Energetic and Exergetic Analysis in a Firewood Boiler

Análise Energética e Exergética de uma Caldeira a Lenha

RUBENS ALVES DIAS
Unesp (Guaratinguetá, Brasil)
rubdias@zipmail.com.br

JOSÉ ANTÔNIO PERRELLA BAILESTIERI
Unesp (Guaratinguetá, Brasil)
perrella@feg.unesp.br

ABSTRACT In this paper, thermodynamics’ first and second laws were applied to a firewood boiler in order to evaluate its performance. Some other physical parameters, such as the electric ones, were taken into account in the development of the analysis for its performance evaluation. The procedure based on thermodynamic laws is recommended as a general tool for the analysis of heat systems, aiming at reaching some operational and design information – mainly qualitative results – by means of the second law analysis, which helps to estimate the critical points for a better energy conservation. The analysis of a firewood boiler in a small pasta factory is presented to illustrate the use of exergetic modeling.

Keywords ENERGY CONSERVATION – EXERGETIC ANALYSIS – PERFORMANCE EVALUATION.

RESUMO Neste artigo, a primeira e a segunda lei da termodinâmica foram aplicadas a uma caldeira a lenha para avaliar seu desempenho. Alguns outros parâmetros físicos e elétricos foram considerados para o desenvolvimento da análise para a avaliação de desempenho. O procedimento baseado nas leis da termodinâmica é recomendado como uma ferramenta geral para a análise de sistemas térmicos, visando obter informações operacionais e de projeto, em especial resultados qualitativos, por meio da análise a partir da segunda lei, que auxilia na estimativa dos pontos críticos para um melhor aproveitamento da energia. A análise de uma caldeira a lenha de uma pequena fábrica de massas é apresentada para ilustrar a potencialidade do uso da modelagem exergética.

Palavras-chave CONSERVAÇÃO DE ENERGIA – ANÁLISE EXERGÉTICA – AVALIAÇÃO DE DESEMPENHO.
he performance of an energy system, from the thermodynamic viewpoint, can be evaluated by the first (energy) and second (exergy) laws; the energy balance provides a quantitative interpretation of the thermodynamic analysis, while the exergetic balance is associated to qualitative information, describing the system in its critical points by the irreversibilities (losses) occurred in the process.

First and Second Thermodynamics’ Law efficiencies can be useful for a decision making process: their results illustrate, respectively, operational and design conditions for a thermal system under analysis. The values obtained for energetic and exergetic efficiency, as well as the evaluation of the irreversibilities presented by the system, serve as a reference when comparing different technologies according to the capacity of converting the input energy into some useful forms of energy, and are indicative of some possible adjustment and modification necessary to warranty a thermal system performance improvement.

In this paper the firewood boiler of a pasta factory is analyzed in its energetic and exergetic efficiency. Irreversibilities are calculated for the fireside and waterside streams, to identify their behavior according to the variation of the waterside stream temperature profile.

EXERGETIC BALANCE

For the technical evaluation of the proposed system, first and second thermodynamic law equations were used; for the control volume of figure 1, energy conservation first law can be written by Eq. (1).

\[ \dot{Q} - \dot{W} = \sum \dot{m}(h + \frac{v^2}{2} + gz) - \sum \dot{m}(h + \frac{v^2}{2} + gz) \]

Fig. 1. Control volume.

This formulation lets one knows that the quantity of thermal (heat) and mechanical/electric energy is transformed internally into kinetic or potential energy, as well as the pressure energy. It is the basis for the most common efficiency evaluation rate, calculated by Eq. (2).
For the evaluation of the losses that occurred into the steam generating system, the exergetic balance rate can be applied to the thermal system, according to Eq. (3):

\[ I = \sum_j \left[ \frac{Q_j}{T_j} - \frac{T_0}{T_j} \right] - W + \sum_i m_{a_i} - \sum_i m_{a_i}. \text{ for } j = 1, 2, 3, ... \]

that expresses the irreversibility that are associated to the process when the other parameters are known. According to the evaluation of irreversibilities and exergetic efficiency it is possible to identify major losses incurred in a thermal system to provide further design improvements.

