evaporating the water. The chimney gases leave the boiler installation with T=120° C. The steam produced with P=1.8 MPa and T=210°C is passed to a distributing unit where the necessary quantities are delivered to the different consumers. A block diagram of the process described is presented in Fig.1.

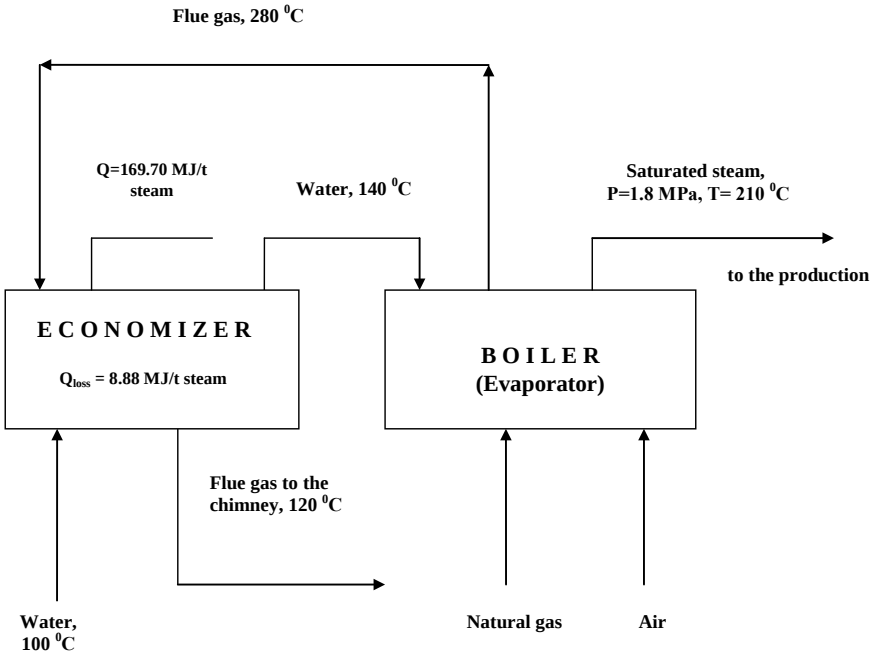


Fig. 1. Block diagram of a boiler installation

3. MATERIAL, ENERGY AND EXERGY BALANCES OF A BOILER INSTALLATION

3.1. Material balance

The material balance of the process of combustion of natural gas with atmospheric air in the boiler installation was elaborated using production data. The quantities and compositions of the natural gas and air were calculated, as well as these for the chimney gas resulting from the combustion. The natural gas consumption was determined. All eh calculations were carried out per ton saturated steam produced with pressure of 1.8 MPa. The results obtained for the material balance are shown in Table 1. According to the production data, combustion air was used in excess (α) compared to the stoichiometrically required at α = 1.10.

Table 1. Composition of the in- and outgoing flows of the boiler facility

Flow	Composition, vol. %								
	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2	O_2	H_2O	
Natural gas	98.61	0.41	0.11	0.03	0.80	0.04			
Combustion Air					77.26		20.54	2.20	
Flue gas after the combustion chamber					70.50	8.62	1.70	19.18	
Flue gas after the evaporator					70.50	8.62	1.70	19.18	
Flue gas after the water heater					70.50	8.62	1.70	19.18	
Water								100.00	
Saturation Steam								100.00	
Water								100.00	

Table 2. The temperature, amount and exergy of the in- and outgoing flows of the boiler facility

Flow	T, ^0C	Amount, $kg.t^{-1}$ steam	Exergy flow, $KJ.kmol^{-1}$
Natural gas	25	45.58	833 620
Combustion Air	25	850.95	0
Flue gas after the combustion chamber	2087	896.53	50 560
Flue gas after the evaporator	280	896.53	4 395
Flue gas after the water heater	120	896.53	2 562
Water, P=1.8 MPa	140	1000.00	4288.96
Saturation Steam, P=1.8 MPa	210	1000.00	19087.14
Water, P=1.8 MPa	100	1000.00	3552.23

On the basis of the material balance, the energy (heat) balance was elaborated for:

- The combustion chamber where the fuel combusts;
- Evaporator where the saturated steam is produced at P= 1.8 MPa;
- Water heater (economizer) where water is heated before it is flown to the evaporator.

