Exergy Efficiency of Paper Machine’s Drying Section

IOANA DIACONESCU, LUIZA GRIGORESCU
Engineering Faculty of Braila
“Dunarea de Jos” University of Galati
Domneasca Street no. 47, 800008 Galati
ROMANIA
ioana.diaconescu@ugal.ro, http//www.ugal.ro

ROXANA PATRASCU
Power Engineering Faculty
University “Politehnica” of Bucharest
313, Splaiul Independentei Street
ROMANIA
op3003@yahoo.com

Abstract: - The paper making process is essentially a very large dewatering operation where a diluted solution of pulp suspension with less than 0.5% fibre solid is used. The dryer section of a paper machine removes between 1.1 and 1.3 kg of water per kg of paper compared to 200 kg and 2.6 kg in the forming and press sections respectively. It is significantly more expensive to remove this water than for any other section of the machine (Reese, 1988). The relative costs of dewatering are: forming section 10%; press section 12% and dryer section 78%. The dryer section is by far the largest consumer of thermal energy of a paper machine. Rising energy costs are forcing papermakers to pay more attention to energy efficiency, and specially steam usage.

Key-Words: - efficiency, exergy, drying section, drying cylinder, heating battery

1. Introduction

The concept of efficiency consists in an action effects comparison, with necessary efforts for its fulfillment and someone can draw the conclusion that the efficiency expresses a complex structure of causality relations between positive and negative effects of one action finality. Generally speaking, an activity is more efficient under energy aspect if energy loss from the thermodynamics boundary of that activity is smaller. The concept of energy efficiency gets a specific meaning only if it is connected with a well defined boundary and with an activity which is running into an organized manner inside this boundary.

Energy efficiency involves many action ways, such as:
- The identification of all energy flows which are involved into the process realization[1];
- The identification of lost energy flows;
- The identification of the best advantageous measures for loss reduction taking into account their preliminary costs estimation in comparison with the profits result through energy efficiency growing;
- To apply the measures considered efficient, able to eliminate energy loss.

In a restricted way, energy efficiency concept has the meaning of energy performance [4]. So that, energy efficiency growing in restricted way has as consequence the energy saving. The final result of energy efficiency growing consists in energy bill or specific expenses reductions.

2. Drying Section’s Energy Flows

Contact drying with steam heated cylinders is the predominant method of drying in paper and paperboard machines. Besides conductive heat transfer between hot cylinder surface and the wet web, the role of air that is either the drying medium or surrounds the drying atmosphere is very significant. Paper drying is associated with both heat and mass transfer.

The heat energy released when steam condenses is transmitted through the dryer shell to the wet paper and this constitutes the heat transfer aspect of drying. The air receives the water vapour evaporated
from the paper. The removal of this vapour from the sheet into the air stream constitutes the mass transfer aspect of paper drying [2]. As a result, the operation of a dryer section must be optimized in terms of both heat transfer and water removal. The factors which most influence paper drying operation are steam pressure and temperature, temperature and humidity of air, energy content of steam and heat and mass transfer coefficients.

In paper drying the predominant mode of heat transfer is by conduction for manufacturing majority of paper grades. Convective heat transfer also play significant role in dryer pocket ventilation system. For tissue grades where hot air impingement on the web is applied, heat transfer by convection is most important. Radiation heat transfer is usually ignored in conventional paper drying since its contribution to the overall heat transfer is much less than that due to conduction and convection.

