Black Liquor Recovery Boiler Performance Improving Through Exergy and Energy Analysis

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***Abstract*-- National Wood and Paper Factories produce materials that are called "Black Liquor" during the process of pulp production from woods by chemical methods and this product is used by a recovery boiler due to high heat value in order to produce steam which is necessity for process and recycle the chemicals. Nowadays, one of the existent requirements of this part of industry is improvement the performance of such type of boilers which have special designing and different operation conditions because of its used fuel. One of the available methods in this field is applying thermal equilibrium. Because there hasn't been considered the irrevocability of process and equipment during thermal equilibrium (first law of thermodynamic), this paper deal with existing irreversibility and its place of occurrence in Black liquor-recovery boiler in one of national wood and paper factories by doing energy and exergy analysis. Exergy waste points have been detected in the studied boiler by applying mass, energy and exergy balance. At the end of study the necessary approaches are provided to use energy in this equipment better and also improve its performance.**

Keywords—Paper, Wood, liquor, Energy and Exergy Balance, Boiler performance, Improvement.

I. INTRODUCTION

One of the pulp production's methods from wood is using chemicals methods that the most important method of this group is "Kraft Method". In this method, chemical compound including sodium hydroxide and sodium sulfiteis used in order to separate the lignin from wood fibers in a reactor called "Digester". Its final products include (1) pulp and (2) lignin, water and chemical mixture. Pulp is sent to paper machine after passing different units such as washing, deinking to produce paper , and liquor after concentrating in Evaporation unit, it is sent to recovery boiler as the first step to obtain chemicals and also produce a part of steam which is needed for process by combustion of the materials in the fuel.

Although the Liquor used in recovery boilers of paper producing factories by chemical method are considered as liquid fuel, but their combustion process nature has more similarity with solid fuels such as Coal. As Fig. 1 indicates, there are four stages for liquor combustion process including (1) drying, (2) removing volatiles, (3) oxidation and (4) molten reduction reactions.

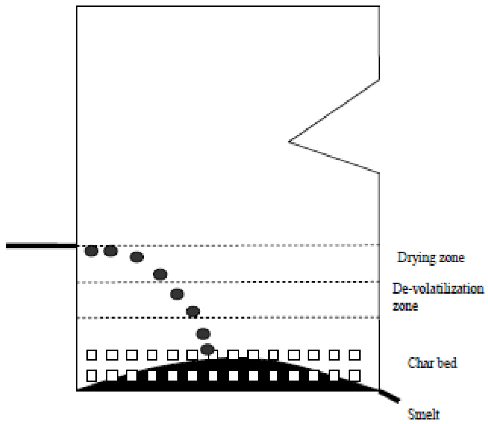

Fig. 1. Black Liquor Combustion Process Stages in a Recovery Boiler

Table 1 indicates the specifications of liquor entered to related boiler, in one selected Iranian paper factories as a case study, with its thermal value that is equal to 14700 (kj/kg) and percentage of solid particles when entering to boiler is equal to 63(%).

Table I
Weight Percent of Black Liquor Fuel's Elements.

Element	(%) Mean
Carbon	42.6
Sodium	18.3
Hydrogen	3.6
Oxygen and Nitrogen	31.9
Sulfur	3.6

This boiler has four spraying nuzzles for black liquor, four gas or gasoil burners in the bottom and also four gas or gasoil burners in the upper part of black liquor nuzzles.

Main fuel of recovery boiler is black liquor and upon the needs (mainly for launching) it is also use gas or gasoilin four bottom burners. The ash which is produced by liquor fuel enter into the bottommost part of gases combustion exhausting (called ash funnel which is placed under economizer) and return back to the system and thus it lead to reduction environmental pollution. The specifications of liquor recovery boiler that was studied in this paper is shown in Table II.

Table II
Specifications of Studied Black Liquor Recovery Boiler

Specifications	Unit	Values
Designing pressure	(Kg/Cm^2)	70.5
Operational pressure	(Kg/Cm^2)	60
Steam temprature	(°C)	445
Feed water temprature	(°C)	193
Air Temprature at Enterance of Air Heater	(°C)	26.7
Combustion Air Temprature	(°C)	149
Ecomizer Output Gas Temprature	(°C)	218
Temprature of black liquor input to Burner	(°C)	93.5
Steam Producted	(ton/hr)	74
Value of Liquor used	(tds/day)	440
Design Efficiency of boiler	(%)	72

II. Governing Equations

A. *Mass and energy balance of liquor recovery boiler*

In this part, the values of mass and energy flow in output and input are calculated by feed water temperature, exhausting flue gases temperature, entrance air temperature and etc. based on the fuel chemical combination, gross fuel heat value is calculated according to solid particle percent and other thermodynamic attributes.