3.2. Energy balance

3.2.1. Energy balance of the combustion chamber

The overall balance equation for the combustion chamber is:

$$Q_{comb.of.nat.gas} + Q_{phys.\ of\ comb.air} = Q_{phys.\ chimney\ gas} + Q_{losses} \quad (1)$$

$$Q_{comb.of.nat.gas} = \Delta H_{comb\ CH4}.X_{CH4} + \Delta H_{comb\ C2H6}.X_{C2H6} + \Delta H_{comb\ C3H8}.X_{CH4} + \Delta H_{comb\ C4H10}.X_{C4H10} \quad (2)$$

where:

$Q_{comb.of.nat.gas}$ is the heat generated by the combustion of the natural gas;

$\Delta H_{comb\ CH4}$, $\Delta H_{comb\ C2H6}$, $\Delta H_{comb\ C3H8}$, $\Delta H_{comb\ C4H10}$ – heats of buring of the corresponding components (Szargut and Petela, 1968).

X_{CH4},X_{C2H6}, X_{CH4}, X_{C4H10} – mole parts of the natural gas combusting components

$Q_{phys.comb.air}$ – physical heat of the combustion air

Since the combustion air temperature is equal to that of the environment, the physical heat of the combustion air is null.

$Q_{phys.chimney\ gas}$ – physical heat of the chimney gas

It was calculated by the formula:

$$Q_{phys.chimney\ gas} = (H_{P,T} - H_{P0,T0})_{chimney\ gas} x V_{chimney\ gas}/22.4 \quad (3)$$

where

$H_{P,T}$ - $H_{P0,T0}$ – change of chimney gas enthalpy, KJ/kmol

$V_{chimney\ gas}$ – volume of the chimney gas produced per Nm^3/t пара

The chimney gas was regarded as an ideal mixture of real gases. The change of the chimney gas enthalpy was calculated by summing the changes of the enthalpies of all of its components (Karapetianc, 1975; Rivkin and Aleksandrov, 1988). gain

The chimney gas temperature after the combustion chamber was determined iteratively (Table 2). The results obtained for the energy balance of the combustion chamber are shown in Table 3.

Table 3. Heat balance of the combustion chamber

Yield	MJ/t steam	Losses	MJ/t steam
Heat generated by natural gas combustion	2250.80	Physical heat of the chimney gas	2138.28
		Heat losses	112.52
Total	2250.80	Total	2250.80

3.2.2 Energy balance of the water heater and evaporator

In the water heater (economizer), the water is heated from 100 to 140ºC under high pressure (1.8 MPa) using chimney gas heat. The chimney gas cools from 280 to 120ºC. The heats were calculated by the formulae:

$$T_{ransferred\ from\ chimney\ gas} = (H_{280} - H_{120}) x V_{chimney\ gas}/22.4 \quad (4)$$

H_{280} and H_{120} are the enthalpies of the chimney gas at the corresponding temperatures, KJ/kmol.

$T_{ransferred\ from\ chimney\ gas}$ – heat transferred from the chimney gas, KJ/t steam

$$Q_{water} = (H_{140} - H_{100}) x 1000 \quad (5)$$

Q_{water} – heat absorbed by water, KJ/t steam

H_{140} and H_{100} are the water wnthalpies at the corresponding temperatures, KJ/kg (Rivkin and Aleksandrov, 1988).

The results obtained from the energy balance a summarized in Fig.2.