The basic form for one dimensional steady state heat conduction is shown in equation (1), while that of convective heat transfer is shown in equation (2).

\[ Q = k \cdot A \cdot \Delta T / \Delta X \]  
\[ Q = h \cdot A \cdot \Delta T \]

where

\( Q \) is heat transfer rate, [W]
\( k \) is thermal conductivity, [W/m.K]
\( A \) is heat transfer surface area, [m²]
\( T \) is temperature, [K]
\( X \) is diameter or thickness, [m]
\( h \) is thermal conductive conductance, [W/m² K]

The rate of heat transferred from the hot steam inside the cylinder to the cooler paper on the outside depends on the overall temperature gradient and on the different resistances to heat transfer:

\[ Q = U \cdot A \cdot (T_{ab} - T_p) \]  

Where:

\( Q \) rate of heat flow from inside dryer to paper, [W]
\( U \) overall heat transfer coefficient, [W/m²K]
\( T_{ab} \) steam temperature, [K]
\( T_p \) paper temperature, [K]

The resistance due to scaling inside the cylinder could be lumped together as resistance due to dryer shell. The various resistances to heat flows are shown in Table 1.

Since under the steady state conditions heat transferred through each layer is the same, all \( q \)’s are equal. The heat flow is equal to the total driving force divided by the total resistance, therefore [7]:

\[ q = \frac{\sum \Delta T_i}{\sum R_i} ; q = U \cdot A \cdot \Delta T \]  
\[ U = \frac{1}{1 / h_s A_s + L_c / k_c A_c + \ldots + 1 / h_a A} \]

Table 1

<table>
<thead>
<tr>
<th>Source of resistance</th>
<th>Specific heat flow, ( q ), [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam film</td>
<td>( q_1 = \frac{(T_1 - T_2)}{1/(A_s h_s)} )</td>
</tr>
<tr>
<td>Condensate layer</td>
<td>( q_2 = \frac{(T_2 - T_1)}{L_c / (A_s k_s)} )</td>
</tr>
<tr>
<td>Dryer shell</td>
<td>( q_3 = \frac{(T_3 - T_s)}{L_s / (A_s k_s)} )</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>( q_4 = \frac{(T_4 - T_5)}{1/(A_s k_s)} )</td>
</tr>
<tr>
<td>Paper</td>
<td>( q_5 = \frac{(T_s - T_6)}{L_s / (A_s k_s)} )</td>
</tr>
<tr>
<td>Air film</td>
<td>( q_6 = \frac{(T_6 - T_7)}{1/(A_s k_s)} )</td>
</tr>
</tbody>
</table>

It is evident from equation (3) that the amount of heat transferred may be increased by increasing \( U \) (reduce condensate layer inside cylinder, eliminate non-condensibles, increase felt tension, increase contact area of felt, increase contact felt permeability, ensure dryer surface is clean, optimal shell thickness) ; increasing \( A \) (add more dryer cylinders, increase contact area with larger diameter dryer or single tier arrangement with larger sheet wrap); increasing \( T_s \) (raise steam temperature) and decreasing \( T_p \) (lower sheet temperature by good pocket ventilation).

3. Exergy Efficiency Analysis of the Drying Process

Exergy analysis of drying paper process studies potential of drying system in relation with the environment and allows drawing up correctly of balance and determining losses and rational efficiency that occur in the drying process. Exergy and anergy are energy characteristics that depend on the system state, on the type of energy used, on the irreversibility of the processes and on the environment state. So, these characteristics contain parameters of the environment that establish limit of possible evolution of the thermodynamic system considered. Heat that is energy with transformer capacity limited, transformers partially in the another type energy. Exergy of heat is that component of heat which it can transformer in any type of energy [3].

On basis of the results of the exergy analysis improvements are suggested. Suggestions for improvements are based on two criteria, the exergy
losses and the efficiency of the components. On the basis of the exergy losses the maximum amount of exergy saving is known, while the efficiency of the components gives an indication of the technical possibilities for improvements.

In this paper are analyzed main components where the heat transfer is considerable: drying cylinder and heat batteries of the air.

3.1 Exergy and Rational Efficiency Determination

The general form of the rational efficiency, $\eta_{ex}$, is defined as the ratio of useful exergy, $E_u$, to the used exergy, $E_c$:

$$\eta_{ex} = \frac{E_u}{E_c} \quad (6)$$

and exergy losses, $\eta_{ec}$, are:

$$\eta_{ec} = E_c - E_u$$

From viewpoint of heat transfer process, drying cylinder can be assimilated with a heat exchanger. Its heat transfer area is the cylinder shell where it is realized heat transfer from steam to the sheet.

