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**Research paper**

# Improving energy efficiency and heat recovery performance in paper machine drying section

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**Abstract**

In this study, the energy assessment and heat recovery analysis of the multi-cylinder drying section were carried out in a fluting paper machine. The specific heat consumption per unit of paper was determined to be about 4.7 GJ/ton of paper and accordingly, the machine consumed about 1.71 tons of steam per ton of produced paper. The temperature efficiency of the heat exchanger and the recovering efficiency of the heat recovery system within the paper machine have been determined to be about 50% and 4%, respectively. The results show that the steam used in the heat recovery system can be reduced by about 0.95 tons/h due to adjusting the supply air temperature to the optimum range, which corresponds to about a 5.2% reduction in energy input and 4% improvement in dryer efficiency resulting nearly 31,000 $ savings per year. Also, the $CO_2$ emission due to gas use can be decreased by about 925 tons/y.

## 1. Introduction

Paper is principally a mixture of fiber and water, and paper manufacturing is mostly a substantial dewatering process. The water in the paper web is first removed in the wet section followed by the drying process. Dewatering in the wet section of the paper machine consists of forming and pressing processes and the purpose of the drying process is to supply adequate heat to the dryer to decrease the moisture of the wet paper to the desired content. Multi-cylinder dryers are the most common types of dryers in the paper industry and steam is the main heat source in most cases fed into the drying cylinders [1]. In general, the multi-cylinder dryers include some groups of steam-heated cylinders that are entirely covered by a hood. The dryer hood operates under slightly negative pressure and it encloses the entire drying section, which consists of the dryer cylinders, the ventilation system, the dryer fabrics, and the paper web [2]. Furthermore, the air system is used to control the drying surroundings and optimize energy efficiency [3].

In the studied machine, a fiber-water suspension with an original consistency (mass percent of fiber content in the suspension) of about 1% is conveyed to the headbox and spread on the forming wire; the consistency increases to about 20%, and the paper web is formed. Then much of the free water is drained off through the press section to achieve the dryness (percentage of fiber content in the web) of about 40-50%. The remaining water is removed in the drying section to attain the final moisture content [4, 5].
The pulp and paper industry is the fourth main energy consumer in the world [3]. The drying section eliminates about 1% of the initial water content, but it utilizes more than 65% of the whole energy needed and 80% of the total steam consumption in the paper machine [6-8].
Given that, an energy model based on the mass and energy balances can be applied to assess the energy performance in the paper drying section.
In 2012, a static energy model was established by Lingbo Kong and Huanbin Liu to evaluate the multi-cylinder drying process of a newsprint paper machine according to the mass and energy balance relationships. Their model can be applied to estimate specific energy consumption and to identify drying performance and energy-saving opportunities [3].
The assessment of energy use in the paper drying process can be applied to present achievable opportunities and decrease the energy indices based on the modeling. Few studies have been reported to evaluate energy consumption in the fluting drying sections.

## 2. Modeling description

In this study, a previously developed model was used to determine the energy efficiency and heat recovery performance of the drying section in a fluting paper machine. The methodology to attain the used model formulation, the solving procedure of the main equations, and the correlating methods to calculate the heat and mass transfer coefficients and drying parameters have been described in the published paper [9].
The developed model can be appropriately used to evaluate the temperature and dryness of the paper, as well as the temperature of the cylinders. Furthermore, the model can predict the variation of humidity and temperature at pocket dryers and exhaust air. Therefore, the model can be easily applied to estimate the energy indices, drying efficiency, and heat recovery performance of the machine. Accordingly, some energy reduction opportunities for the studied drying section have been investigated.
The auxiliary relationships used in the modeling can be represented as follows:

### *2.1. Paper properties*

Heat capacity of the paper can be expressed as follows [3]:

$$C_p = \frac{C_f + H_p\, C_w\big|_{T_p}}{1 + H_p} \tag{1}$$

here $H_p$ is the paper moisture ratio or absolute humidity of paper. $C_p$, $C_f$, and $C_w$ are the heat capacity of the paper, fiber, and water, respectively. Also, $T_p$ represents the paper temperature. In this study, the value of $C_f$ was considered to be 1.55 kJ/kg.K.
The following relation can be applied to obtain the moisture ratio of the paper web:

$$H_p = \frac{100 - D_p}{D_p} = \frac{m_w}{m_f} \tag{2}$$

The energy content of the paper web can be determined as follows:

$$Q_p = (\dot{m}_f\, C_f + \dot{m}_w\, C_w)\, T_p \tag{3}$$

where $D_p$ is the dryness of the paper web. $m_w$ and $m_f$ are the total mass of water and fiber in the paper web, respectively. $\dot{m}_f$ and $\dot{m}_w$ also represent the mass flow rate of fiber and water, respectively.