For the evaporator, the heat utilized from the chimney gases to heat the water from 140 to 210ºC was calculated by formula (4). The chimney gas cools down from 2087ºC to 280ºC. Water is heated from

140ºC to 210ºC when it is in a state of saturated liquid and then it evaporates isothermally to saturated steam. The heat necessary to heat the water was calculated by formula (5) AND THE HEAT NECESSARY FOR THE EVAPORATION – BY FORMULA (6):

$Q_{evaporation.} = R. 1000$ (6)

where R – heat of water evaporation at 210ºC , KJ/kg (Rivkin and Aleksandrov, 1988).

$Q_{evaporation}$, KJ/t steam

The results obtained for the heat balance are presented in a T-Q diagram (Fig.3).

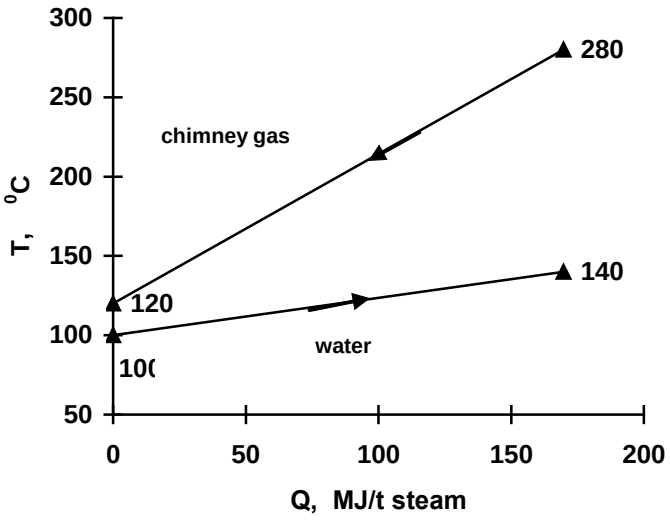


Fig. 2 T-Q diagram of the water heater (economizer)

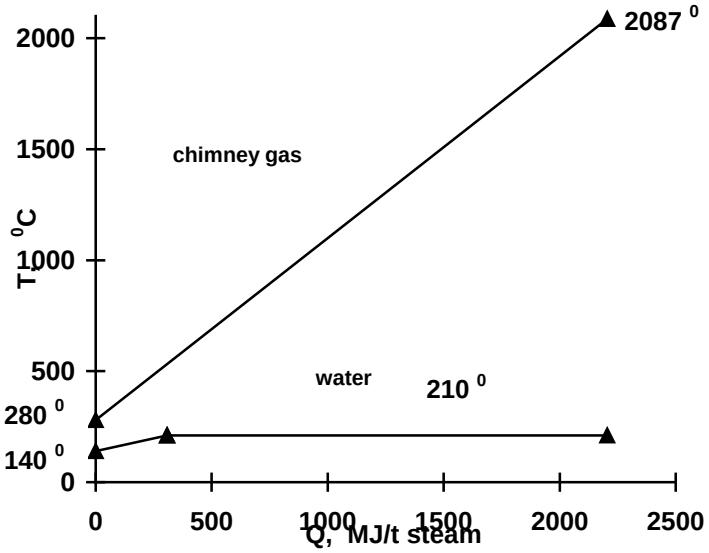


Fig. 3 T-Q diagram of the evaporator

3.3. Exergy balance

The exergy balances of the whole boiler installation and its components: combustion chamber, evaporator and economizer were elaborated (Tables 4-). The exergies of the material and energy flows

were preliminarily calculated. (Table 2) (Kotas, 1995; Szargut, 1988; Dincer and Rosen, 2007; Brodyanski, 1973; Szargut and Petela, 1968). Each material flow taking part in the processes studied consists of a number of individual substances. All the material flows studied are at atmospheric pressure. Therefore, the exergy of each phase is considered to be the exergy of an ideal mixture of individual substances (Karapetianc, 1975). The exergy of each material flow is calculated as the sum of its physical and chemical exergy and the exergy of mixing (Table 2).