The second law efficiency may present different definitions; in this analysis it will be considered the following expressions:
- the rational efficiency, showed in Eq. (4) (Kotas, 1985):

\[ \psi = \frac{\sum A_{out}}{\sum A_m} = \frac{\sum m_{out} a_{out}}{\sum m_{in} a_{in}} = 1 - \frac{1}{\sum m_{m} a_{m}} \]

which represents the ratio of the exergy transfer associated with the plant output to the exergy transfer rate associated with the corresponding exergy input;
- for clearly identifying the fraction of the input exergy which is lost through irreversibility in a multi-component system, the efficiency defect for a system of N components is presented in Eq. (5):

\[ 1 - \psi = \frac{\sum f_j}{\sum A_{in}} = \frac{f_1}{A_{in}} + \frac{f_2}{A_{in}} + \ldots + \frac{f_N}{A_{in}} = \delta_1 + \delta_2 + \ldots + \delta_N \]

for which the numerator is relative to the whole plant.
- by isolating the waterside expression of exergetic balance into the numerator, the boiler efficiency can be stated by Eq. (6) (Moran and Shapiro, 1995):

\[ \epsilon = \frac{m_{water}(a_e - a_i)}{m_{wood} a_{wood} + m_{air} a_{air} - m_{e}} \]

that evaluates the exergetic exchanges efficiency from a system to another one. In this case, from fireside to waterside.

**ENERGETIC AND EXERGETIC ANALYSIS**

A hot water generating system of a small pasta factory is described in its components to illustrate the energetic and exergetic analysis performed in an old firewood boiler. The configuration presented in figure 2 illustrates the system under analysis, which is slightly different from the usually met in the pasta sector because this one doesn’t present a return tank to receive the industrial process and the reposition water. The water system operates in a closed loop, and a pressure vessel, which controls the water inlet when the pressure decreases in the main pump suction, regulates water replacement.

For the proposed analysis, an estimation of the water flow in the boiler main pump were necessary because of the lack of an adequate instrumentation for that; some data were then measured for an approximation of the hot water flow. The following values were obtained by direct inspection of the existing system:
- pressure pump inlet = 0.2 MPa
- pressure pump outlet = 0.35 MPa
- external diameter of the pump rotor = 210 mm
- nominal rotation = 1.750 rpm
Fig. 2. Hot water generating unit of the pasta factory.

Legend:
1. return of hot water
2. hot water outlet
3. replacement water inlet
4. compressed air inlet
5. fuel inlet
6. air inlet
7. combustion gases outlet
8. firetube boiler
9. main pump
10. pressure vase
11. replacement pump
12. Retention valve
13. manual valve
14. pneumatic valve

From the curve of total head versus flow for main pump (figure 3), according to the manufacturer (Mark Peerless, 1998), the estimated water flow is 34 m$^3$/h (9.4 kg/s). However, this value could be considered adequate for the design point of the equipment, and the operational load may differ substantially. By means of a wattmeter, the electric power of the three-phase induction motor of 15 cv (11 kW) that drives the pump was measured, staying at a steady state regime whose average value was 3.59 kW.

Fig. 3. Curve of total head and power versus flow for main pump
From the characteristic curve of the electric motor (figure 4), for the average electric current of 17.4 A measured the electric motor was operating with 75% of efficiency, and so the mechanic power was determined according to Eq. (7). Considering the mechanic power (converted into cv) and the external diameter of the pump rotor, the characteristic curves of this pump (see figure 3) was consulted and a flow of approximately 34 m³/h was the one that best fitted the crossing values of the mechanical power demanded and the external rotor diameter of the available pump, confirming that stream flow as the operational data for this analysis.

\[
P_{\text{mec}} = \eta_{el} \times P_{el} = 2.69\text{kW}
\]

From the collected data, the following values are available for analysis (only LHV of wood was not measured and it was taken the mean value cited in BEESPR, 1997):

- average amount of measured firewood: \( \dot{m}_{\text{wood}} = 0.0127\text{kg/s} \)
- average mass flow of water: \( \dot{m}_{\text{water}} = 9.4\text{kg/s} \)
- firewood lower heating value: \( LHV_{\text{wood}} = 10575\text{ kJ/kg with 25\% of humidity} \)

average values of temperature and pressure according to table 1:

**Tab. 1.** Measured values in the pasta factory boiler.

<table>
<thead>
<tr>
<th>WATER</th>
<th>AIR</th>
<th>EXHAUST GASES</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATURE (°C)</td>
<td>PRESSURE(MPa)</td>
<td>TEMPERATURE (°C)</td>
</tr>
<tr>
<td><strong>INPUT</strong></td>
<td><strong>OUTPUT</strong></td>
<td>0.35</td>
</tr>
<tr>
<td>90.5</td>
<td>93.0</td>
<td></td>
</tr>
</tbody>
</table>