The required air proportion and output flue gases proportion are evaluated by fuel chemical combination, excess air percentage and energy balance. The required fuel is calculated according to the air consumption, the value of exhausting gases, fuel heat value with air flow, entrance water and exhausting flue gases.

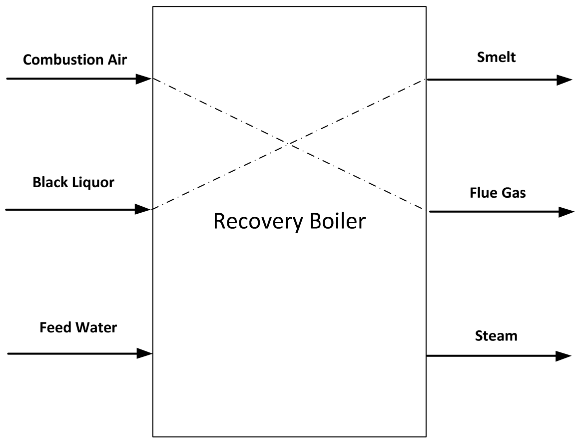

Fig. 2. Schematic of Mass Flow for Liquor Recovery Boiler

According to Fig. 2 energy and mass flows are calculated by following equations [1]:

$$f_{air,min} = 22.7 \times \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_s}{32} - \frac{w_{H2O}}{18} \right) \qquad (1)$$

$$f_{air} = f_{air,min} \times \left(100 + C\%\right) / 100 \qquad (2)$$

$$m^3(n) / kg\ dry\ fuel$$

$$f_{flue\ gas} = 22.7 \times \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_{H2O}}{32} + \frac{w_s}{32} + \frac{w_N}{32} \right) + f_{air,min} \times \left(\frac{0.791}{0.209} + c \right) - f_{CO,melt} \qquad (3)$$

$$m^3(n) / kg\ dry\ fuel$$

Where $f_{CO,melt}$ is the mass value of oxygen and carbon in output melted carbonate sodium of the boiler ($Na + C + O \rightarrow Na_2Co_3$). The following relation is used in order to calculate the amount of output melted carbonsodium in which TS (%) is the percent of solid particles in entrance black liquor [2] - [4].

$$f_{Na2Co3} = 0.53 \frac{(w_{Na} + w_k)}{(1 + \frac{1 - TS\% / 100}{TS\% / 100})} \qquad (4)$$

$$kg / kg\ wet\ fuel$$

Reference temperature is equal to 20 (°C) to balance energy and all the antalpies except water and air flows are calculated by following equation in a specific tempreture:

$$h = f \times C_p \times (t - 20) \qquad (5)$$

Whereas the heat capacity of liquor changes with solid particle percent and its temperature, heat capacity of input liquor should be calculated by following relation in order to account input fuel enthalpy.

$$C_P = 4.216 \times (1 - TS) + (1.675 + 3.31 \times t / 1000) \times TS + (4.87 - 20t / 1000) \times (1 - TS) \times TS^3 \qquad (6)$$

The final energy balance of boiler is:

$$h_{air} + h_{blackliquor} + f_{water} h_{water} + f_{blackliquor} h_{heatvalue} + h_{heatloss} = h_{fluegas} + h_{melt} + f_{water} h_{steam} \qquad (7)$$

B. *Mass and exergy balance of liquor recovery boiler*

The boiler structure supposed to be enblock in order to exergy analysis in recovery boiler. Different parts of recovery boiler are defiened in Fig. 3. The name of every part is: 1- fuel feeder, 2- burner, 3- downcomer, 4- boiler drum, 5- ceiling superheater, 6- plate superheater, 7- high tempreture superheater, 8- low tempreture superheater, 9- waterwall, 10- combustion chamber, 11- economizer, 12- air fan, 13- shocker, 14- input air heater, 15- induction sucking fan, 16- chimney, 17- melt tank, 18- feed water pump and 19- water storage. Input and output exergy are defined as follows according to Fig. 3. E_1 is exergy losses due to output gases, E_2 is output exergy of superheatt steam, E_3 is exergy losses due to boiler losses, E_4 is total exergy losses in boiler, E_5 is input exergy of feed water, E_6 is input exergy of fuel and E_7 is input exergy of air combustion [5].