Table 4. Exergy balance of the combustion chamber

Flows	Input exergy, $MJ.t^{-1}$ steam	Flows	Output exergy, $MJ.t^{-1}$ steam
Natural gas	2344.56	Flue gas with temperature 2087 ^{0}C	1646.54
Air	0.00	Useful exergy	1646.54
		External exergy losses from the heat losses	98.31
		Internal exergy losses	599.56
Total	2344.56	Total	2344.56
Exergy Efficiency = 0.7023			

Table 5. Exergy balance of the evaporator

Flows	Input exergy, $MJ.t^{-1}$ steam	Flows	Output exergy, $MJ.t^{-1}$ steam
Decrease of chimney gas exergy	1503.41	Increase of water exergy	829.82
Всичко	1503.41	External exergy losses from the heat losses	32.43
		Internal exergy losses	641.16
Всичко	1503.41	Total	1503.41
Exergy Efficiency = 0.5519			

$$e_{ex} = e_{ex}^{PH} + e_{ex}^{CH} + e_{ex}^{mixing} \quad (7)$$

$$e_{ex}^{PH} = (h - h_0) - T_0(s - s_0) \quad (8)$$

where h and s are the enthalpy and entropy of the material flow at its working parameters (temperature, pressure and composition), respectively, while h_0 and s_0 – the enthalpy and entropy under environmental conditions, T_0 = 298.15 K and P_0 = 101 325 Pa (Szargut and Petela, 1968).

Table 6. Exergy balance of water heater

Flows	Input exergy, MJ.t^{-1} steam	Flows	Output exergy, MJ.t^{-1} steam
Decrease of chimney gas exergy	59.69	Increase of water exergy	40.92
		External exergy losses from the heat losses	3.25
		Internal exergy losses	15.52
Total	59.69	Total	59.69
Exergy Efficiency = 0.6855			

Table 7. Exergy balance of the boiler installation

Flows	Input exergy, MJ.t^{-1} steam	Flows	Output exergy, MJ.t^{-1} steam
Natural gas	2344.56	Saturated steam with P=1.8 MPa to the technology	1079.34
Air	0.00	Useful exergy	1079.34
Water, 100^{0}C	208.61	External exergy losses from the heat losses	133.99
		External losses from the flue gas to the chimney	83.43
Electricity	34.60	Internal exergy losses	1291.01
Total	2587.77	Total	2587.77
Exergy Efficiency = 0.4171			

The enthalpy and entropy of a mixture of substances are calculated by summing the enthalpies and entropies of the individual substances present in the mixture. The values of the individual enthalpies and entropies are taken from reference literature (Karapetianc, 1975).

The chemical exergy is calculated using the method of Szargut described in (Szargut and Petela, 1968).

The exergy of mixing is calculated by the formula:

$$E_{ex}^{mixing} = -RT_0 \Sigma x_i \ln x_i \quad (9)$$

where R is the universal gas constant, T_0 is the environmental temperature (298.15 K) and x_i is the mole fraction of the i^{th} component of the mixture.

The dead state conditions in all the calculations were: temperature T_0 = 298.15 K, pressure P_0 = 101 325 Pa and composition x_0 = Szargut model (Szargut and Petela, 1968).

The inflowing exergy is calculated as the sum of the exergies of all the incoming flows in the system analyzed: E_{in}. The outflowing exergy is calculated as the sum of all the useful flows that leave the system: E_{out}. The difference between inflowing and outflowing exergy streams is the net exergy loss, D:

$$D = E_{in} – E_{out} \quad (10)$$

The total exergy losses are apportioned to internal and external regions. The external exergy losses are the sum of the exergies of material and energy flows that are discharged in the environment without further utilization, D_{ext}. The internal exergy losses D_{int} are determined as the difference between the total and the external exergy losses:

$$D_{int} = D – D_{ext} \quad (11)$$

The exergy efficiency η_e is determined as the ratio of outflowing to inflowing exergy (Kotas, 1995; Dincer and Rosen, 2007).

$$\eta_e = E_{out}/E_{in} \quad (12)$$

The exergy of the heat flows was calculated by the formula:

$$E_Q = Q.\tau \quad (13)$$

where:

Q is the quantity of heat

τ - thermodynamic temperature

$\tau = 1- T_0/T$

T_0 – temperature of the environment (298.15 K)

T – temperature of the heat flow

4. DISCUSSION

The exergy efficiency of the boiler installation comprising combustion chamber, evaporator and economizer was calculated to be 41.71 % (Table 7).

