THERMO ECONOMIC ANALYSIS OF HOT WATER PREPARATION IN A MEDIUM SIZED POWER PLANT

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Rezumat. Această lucrare prezintă rezultatele privind bilanţurile termo-energetice reale pentru o instalăţie de putere medie folosită pentru producerea apei calde de încălzire precum şi a celei menajere într-o zona rezidenţială. Sunt prezentate şi problemele legate de consumul de combustibil si energie si aspecte referitoare la costurile asociate si la impactul ecologic.

Abstract. This work presents results on the real thermo energetic balances in a medium sized power plant which delivers hot water for heating and household use in a residential area. Issues on the fuel and energy consumptions of this activity and its corresponding costs and ecological implications are also presented.

Keywords: medium sized power plant/ hot water/ real thermo-energetic balances.

1. INTRODUCTION

The production, transport and usage of heat are important problems for both heat suppliers and consumers. In the case of Romania, the law promoting the efficient use of energy [6] creates the legal framework for the conception and implementation of a national policy for efficient utilization of energy, following the Energy Carta Treaty, the Energy Carta Protocol for energy efficiency and environment issues, and principles for sustainable development. This law defines efficient energy utilization as the set of actions involved in creating a product, good or service with reduced energy while not compromising on its quality or performance. The main means for implementation of energy savings is the energetic balance, which allows a quantitative and qualitative evaluation of the utilization of fuel and other energy sources in a given system.

2. DESCRIPTION OF THE POWER PLANT

2.1. Contour definition

We compile the thermo energetic balances for a medium sized power plant which supplies hot water for heating and household usage. The users are businesses and residential flats in a residential area. The plant functions intermittently following a schedule defined by the agreement between the residential association and the power plant owner (the town hall). The plant uses natural gas with a methane volume fraction of 99.12% and inferior caloric power of 36012 kJ(Nm3)-1. We compiled the real thermo energetic balances in the power plant by considering as units of reference the kiloJoule and the hour. For some specific computations we used as units of reference the ton, the normal cubic meter of fuel, the ton-equivalent petrol (tep), the gigacalorie, etc.

2.2. Technical characteristics of the main system components contained in the contour

The power plant contains four hot water ignitubular boilers: three of type BAR1930 and one of type BAR 1740. The technical specifications state that for the BAR 1930 boilers the useful power (useful thermal flow/thermal power/caloric debit) is 1744 kW, the power in the furnace is 1907 kW, the volume capacity is 2200 L, the gas fuel debit (methane) is 192 Nm3·h-1, and the liquid fuel debit is 161 kg.h-1, while for the BAR 1740 the useful power is 1569 kW, the power in the furnace is 1719 kW, the volume capacity is 2020 L, the gas fuel debit (methane) is 173 Nm3·h-1, and the liquid fuel debit is 145 kg.h-1. Hot water produced by the boilers has pressure of 5 bar and temperature of 90 °C. The heat exchangers are made of stainless-steel; three of the exchangers are used for household water preparation, with thermal power of 1690 kW, and the other three are used for the heating agent, with thermal power 1990 kW. The furnace is 25 m in height.

3. COMPUTATION FORMULAE

3.1. Material balance equations

The material balance of complete combustion was compiled by combustion computations, using methods introduced in [1], [2], [3], [4], [5], and [7]. Figure 1 shows the schematics of the material balance for the water circuit in the power plant. The material balance equation of the water circuit is:

\[
\dot{m}_7 + \dot{m}_{10} = \dot{m}_6 + \dot{m}_8 + \dot{m}_{11}
\]

The legend to the indexes of the mass debits in (1) is presented in Section 3.2.

3.2. Thermo energetic balance equations

Based on the computation of full combustion [1], [2], [3], [4], [5], [7], we compiled the combustion thermo energetic balance.

In a power plant, the thermal contour used in computing the thermo energetic balance based on heat exchange is the separation area between the building of the power plant and the exterior. Figure 2...
shows the schematics of the thermo energetic balance in a power plant.

Thus, the thermo energetic balance equation is:

\[ \dot{Q}_I = \dot{Q}_E \]  

(2)

where \( \dot{Q}_I \) is the incoming energy flow and is formed by the sum of heat flows and other energy flows that are introduced in or generated by the chosen thermal contour:

\[ \dot{Q}_I = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_{10} + \dot{Q}_{W12} \]  

(3)

\( \dot{Q}_E \) is the output energy flow formed by the sum of thermal flows that are evacuated, respectively dissipated from the thermal contour to the outside:

\[ \dot{Q}_E = \dot{Q}_6 + \dot{Q}_8 + \dot{Q}_{P11} + \dot{Q}_{P_{ch}} + \dot{Q}_{P_m} + \dot{Q}_{P_{ext}} + \dot{Q}_{UW12} + \dot{Q}_{PW12} \]  

(4)

We now present the equations that are used for computation of the thermal balance equations in a power plant, and their interpretation.