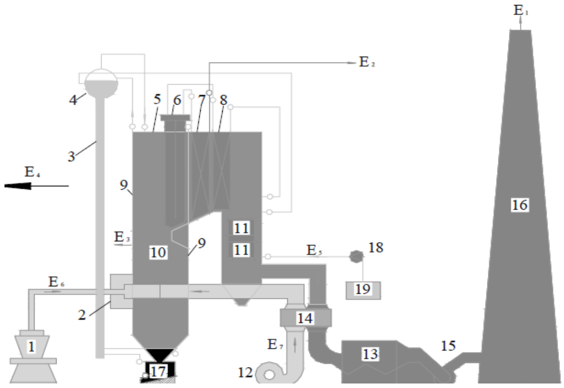

Fig. 3. Different Parts of Liquor Recovery Boiler.

Exergy balance for liquor recovery boiler is presented as follows:

$$E_1 + E_2 + E_3 + E_4 = E_5 + E_6 + E_7 \quad (8)$$

$$m_1 e_1 + m_2 e_2 + m_3 e_3 + m_4 e_4 = m_5 e_5 + m_6 e_6 + m_7 e_7 \quad (9)$$

In the last equation $m_2 = m_5$ so the equation can be rewrite as follow:

$$m_1 e_1 + m_2 (e_2 - e_5) + m_3 e_3 + m_4 e_4 = m_6 e_6 + m_7 e_7 \quad (10)$$

C. The exergy of liquid fuel

The chemical exergy of liquid fuel is calculated by bottom relation [6].

$$e_{ch} = Q_1 (1.0038 + 0.1365 \frac{H}{C} + 0.0308 \frac{O}{C} + 0.0104 \frac{S}{C}) \ [KJ / kg(F)] \quad (11)$$

Where S, C, O and H are mass percent of Sulfur, Carbon, Oxygen and Hydrogen respectively in the fuel and Q_1 is low heat value of fuel. The physical exergy of liquid fuel is defined as:

$$e_{Ph} = c_f [(T - T_0) - T_0 \ln \frac{T}{T_0}] \quad (12)$$

So, the total exergy of liquid fuel is equal to:

$$e_6 = e_{ch} + e_{Ph} \quad (13)$$

D. Exergy loss in combustion process

There is no loss in every adiabatic combustion process, so the exergy of output gases is equivalent to the exergy of input fuel and air. Because of existing irreversibility, the actual exergy of output gases is lower than its ideal.

As we know the maximum temperature of combustion gases during the combustion process is adiabatic combustion temperature [7]. Whit this expression the heat balance of combustion process can be writing as:

$$V_g c'_{p,m} (T_{ad} - T_0) = Q_1 \quad (14)$$

The adiabatic temperature is got from bottom equation:

$$T_{ad} = T_0 + \frac{Q_1}{V_g c'_{p,m}} \quad (15)$$

The exergy of output gases of combustion is expressed by:

$$e_{ad} = V_g c'_{p,m} (T_{ad} - T_0)(1 - \frac{T_0}{T_{ad} - T_0} \ln \frac{T_{ad}}{T_0}) \quad (16)$$

$$= Q_1 (1 - \frac{T_0}{T_{ad} - T_0} \ln \frac{T_{ad}}{T_0}) \ [kj / kg(F)]$$

Where V_g is the actual volume of output gases and $c_{p,m}$ is the average heat capacity in pressure constant.

Input air enthalpy is calculated by:

$$e_7 = m_7 [(h_7 - h_{07}) - T_0 (s_7 - s_{07})] \ [kj / kg(F)] \quad (17)$$

Where h_7 is the input air enthalpy, h_{07} is the input air enthalpy in ambient temperature, s_7 is input air entropy, s_{07} is input air entropy in ambient temperature and m_7 is mass air of combustion per every kilogram of fuel [8]-[10]. Fuel exergy and losses of exergy can be accounted by:

$$e_f = e_6 + e_7 \quad (18)$$

$$e_{l,c} = e_f - e_{ad} = T_0 \Delta s + Q_1 \frac{T_0}{T_{ad} - T_0} \ln \frac{T_{ad}}{T_0} \quad (19)$$