**Tab. 2.** Pasta factory enthalpy values of water.

<table>
<thead>
<tr>
<th>TEMPERATURE (°C)</th>
<th>ENTHALPY (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>90.5</td>
</tr>
<tr>
<td>Output</td>
<td>93.0</td>
</tr>
</tbody>
</table>

**Fig. 4.** Characteristic curve of the electric motor 15cv – 220/380V (WEG, 1998).

Table 2 presents the enthalpy of saturated steam and liquid water according to the measured values. The first law boiler efficiency is calculated using the Eq. (2) and resulted in \( \eta_{SG} = 73.5\% \). This value is considered adequate for the firewood boiler, specially because it is an old and highly used equipment.

For the exergetic analysis, it is necessary to know the chemical composition of the firewood; the average values in dry condition (Carvalho Junior et al., 1995) were theoretically increased of a certain amount of
water to consider 25% of humidity because the reference data collected (BEESP, 1997; BEN, 1998) take into account this humidity percentage in their analysis. Such values are showed in Table 3, and the stoichiometric condition adopted in the process of firewood combustion (with 25% of humidity) may be represented by the following balance equation:

\[
\frac{C_3H_7.3O_{55.2} + 3.1O_2 + 11.7N_2}{16} \rightarrow 3CO_2 + 3.65H_2O + 11.7N_2
\]

**Table 3.** Firewood average chemical composition.

<table>
<thead>
<tr>
<th>COMPOSITION IN MASS (%)</th>
<th>CARBON</th>
<th>HYDROGEN</th>
<th>OXYGEN</th>
<th>ASHES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>48.0</td>
<td>6.0</td>
<td>44.0</td>
<td>2.0</td>
</tr>
<tr>
<td>25% humidity</td>
<td>36.0</td>
<td>7.3</td>
<td>55.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

For the specific heat at constant pressure calculation of the combustion gases and using the specific heat equations of the carbon dioxide, water steam and nitrogen (Perry, Chilton and Kirkpatrick, 1963), an expression can be proposed for representing the variation of the specific heat of the combustion gases of the firewood as a function of the temperature, as shown below:

\[
c_{p, eg}(T) = \frac{0.163}{44}c_{p, CO_2} + \frac{0.199}{18}c_{p, H_2O} + \frac{0.638}{28}c_{p, N_2}
\]

in which the numerator expresses the product of the molars fractions of each chemical substance by the respective specific heat in the molar basis, and the denominator expresses the molecular masses. Considering the specific heat equations of CO2, H2O and N2:

\[
c_{p, eg}(T) = \left(\frac{0.163}{44}\right)\left(10.34 + 0.00274T - \frac{19555000}{T^2}\right) + \frac{0.199}{18}\left(8.22 + 0.00015T + 0.00000134T^2\right) + \frac{0.638}{28}\left(6.50 + 0.001T\right)
\]

Reducing the expression and converting it to the International System, Eq. 8 can be obtained:

\[
c_{p, eg}(T) = 1.167 + 0.000144T - \frac{502732}{T^2} + 0.6\times10^{-7}T^2
\]

For the exhaust gas temperature measured in the boiler stack \(c_{p, eg}(393) = 1.2 \text{ kJ/kgK}\). The specific heat of the air is calculated using the Eq. 9 (Shieh and Fan, 1982) for a local temperature of 30°C (303 K), resulting:

\[
c_{p, air}(T) = 1.04841 - 0.00038372T + \frac{945378}{10^7}T^2 - \frac{549031}{10^{10}}T^3 + \frac{722981}{10^{14}}T^4
\]

\[
c_{p, air} = (303) = 1.0037 \text{ kJ/kgK}
\]

Equation (10) is used for the exergy calculation in the work fluid, according to the C.V showed in figure 5 and assuming the temperature \(T_0 = 298 \text{ K (25°C)}\) as reference state. For the enthalpy and entropy values taken from thermodynamics tables, \(h_0 = 104.87 \text{ kJ/kg} \) and \(s_0 = 0.3673 \text{ kJ/kg K}\). The portions of the kinetic and potential energy were not considered. Table 4 shows the enthalpy and entropy values of the water used in this analysis.
In that way, it was obtained the exergy in the C.V. boundary for water, at inlet and outlet conditions:

\[ a = (h - h_0) - T_0(s - s_0) \]
\[ a_i = 26.58 \text{ kJ/kg} \]  
\[ a_o = 26.58 \text{ kJ/kg} \]  