### *2.2. Air properties*

The air enthalpy can be calculated as follows:

$$h_a = (C_a + X_a C_v)T_a + X_a \lambda \tag{4}$$

where $h_a$ is the air enthalpy. $C_a$ and $C_v$ show the heat capacity of air and vapor, respectively. $T_a$

and $X_a$ represent the temperature and moisture ratio of air, respectively. In addition, λ represents the latent heat of water.

*2.3. Steam and condensate properties:*

The steam and water energy can be calculated from Eq. (5) and Eq. (6), respectively:

$$Q_s = \dot{m}_s \; h_s \tag{5}$$

$$Q_w = \dot{m}_w \; h_w \tag{6}$$

here Q, ṁ, and h are the energy, mass rate, and enthalpy, respectively. Subscripts s and w represent the steam and water, respectively.

*2.4. Mass balance equations*

The paper drying process includes four main components: fiber, water, steam and air. Mass balance equations have been written for these components. It was assumed that the system is in steady state condition, therefore, the equations used for modeling can be expressed as follows:

*- for fiber:*

The fiber mass rate is calculated in terms of the moisture content of the paper as below, which is assumed to be constant during the drying process. The mass rate of fiber can be calculated as follows:

$$\dot{m}_f = \frac{\dot{m}_{p,out}}{1+H_{p,out}} \tag{7}$$

where $H_{p,out}$ is the moisture ratio of the final product. $\dot{m}_{p,out}$ is the mass rate of paper leaving from the drying section and can be obtained by the following relation:

$$\dot{m}_{p,out} = G_{dry} \; V \, W \tag{8}$$

here $G_{dry}$ denotes the basis weight or grammage of the dry paper which is defined as the mass of the product per unit of area for a paper or paperboard and can be determined with an experimental procedure and standard techniques. V and W represent the web speed and the paper width in the drying section, respectively.

*- for water:*

The mass flow rate of the moisture in the paper can be computed as:

$$\dot{m}_w = \dot{m}_f \; H_p = \frac{G_{dry} \; W \, V \; H_p}{1+H_{p,out}} \tag{9}$$

Hence, the mass balance equation for water across the dryer can be written as:

$$\dot{m}_{p\,in}\left(\frac{100 - D_{p\,in}}{D_{p\,in}}\right) + \dot{m}_{a\,in} X_{a\,in} = \dot{m}_{p\,out}\left(\frac{100 - D_{p\,out}}{D_{p\,out}}\right) \dot{m}_{a\,out} X_{a\,out} \tag{10}$$

$$\dot{m}_{a,in} = \sum \dot{m}_{sa} + \sum \dot{m}_{la} \tag{11}$$

$$\dot{m}_{a,out} = \sum \dot{m}_{ea} \tag{12}$$

where subscripts sa, la, and ea refer to supply air, leakage air, and exhaust air, respectively.
The mass flow rate of the paper at each point of drying path can be written as:

$$\dot{m}_p = G_{dry} V \;\; W \;\; \left(\frac{1+H_p}{1+H_{p,out}}\right) \tag{13}$$

*for air:*

$$\sum \dot{m}_{ea} = \sum \dot{m}_{sa} + \sum \dot{m}_{la} \tag{14}$$

The proportion between the amounts of dry supply air and dry exhaust air is named the hood balance and it can be defined as:

$$HB = \frac{\sum \dot{m}_{sa}}{\sum \dot{m}_{ea}} \tag{15}$$

Then:

$$\sum \dot{m}_{la} = \frac{1-HB}{HB} \sum \dot{m}_{sa} \tag{16}$$

*for steam:*

$$\sum \dot{m}_s = \sum \dot{m}_c + \sum \dot{m}_{bts} \tag{17}$$

here subscripts s, c and bts represent steam, condensation, and blow-through steam, respectively. The parameter 'blow-through steam (BTS)' is termed as the percentage of uncondensed steam of total steam inflowing to the dryer cylinders which exits from the dryer with condensate as a two-phase flow [10]. It was shown by Ali that the amount of blow through steam for each steam group of the drying section can be determined based on the type and size of the siphon, and the differential pressure to attain the continuous removal of the condensate through the siphon [11]. Accordingly, regarding the diameter of the rotary siphon pipes and the mean differential pressure between the steam and condensate in the drying section of the studied machine, the blow-through steam of the cylinder dryers can be assumed in the range of 10-12%.