\( \dot{Q}_f \) is the thermal flow developed by fuel combustion:

\[ \dot{Q}_f = B_c H_i \]  

(5)

\( \dot{Q}_1 \) is the thermal flow corresponding to the fuel enthalpy at the input of the combustion volume:

\[ \dot{Q}_1 = B_c H_c \]  

(6)

\( \dot{Q}_2 \) is the thermal flow corresponding to the air enthalpy at the input of the combustion volume:

\[ \dot{Q}_2 = B_c H_{\text{air}} \]  

(7)

\( \dot{Q}_3 \) is the thermal flow corresponding to the water enthalpy from the secondary return heat circuit at the input in the power plant:

\[ \dot{Q}_3 = m_7 H_7 \]  

(8)

\( \dot{Q}_{10} \) is the thermal flow corresponding to the brute water enthalpy at the input in the power plant:

\[ \dot{Q}_{10} = m_{10} H_{10} \]  

(9)

\( \dot{Q}_{W12} \) is the energy flow equivalent to the absorbed electrical energy.

\( \dot{Q}_6 \) is the thermal flow corresponding to the water enthalpy in the secondary onward heating circuit at the output of the power plant:

\[ \dot{Q}_6 = m_6 H_6 \]  

(10)

\( \dot{Q}_8 \) is the thermal flow corresponding to the water enthalpy in the onward household hot water circuit at the output of the power plant:

\[ \dot{Q}_8 = m_8 H_8 \]  

(11)

\( \dot{Q}_{P11} \) is the thermal flow dissipated through the enthalpy of the water evacuated from the power plant to the sewing system:

\[ \dot{Q}_{P11} = m_{11} H_{11} \]  

(12)

\( \dot{Q}_{P_{ch}} \) is the thermal flow dissipated through the combustion gases evacuated from the boiler, computed from the combustion thermo energetic balance. \( \dot{Q}_{P_{ch}} \) is the dissipated thermal flow corresponding to incomplete combustion due to chemical reasons, which can be detected by the presence of either fuel gases (CO, CH₄, H₂ etc.) in the combustion gases or ashes (non-burnt carbon); in the case we analyze, this flow is assumed null.

\( \dot{Q}_{P_m} \) is the thermal flow dissipated through incomplete combustion due to mechanical reasons; in the case we analyze, this flow is assumed null as well.

\( \dot{Q}_{P_{ext}} \) is the thermal flow dissipated from the inside of the power plant to the exterior:

\[ \dot{Q}_{P_{ext}} = (k_p S_p + k_a S_a)(t_{in} - t_{ext}) + k_i S_l (t_{in} - t_s) \]  

(13)

\( \dot{Q}_{UW12} \) is the energy flow equivalent to the useful electrical energy.

The error of the balance is computed using:

\[ \varepsilon = \frac{\dot{Q}_E - \dot{Q}_I}{\dot{Q}_I} \times 100 \% \]  

(14)

The conventional energy transformation yield is obtained by using the formula:

\[ \eta_c = \frac{\dot{Q}_6 + \dot{Q}_k + \dot{Q}_{UW12}}{\dot{Q}_I} \times 100 \% \]  

(15)

3.3 Evaluation of the energy efficiency

The qualitative and quantitative evaluation of a process or installation is done using energy efficiency indicators [7] computed using the thermo energetic balances.

- Specific fuel consumption for producing an unit of product \( Z \), \( c_{f/Z} \) [(tep).(up)⁻¹], is defined as the ratio between the sum \( \sum B_i \) of fuel and hot gas amounts input into the process and consumed during the process, expressed in equivalent petrol tons (tep), and the
production volume $V_Z$, expressed in production units (up):

$$c_{i/Z} = \frac{\sum B_i}{V_Z}$$ (16)

- **Specific thermal energy consumption** for producing an unit of product $Z$, $c_{i/Z} [\text{J.(up)}^{-1}]$, is defined as the ratio between the sum of heat amounts $\sum Q_i$ input into the process and consumed during the process, expressed in [J], and the production volume $V_Z$, expressed in production units (up):

$$c_{i/Z} = \frac{\sum Q_i}{V_Z}$$ (17)

- **Specific electrical energy consumption** for producing a unit of product $Z$, $c_{e/Z} [\text{kWh.(up)}^{-1}]$, is defined as the ratio between the sum of electrical energy amounts $\sum W_i$ input into the process and consumed during the process, expressed in [kWh], and the production volume $V_Z$, expressed in production units (up):

$$c_{e/Z} = \frac{\sum W_i}{V_Z}$$ (18)

- **Specific complex energy consumption** for producing a unit of product $Z$, $c_{\text{complex/Z}}$ [tep/up], expressed in [tep/up] is:

$$c_{\text{complex/Z}} = \frac{\sum E_i}{V_Z}$$ (19)

where $\sum E_i$ is the sum of electrical, thermal, fuel and hot gases energy input into the process from the exterior [tep].