The equation proposed by Shieh and Fan (1982) for calculating the exergy of a fuel (Eq. 11) is adjusted to the data presented in table 3.

\[ a_{\text{fuel}}^o = 34183.16(C) + 21.95(N) + 11659.19(H) + 18242.90(S) - 13265.90(O) + 24091.05(F) + 1174.18(Cl) + 5033.97(Br) + 2894.65(I) - (298.15 \times s_{\text{ashes}} \times m_{\text{ashes}}) + 0.63(O) \{ 7837.667(C) + 33888.889(H) - 4236.10(O) + 3828.75(S) + 4447.37(F) + 1790.90(Cl) + 681.97(Br) + 334.86(I) \} \]

in which:
- the values in parentheses are the percentage in mass of the carbon (C), nitrogen (N), hydrogen (H), sulfur (S), oxygen (O), fluorine (F), chlorine (Cl), bromine (Br) and iodine (I), that can compose a fuel:
  - \( s_{\text{ashes}} \) is the entropy of formation of the ashes: = 0.84 kJ/kg K [8]
  - \( m_{\text{ashes}} \) is the mass of ashes in one kilogram of fuel (kg).
- Substituting the values for the firewood with 25% of humidity:

\[ a_{\text{wood}}^o = 34183.16(0.36) + 116591.19(0.073) - 13265.90(0.552) + - (298.15 \times 0.84 \times 0.015) 0.63(0.55) \{ 7837.667(0.36) + 33888.889(0.073) + - 4236.10(0.552) \} \]
\[ a_{\text{wood}}^o = 14515.20 \text{ kJ/kg} \]

The exergy value of the firewood is very close to its higher heating value (\( HHV_{\text{wood}} = 13794 \text{ kJ/kg} \) with 25% of humidity (BEESP, 1997)), representing a variation of 5.2% among these. Kotas (1985) suggests that the ratio \( (a_{\text{wood}}^o/HHV_{\text{wood}}) \) should stay between 1.15 and 1.30; in this analysis, such value is 1.05 and this difference is specially attributed to the \( HHV \) considered, that in our calculation was not directly measured but collected from national average data available.

For the data presented in Table 1 and the calculated values of the specific heats, Eq. (12) can calculate exhaust gas and air exergy:
The mass flows that cross the control volume at figure 5 is calculated from the molecular masses of the firewood and the present air in the combustion process (calculated at stoichiometric condition), resulting an air/fuel relation of 4.33. The average consumption of firewood in the furnace was accompanied and estimated to be 0.0127 kg/s, resulting:

\[ m_{\text{air}} = 4.33 \times 0.0127 = 0.055 \text{ kg/s} \]
\[ m_{\text{eg}} = m_{\text{wood}} + m_{\text{air}} = 0.0677 \text{ kg/s} \]

The values of boiler irreversibility and efficiency, for the control volume of figure 5, are calculated, respectively, by Eqs. (13) and (6); this value of irreversibility includes the combustion process irreversibility.

\[ 0 = \left( m_{\text{wood}} a_{\text{wood}} + m_{\text{air}} a_{\text{air}} + m_{\text{water}} a_{\text{w}} \right) - \left( m_{\text{eg}} a_{\text{eg}} + m_{\text{water}} a_{\text{w}} \right) - I_{CV} \]
\[ I_{CV} = 165.85 \text{ kW} \]
\[ \varepsilon = 9.54\% \]

The rational efficiency is calculated by using Eq. (4):

\[ \psi = \frac{m_{\text{eg}} a_{\text{eg}} + m_{\text{water}} a_{\text{w}}}{m_{\text{wood}} a_{\text{wood}} + m_{\text{air}} a_{\text{air}} + m_{\text{water}} a_{\text{w}}} = 61.80\% \]

Figure 6 shows the previous CV changed for the irreversibility calculation of heat transfer components; it discriminates the contributions of waterside irreversibility, and is designated as CV2. Hence, it is used the exergetic balance again expressed by the Eq. (14), considering the portion of the heat transfer at a given temperature. Here it is interesting to stand out, in supplement, that such procedure can be extended for the other parts of the equipment under analysis, that the necessary care about the CV location and the instrumentation that will be needed for the correct data acquisition.