The condensate temperature is constant and equal with saturation temperature corresponding to the pressure inside the cylinder. Useful exergy is heat exergy received by paper sheet from all drying cylinders. For cylinder “i”, this is [8]:

$$E_{u,i} = \left(1 - \frac{T_0}{T_{hm,i}}\right) \cdot k_i \cdot A_i \cdot \Delta t_{med,i} +$$

$$+ W_i \left[h_{vap,i} - h_0 - T_0 \cdot (s_{vap,i} - s_0)\right] \quad (7)$$

where: $T_0 = 18+273,15[K]$ is reference temperature of the environment; $T_{hm,i}$ is average temperature of the sheet on the cylinder “i”, [K]; $\Delta t_{med,i}$ is logarithmic average temperature between condensate inside cylinder and paper sheet, [$^\circ$C]; $k_i$ is over all heat temperature coefficient, [W/m$^2$.K]; $A_i$ is contact area between cylinder “i” and paper sheet, [m$^2$]; $W_i$ evaporated water from sheet on the cylinder “i”,[kg]; $h_{vap,i}$ is steam enthalpy removed from paper sheet, [J/kg]; $h_0$ is steam enthalpy for reference temperature, [J/kg]; $s_{vap,i}$ and $s_0$ are steam entropy for average temperature of the sheet, respectively for the reference temperature, [J/kg.K].

Used exergy is steam exergy inside of all cylinder of drying section. For cylinder “i”, this exergy is:

$$E_{c,i} = D_i \cdot \left[\bar{h}_{ab,i} - \bar{h}_{cd,i} - T \cdot (s_{ab,i} - s_{cd,i})\right] \quad (8)$$

where: $D_i$ is steam flow inside the cylinder “i”, [kg/s]; $h_{ab,i}$ and $h_{cd,i}$ are steam enthalpy at the steam admission in cylinder “i”, respectively condensate enthalpy evacuated from cylinder “i”, [J/kg]; $s_{ab,i}$ and $s_{cd,i}$ are steam entropy at the admission in cylinder “i”, respectively condensate entropy evacuated from cylinder “i”, [J/kgK].

Useful exergy for the heat batteries of the air, that are heat exchangers type condenser, is heat exergy received by the air at the average temperature of the air in the battery. Used exergy of these is heat exergy given up by the steam at the saturation temperature corresponding to the pressure inside the battery. These exergies are calculated with the following type of relation:

$$E = \left(1 - \frac{T_0}{T_m}\right) \cdot Q \quad (9)$$

where: $E$ is heat exergy, [W]; $T_m$ is average temperature inside the battery, [K]; $Q$ is battery’s heat, [W].

3.2 Numerical Results

Using the relations above mentioned, it was an experimental analysis for a paper mill with 23 cylinders in a drying section.

In the ventilation circuit are four heating batteries for air flow: two for the air blow under machine hood (B$_1$ and B$_2$), one for the air blow on the ceiling (B$_3$) and one for the air blow on the wall (B$_4$).

In the table 1 are presented the values of the calculated heat and in the table 2 the values of the calculated exergy.

In the drying section of the machine, useful exergy is only 14% from useful energy and exergy losses are more than energy losses, 115%. Just thermal efficiency achieves approximate 88% while exergy efficiency does not exceed 51%.

In the heating battery of the air, the weight of the useful exergy unto the useful energy decreases from 12% to 2%. In the same time, the weight of the exergy loss increases and exergy efficiency decreases. Exergy efficiency decreases because of the average temperature of the cold stream (air) decreases and of the average temperature difference between cold stream and cold stream increases [5].

It is noticed that both exergy and energy losses are more in the heating batteries than in drying cylinders. Total amount of exergy losses is 345 kW and total amount of energy losses is 216 kW. Exergy efficiency is 38% and thermal efficiency is 84%.