- **Fraction of electrical energy consumption** $P_{e/Z}$ from the total energy consumption used to produce a unit of $Z$:

$$P_{e/Z} = \frac{\sum W_i}{\sum E_i} \times 100 \%$$ (20)

- **Energy cost value** to produce a unit of product $Z$, expressed in [currency/up]:

$$v_{en/Z} = \frac{\sum C_{en}}{V_Z}$$ (21)

where $\sum C_{en}$ are the total energy expenses to produce a production volume $V_Z$ of product $Z$.

- **Fraction of energy costs [%]** from the total cost to produce a unit of product $Z$:

$$P_{Cen} = \frac{v_{en/Z}}{C_Z} \times 100$$ (22)

where $C_Z$ is the total cost for a unit of production [currency/up]. We used as currency the Romanian leu.

4. RESULTS AND DISCUSSION

4.1 Real thermo energetic balances

Real thermo energetic balances were evaluated for three different operating conditions, using equations (1)...(15). Operating condition I measurements were taken when heating energy and household water were produced using two boilers, one BAR 1930 and one BAR 1740; in operating condition II heating energy was produced using two BAR 1930 boilers; and in operating condition III household water was produced using one BAR 1930 boiler. Table I shows the values of the thermal flows at the input and output of the thermal contour and the dissipated (lost) thermal flows; the balance error is $e = 0$ and the conventional yield of energy transformation has values:

$$\eta_{d} = 60.16\%; \quad \eta_{dH} = 50.61\%; \quad \eta_{dEF} = 72.71\%.$$
4.2. Energy efficiency indicators

Table II contains measurement results of the thermal energy indicators in the power plant, using (16)...(22). We used energy and fuel prices corresponding to the period when those balances were compiled, i.e. first half of 2007.

4.3. Ecological implications

The use of a medium size power plant for the supply of heating and household hot water in a residential area exhibits a set of advantages over both individual household power plants and large sized power plants. The power plant has a 25m-high furnace which ensures the evacuation of combustion gases to the exterior; it works with sulfur-free gaseous fuel, the boilers have modern automatic systems, and combustion is controlled by expert personnel which leads to increased operating safety and a decrease in emissions of carbon monoxide or other non-burnt products.

5. CONCLUSIONS

1. The balance of real thermo energetic balances is compiled using data regarding energy flows entering and exiting the thermal contour. Such analysis leads to the identification and classification of energy losses and their fraction from the total amounts of energy used, and helps in determining the causes that generate such losses, as well as ways to save energy.

2. The energy efficiency indicators show the costs corresponding to hot water production, their fraction in the total costs, and helps in identifying energy related factors that influence these costs.

3. Medium sized power plants are likely to exhibit a set of advantages over other types of plants, especially regarding the costs incurred by the users, and an increased operating safety in producing heating and household hot water.

Table I
Thermal flows corresponding to the real thermo energetic balance

<table>
<thead>
<tr>
<th>No.</th>
<th>Thermal flow</th>
<th>Symbol</th>
<th>Operating conditions I</th>
<th>Operating conditions II</th>
<th>Operating conditions III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>( Q_f )</strong> Resulted from fuel combustion</td>
<td>1</td>
<td>10 083 360</td>
<td>67.02</td>
<td>7 232 290</td>
</tr>
<tr>
<td>2</td>
<td><strong>( Q_2 )</strong> Fuel</td>
<td>0</td>
<td>0</td>
<td>623</td>
<td>1435</td>
</tr>
<tr>
<td>3</td>
<td><strong>( Q_3 )</strong> Combustion air</td>
<td>125 096</td>
<td>0.83</td>
<td>89 725</td>
<td>29 518</td>
</tr>
<tr>
<td>4</td>
<td><strong>( Q_4 )</strong> Secondary return heating water circuit</td>
<td>4 214 574</td>
<td>28.01</td>
<td>4 293 475</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td><strong>( Q_{10} )</strong> Brute water</td>
<td>551 000</td>
<td>3.66</td>
<td>44 840</td>
<td>249 480</td>
</tr>
<tr>
<td>6</td>
<td><strong>( Q_{W_{12}} )</strong> Electrical energy equivalent</td>
<td>72 000</td>
<td>0.48</td>
<td>58 909</td>
<td>10 800</td>
</tr>
<tr>
<td></td>
<td><strong>( Q_{I} )</strong> Total inputs</td>
<td>15 046 030</td>
<td>11 719 862</td>
<td>1 990 999</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Thermal flow</th>
<th>Symbol</th>
<th>Operating conditions</th>
<th>Operating conditions II</th>
<th>Operating conditions III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>( Q_h )</strong> Secondary return heating water circuit</td>
<td>6 598 800</td>
<td>43.86</td>
<td>5 889 600</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td><strong>( Q_k )</strong> Household water</td>
<td>2 401 200</td>
<td>15.97</td>
<td>-</td>
<td>1 440 000</td>
</tr>
<tr>
<td>3</td>
<td><strong>( Q_{W_{12}} )</strong> Useful electrical energy equivalent</td>
<td>50 400</td>
<td>0.33</td>
<td>41 236</td>
<td>7 560</td>
</tr>
<tr>
<td>4</td>
<td><strong>( Q_{P_{12}} )</strong> Lost electrical energy equivalent</td>
<td>21 600</td>
<td>0.14</td>
<td>17 673</td>
<td>3 240</td>
</tr>
<tr>
<td>5</td>
<td><strong>( Q_{P_{gg}} )</strong> Loss by evacuation of combustion gases in the boilers</td>
<td>1 120 000</td>
<td>7.44</td>
<td>803 320</td>
<td>188 800</td>
</tr>
<tr>
<td>6</td>
<td><strong>( Q_{P_{ext}} )</strong> Loss to the exterior and other losses</td>
<td>4 854 030</td>
<td>32.26</td>
<td>4 968 033</td>
<td>351 399</td>
</tr>
<tr>
<td></td>
<td><strong>( Q_{E} )</strong> Total outputs</td>
<td>15 046 030</td>
<td>11 719 862</td>
<td>1 990 999</td>
<td></td>
</tr>
</tbody>
</table>
### Table II