**Fig. 6.** Control volume modified to consider only water flow.

\[ 0 = \sum_{j} \left( 1 - \frac{T_{j}}{T} \right) \dot{Q}_{j} + \sum_{i} m_{i} a_{i} - \sum_{i} \dot{m}_{i} a_{i} - I_{CV} \]
\[ I_{CV2} = \left( 1 - \frac{T_{0}}{T} \right) Q + m_{\text{water}}(a_{i} - a_{w}) \]

in which is \( \dot{Q} \) calculated starting from the balance energy through the Eq. (15).

\[ \dot{Q} = m_{\text{water}}(h_{w} - h_{i}) = 98.7 \text{ kW} \]
\[ I_{CV2} = \left( 1 - \frac{298}{T} \right) 98.7 - 17.48 \]
Table 5 shows how the irreversibility varies inside the control volume of figure 6, together with the combustion process irreversibility \((I_{CV1} = I_{CV} \cdot I_{CV2})\), taken as a function of the heat transfer temperature; such procedure was necessary because of the difficulty of settling the exact temperature for this process, serving as a range of values in an enlarged spectrum which meets the sought value.

### Tab. 5. Irreversibility for the boiler in pasta factory.

<table>
<thead>
<tr>
<th>Temperature in the VC2</th>
<th>Irreversibility (kW)</th>
<th>(I_{VC2})</th>
<th>(I_{VC} - I_{VC2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>323</td>
<td>-9.84</td>
<td>-</td>
</tr>
<tr>
<td>75</td>
<td>348</td>
<td>-3.30</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>373</td>
<td>2.37</td>
<td>163.48</td>
</tr>
<tr>
<td>125</td>
<td>398</td>
<td>7.32</td>
<td>158.53</td>
</tr>
<tr>
<td>150</td>
<td>423</td>
<td>11.69</td>
<td>154.16</td>
</tr>
<tr>
<td>175</td>
<td>448</td>
<td>15.57</td>
<td>150.28</td>
</tr>
<tr>
<td>200</td>
<td>473</td>
<td>19.04</td>
<td>146.81</td>
</tr>
</tbody>
</table>

Note: negatives values despised because they are unfeasible.

An evaluation of efficiency defect is done for the temperature of 100°C, considered as close to the real waterside temperature, for the values of Table 5; according to Eq. (5), the efficiency defect for fire and waterside streams are:

\[ \delta_{CV1} = \frac{I_{CV1}}{m_{\text{wood}} a_{\text{wood}} + m_{\text{air}} a_{\text{air}} + m_{\text{water}} a_{\text{l}}} = \frac{163.48}{434.20} = 37.65\% \]

\[ \delta_{CV2} = \frac{I_{CV2}}{m_{\text{wood}} a_{\text{wood}} + m_{\text{air}} a_{\text{air}} + m_{\text{water}} a_{\text{l}}} = \frac{2.37}{434.20} = 0.55\% \]

### CONCLUSIONS

The first law efficiency for the boiler under analysis resulted 73.5%; for a comparison, in a study applied to the firewood small boilers (Nogueira and Peres, 1996) similar to the one here presented, it was obtained a value of 65.6%. The second law boiler efficiency was 9.54%, and due to its qualitative character, this value should be interpreted as an indicative that the process of obtaining hot water has a considerable irreversibility, being most of this located in the combustion process and in the fireside flow inside the boiler; this information may be of great importance to the equipment manufacturer to decide how to act to reduce the losses incurred in each stream flow.

This fact can be confirmed by the efficiency defects calculated for the fire and waterside sections: the value relative to the fireside is higher than the one of waterside, and the summation of these values is 38.20%, corresponding to the total of boiler irreversibilities and the complement of the rational efficiency, 61.80%.

Based on the analysis of Thermodynamics first and second laws, three action fronts may be prescribed by the Energy Conservation studies: the first is destined to the efficiency estimation of components and/or the whole system, and consequently deciding whether or not it is necessary some intervention; in the second action, by knowing these results more elements are available for decisions about implementing or expanding an industrial plant; last, this analysis can be viewed for the manufacturers as a tool for the performance study of equipment, through the location of critical points, mainly by the use of exergetic analysis.
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Dados dos autores

**RUBENS ALVES DIAS**

Doutor em engenharia mecânica pela Unesp. Professor assistente da UNESP (Campus de Guaratinguetá) e da Universidade Metodista de São Paulo (Campus de Guaratinguetá).

**JOSÉ ANTÔNIO PERRELLA BALESTIERI**

Livre docente em Máquinas Térmicas da Unesp e professor adjunto (MS-5) da Unesp (Campus de Guaratinguetá).

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