E. Exergy of superheat steam and feed water

The exergy of input feed water is:

$$e_5 = (h_5 - h_{05}) - T_0 (s_5 - s_{05}) \ [kj / kg] \quad (20)$$

The exergy of output superheat steam is:

$$e_2 = (h_2 - h_{02}) - T_0 (s_2 - s_{02}) \ [kj / kg] \quad (21)$$

F. Calculate exergetic efficiency of boiler

Combustion exergetic efficiency, heat transfer exergetic efficiency and boiler exergetic efficiency are defiened as follows respectively:

$$\eta_{e,c} = \frac{e_f - e_{l,c}}{e_f} = 1 - \frac{e_{l,c}}{e_f} \quad (22)$$

$$\eta_{e,h} = \frac{m_2 (e_2 - e_5)}{e_f - e_{l,c}} \quad (23)$$

$$\eta_{e,B} = \eta_{e,C} \cdot \eta_{e,h} \quad (24)$$

III. Input Data

A. The specifications of input and output flows of boiler

Table III indicates parameters recorded during operation from actual boiler of factory to use in equations and analysis the performance of the boiler.

Table III
Specifications of Input and Output Streams From Boiler

Boiler feed water temperature	(°C)	145
Black Liquor temperature	(°C)	110
Combustion air temperature	(°C)	90
Steam produced	(ton/hr)	31
Steam pressure	(Bar)	54
Steam Temperature	(°C)	445
Solid Particles% of black liquor	(%)	62
Thermal capacity of fuel	(KJ/kg. °C)	3.74
High thermal value of fuel	(KJ/kg)	14700
Flue gas temperature	(°C)	145
Excess air	(%)	238

IV. Result

Tables IV and V indicate results from mass, energy, exergy equilibrium of considered boiler. As indicated, according to current operation conditions from energetic efficiency of boiler are 63% and its exergetic efficiency is 26.4%.

Table IV
The Results of Exergy Analysis of Recovery Boiler

Total Exergy of Liquid Fuel (KJ/kg)	15290
Specific Exergy of Feed Water (KJ/kg(Fuel))	402.6
Specific Exergy of SuperHeat Steam (KJ/kg(Fuel))	3575.7
Exergy of Combustion Air (kJ/kg(fuel))	69.2
Exergy of Output Flue Gases (KJ/kg(fuel))	8897
Egergy wasted due to process (kJ/kg(fuel)	6463.2
Efficiency of Exergy of Combustion process in the boiler (%)	57.9
Exergetic efficiency of Heat Transfer Process (%)	45.7
Exergetic Efficiency of Boiler (%)	26.4
Exergetic Wastes Percentage of Boiler (%)	73.6

Table V
The Results of Energy Analysis of Recovery Boiler

Thermal power of combustion air(KW)	536
Thermal power of boiler feed water (KW)	5200
Thermal power of fuel input to boiler (KW)	4200
Thermal power of output flue gases (KW)	6262
Thermal power of molten materials output from boiler (KW)	3200
Thermal power of steam output from boiler (KW)	28000
Thermal power of other waste flows (KW)	10117
Energetic efficiency of recovery boiler (%)	63

V. Conclusion

According to results, it is observed that the exergic efficiency of boiler (26.4(%)) is lower than its energetic efficiency (63(%)) and this is due to exergetic efficiency of combustion and thermal conduction in the boiler.

One of reasons for this part is high rate of irreversibility in the liquor combustion process. This reason has an effect on combustion process. Although all chemical energy change to thermal energy, the exergy value reduce remarkably. One of the alternatives in this field is increasing adiabatic temperature by reducing the excess air (current state 238%). But, according to current performance conditions an increase in adiabatic temperature causes an increase in temperature of output flue gases from boiler which can lead to reduction of energetic efficiency. In considered boiler based on 13% increase in flue gas temperate, the energetic efficiency is reduced to 1%. Therefore, in. Hence, to achieve simultaneous increase of energetic and energetic efficiency, besides reduced excess air, it is necessary to increase the overall heat transfer coefficient by continuously cleaning heat transfer surface and keep the output flue gas temperature in a suitable range.

VI. References

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VII. Biographies

Pouria Orouji was born in Tehran, on September 14, 1986. He graduated from the Science and Technology University at B.Sc. of Mechanic Engineering, Power and Water University at M.Sc. and PhD of Energy Engineering systems. special fields of interest included Fuel cells, Exergy and Pinch Analysis, Heat Exchangers Design, Process Plants Design, Energy Audit.