Reducing exergy losses or increasing exergy efficiency, respectively, is possible by reducing average temperature difference between cold stream and hot stream. Mainly, this is realized by decreasing thermal resistance of the heat transfer, eliminating sediments on the heat transfer surfaces, using saturate steam and removing non-condensable inside the cylinders.
For the drying cylinders, a high felt tension value involves the decrease of thermal resistance of heat transfer from the steam inside the cylinder to the paper sheet [9].

### 4. Conclusions

Exergy analysis of the drying paper process emphasizes exergy losses and exergy efficiency of the main heat consuming of the paper machine which is drying section. The exergy analysis was made on heat of steam used in drying cylinders and heating batteries of the air.

From thermal viewpoint, heating batteries have the same performances but there are different from exergy point of view. Useful exergy increases simultaneous with increasing average temperature difference between the thermal streams. The highest values of the exergy losses are in the heating batteries. These losses can be reduced by increasing heat transfer in the batteries by increasing average temperature of the air.

Increasing exergy efficiency of the drying cylinder is limited by the qualitative characteristics of the paper sheet. These allow increasing sheet temperature only corresponding to the admissible diagram temperature of the respective paper sort. Also, to increase the felt tension too much is a not an allowable action.

### References:


### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Useful [kW]</th>
<th>Used [kW]</th>
<th>Losses [kW]</th>
<th>Thermal efficiency [%]</th>
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</thead>
<tbody>
<tr>
<td>Drying cylinders</td>
<td>974</td>
<td>1108</td>
<td>113</td>
<td>87.96</td>
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<tr>
<td>Heating battery B&lt;sub&gt;1&lt;/sub&gt;</td>
<td>285</td>
<td>356</td>
<td>71</td>
<td>80</td>
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<tr>
<td>Heating battery B&lt;sub&gt;2&lt;/sub&gt;</td>
<td>291</td>
<td>364</td>
<td>73</td>
<td>80</td>
</tr>
<tr>
<td>Heating battery B&lt;sub&gt;3&lt;/sub&gt;</td>
<td>178</td>
<td>222</td>
<td>44</td>
<td>80</td>
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<tr>
<td>Heating battery B&lt;sub&gt;4&lt;/sub&gt;</td>
<td>111</td>
<td>139</td>
<td>28</td>
<td>80</td>
</tr>
<tr>
<td>All heating batteries</td>
<td>865</td>
<td>1081</td>
<td>216</td>
<td>80</td>
</tr>
<tr>
<td><strong>Total amount/global efficiency</strong></td>
<td><strong>1839</strong></td>
<td><strong>2189</strong></td>
<td><strong>329</strong></td>
<td><strong>84.011</strong></td>
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</table>

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>Exergy [kW]</th>
<th>Exergy efficiency [%]</th>
<th>Average temp. difference [°C]</th>
<th>Average temp. [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Useful [kW]</td>
<td>Used [kW]</td>
<td>Losses [kW]</td>
<td></td>
</tr>
<tr>
<td>Drying cylinders</td>
<td>136</td>
<td>266</td>
<td>130</td>
<td>51.048</td>
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<td>36</td>
<td>97</td>
<td>61</td>
<td>37.407, 67</td>
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<td>31</td>
<td>100</td>
<td>69</td>
<td>30.876, 75</td>
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<td>Heating battery B&lt;sub&gt;3&lt;/sub&gt;</td>
<td>11</td>
<td>61</td>
<td>50</td>
<td>17.907, 91</td>
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<tr>
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<td>2</td>
<td>38</td>
<td>36</td>
<td>6.018, 103</td>
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<td>296</td>
<td>215</td>
<td>27.167</td>
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<tr>
<td><strong>Total amount/global efficiency</strong></td>
<td><strong>216</strong></td>
<td><strong>559</strong></td>
<td><strong>345</strong></td>
<td><strong>38.64</strong></td>
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