Energetic efficiency indicators for a power plant computed using real thermo energetic balances.

<table>
<thead>
<tr>
<th>No.</th>
<th>Energy efficiency indicator</th>
<th>Symbol/Unit</th>
<th>Operating conditions I</th>
<th>Operating conditions II</th>
<th>Operating conditions III</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific fuel consumption</td>
<td>$c_{f,z}$ [(tep)-GJ⁻¹]</td>
<td>0.02675</td>
<td>0.02932</td>
<td>0.03131</td>
</tr>
<tr>
<td>2</td>
<td>Specific thermal energy consumption</td>
<td>$c_{t,z}$ [J·GJ⁻¹]</td>
<td>0.4682×10⁹</td>
<td>0.729×10⁹</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Specific electrical energy consumption</td>
<td>$c_{e,z}$ [kWh·GJ⁻¹]</td>
<td>2.222</td>
<td>2.778</td>
<td>2.083</td>
</tr>
<tr>
<td>4</td>
<td>Specific complex energy consumption</td>
<td>$c_{complex,z}$ [(tep)-GJ⁻¹]</td>
<td>0.03812</td>
<td>0.04697</td>
<td>0.03149</td>
</tr>
<tr>
<td>5</td>
<td>Fraction of electrical energy consumption</td>
<td>$p_{e,z}$ [%]</td>
<td>0.498</td>
<td>0.629</td>
<td>0.572</td>
</tr>
<tr>
<td>6</td>
<td>Energy costs</td>
<td>$v_{en,z}$ [lei·GJ⁻¹]</td>
<td>30.549</td>
<td>33.646</td>
<td>35.514</td>
</tr>
<tr>
<td>7</td>
<td>Energy costs fraction</td>
<td>$p_{Con}$ [%]</td>
<td>0.5875</td>
<td>0.647</td>
<td>0.683</td>
</tr>
</tbody>
</table>

**List of notations**

- $B_c$ – fuel volume debit, [Nm³·h⁻¹];
- $c$ – specific consumption, [(tep)·(up)⁻¹], [J·(up)⁻¹], [kWh·(up)⁻¹];
- $C$ – cost, [lei];
- $E$ – energy;
- $H$ – mass enthalpy, [kJ·kg⁻¹];
- $H_i$ – inferior calorific power of fuel, [kJ·(Nm⁻³)⁻¹];
- $m$ – mass debit, [kg·h⁻¹];
- $k$ – global heat transfer coefficient, [W·m⁻²K⁻¹];
- $p$ – cost fraction, [%];
- $Q$ – heat, [J];
- $Q$ – thermal flow, [kW];
- $S$ – area, [m²];
- $V$ – production volume, [up];
- $v$ – cost value, [lei·(up)];
- $W$ – electrical energy.

**Indexes**

- aer – air
- $a$ – fuel
- ch – chemical
- $E$ – evacuation
- en – energy
- ext – exterior
- f – furnace
- ga – combustion gases
- int – interior
- $I$ – input
- $m$ – mechanic
- $p$ – walls
- $P$ – dissipated
- s – soil
- $t$ – foundation
- $U$ – useful
- $Z$ – production

**BIBLIOGRAPHY**