The value obtained for this particular installation corresponds to the values characterizing this type of boiler installations (Brodyanski, 1973; Arharov, 1986).

The total exergy losses are high (1508.43 MJ/t steam) with 14.41 % of them being due to external exergy losses and 85.59 % – to internal ones.

The external exergy losses are mainly caused by heat losses and the chimney gas released to the environment. In this case, the exergy of the chimney gas is low because of its low temperature at system outlet.

The high value of the internal losses (1291.01 MJ/t steam) is due to the irreversibility of the combustion process taking place in the combustion chamber and the irreversibility of the heat-exchange in the evaporator and the water heater.

In the evaporator, the internal exergy losses result from the varying temperature difference between the hot and cold flows at the two ends of the heat-exchanger. At the hot end the temperature difference was 1877ºC while at the cold one – 140ºC (Fig.3).

The internal exergy losses were high also in the economizer. They were 82.69 % of the total exergy losses and were due to the varying temperature difference between the hot and cold flows. The temperature difference at the hot end of the heat-exchanger was 140ºC while at the cold one it was 20ºC (Fig.2).

The internal losses in the combustion chamber can be partially reduced by increasing the temperature of the air flown into it.

In the evaporator in the economizer, a decrease of the internal loses can be achieved by improving water parameters.

5. INTRODUCTION

In the present paper, the exergy method of thermodynamic analysis was used to estimate the energy efficiency of a boiler installation for production of saturated steam used in a cellulose production line. The data used were taken from a real installation. The coefficients of exergy efficiency of the boiler installation comprising combustion chamber, evaporator and economizer was 41.71 % .the value obtained for the efficiency of the boiler installation analyzed complies with the values characterizing this type of boiler installations. It was deduced that partial reduction of the internal losses in the combustion chamber can be achieved by increasing the temperature of the air flown into it. In the evaporator and the economizer, the internal losses can be reduced by improving water parameters.

REFERENCES

Arharov, A. (1986) *Thermotechnics*. Moscow: Machinery construction.

Brodyanski, V. (1973) *Exergy analysis*. Moscow: Energy

Dincer, I. and Rosen, M. (2007) *Exergy, Energy, Environment and Sustainable Development*. Oxford: Elsevier.

Dragan M. et al. (2011) The exergetic evaluation for the steam boiler, Recent Advances in Fluid Mechanism and Heat&Mass Transfer. Available from:

http://www.wseas.us/e-library/conferences/2011/Florence/HEAFLU/HEAFLU-44.pdf

[Accessed: 20th March 2015].

Goran, W. (2009) *Exergetics*, Colombia: Bucaramanga.

Hirs, G.(2003) Thermodynamics applied. Where? Why?. *Energy*. 28, p.1303-1313.

Karapetianc, M. (1975) *Chemical Thermodynamics*. Moscow: Chemistry.

Kotas, T. (1995) *The Exergy Method of Thermal plant analysis.* Melbourne: Krieger Pub Co.

Rivkin, S. and Aleksandrov, A. (1988). *Thermochemical properties of the water and steam*, Sofia: Technics.

Silvio, J. (2012) *Exergy*: *Production, Cost and Renewability.* New York: Springer,

Szargut, J., Morris, D. and Steward, F. (1988) *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes.* New York: Hemisphere.

Szargut, J. (2005) *Exergy Method: Technical and Ecologycal Application*s. Boston: WIT PRESS.

Szargut, J. and Petela, R. (1968) *Exergy.* Moscow: Energy.