### *2.5. Calculation of evaporation rate*

The evaporation rate from the web surface in the drying section can be determined by various methods:

Based on the results of the developed model:

By TAPPI procedure that can be calculated as [3]:

$$\dot{m}_{ev} = G_{dry}\, V\, W\, \frac{D_{p,out} - D_{p,in}}{D_{p,out}} \tag{18}$$

According to the moisture balance in the web that can be obtained by the following relation:

$$\dot{m}_{ev} = \dot{m}_{p,in}(1 - D_{p,in}) - \dot{m}_{p,out}(1 - D_{p,out}) \quad or \quad \dot{m}_{ev} = \left(\frac{1}{D_{p,in}} - \frac{1}{D_{p,out}}\right)\dot{m}_f \tag{19}$$

According to the air balance in the web that can be computed as follows:

$$\dot{m}_{ev} = \sum \dot{m}_{a,out}\, X_{a,out} - \sum \dot{m}_{a,in}\, X_{a,in} = \sum \dot{m}_{ea}\, X_{ea} - \left(\sum \dot{m}_{sa}\, X_{sa} + \sum \dot{m}_{la}\, X_{la}\right) \tag{20}$$

### *2.6. Energy balance equations*

The energy streams into and out of the dryer section are also characterized by four major elements; fiber, steam, air, and water. In general, the energy consumption in the drying process can be divided into five parts as follows [3]:
The sensible heat of the web and contained water that can be obtained by the following equation:

$$Q_1 = (\dot{m}_f\, C_f + \dot{m}_{w,out}\, C_w)(T_{p,out} - T_{p,in}) \tag{21}$$

Latent heat to evaporate water can be calculated as follows:

$$Q_2 = \dot{m}_{ev}\, \Delta H_{ev} = \dot{m}_{ev}\,[C_w\,(T_{ev} - T_{p,in}) + \lambda\big|_{T_{ev}} + C_v\,(T_{ea} - T_{ev})] \tag{22}$$

where $\Delta H_{ev}$ represents the needed energy for evaporation and $T_{ev}$ denotes the evaporation temperature.

Heat to supply air system:

$$Q_3 = \dot{m}_{sa}\, (h_{sa,rec} - h_{sa,pd}) \tag{23}$$

here $\dot{m}_{sa}$ is the dry supply air mass rate, $h_{sa,rec}$ is the enthalpy of preheated supply air after primary heat recovery, and $h_{sa,pd}$ denotes the enthalpy of supply air out of the steam heating system, which is blown to the pocket dryers as ventilation air.
Required heat to raise the leakage air temperature to the exhaust air temperature level:

$$Q_4 = \dot{m}_{la}\, (h_{ea} - h_{la}) \tag{24}$$

where ea and la represent exhaust and leakage air, respectively.
Heat loss due to convection and radiation mechanism through drying section ($Q_5$), which is usually 3-5% of total heat [3].

### *2.7. Energy performance indices*

The energy performance of a drying process is described by different indices such as the evaporation rate, specific energy consumption, and energy efficiency [12]. A common indicator for a paper mill is the specific energy consumption (SEC), which identifies the aggregate energy needed to produce one unit of product. The SEC of the paper drying section depends on paper grades and the type of applied dryers. For example, the energy use in tissue mills is somewhat higher than in grades such as board mills, because the energy usage in Yankee dryers is often greater than in multi-cylinder dryers [13].
Frequently, four indices can be applied to evaluate heat consumption in the paper machine.

a) Specific steam consumption per unit of paper ($SSC_{paper}$), which is often quoted for estimation of the energy usage in the paper drying section.
b) Specific steam consumption per unit of evaporated water ($SSC_{water}$) which is more beneficial because normalizing the impact of moisture content enables the drying process to be compared correctly [3].
c) Specific heat consumption per unit of paper ($SHC_{paper}$), which is defined as the amount of heat used to produce one unit of product.
d) Specific heat consumption per unit of evaporated water ($SHC_{water}$), which is widely used to estimate the drying efficiency in industrial dryers and is determined as the amount of required heat to remove one unit of water from a wet web.
The specific heat consumption per unit of evaporation is the appropriate index for measuring the energy usage of a paper drying section, but energy efficiency is more effective for determining the energy utilization degree for different paper machines. Energy efficiency is defined as the ratio of energy utilized for water evaporation to the total energy fed to the drying section. On the other hand, it demonstrates the amount of energy which is solely used, by paper drying efficiently [2]. An energy balance can be developed to calculate the dryer efficiency. If the used steam was saturated, the enthalpy of the steam would be totally transferred to the moisture in the web, and the dryer efficiency can be computed as follows:

$$\text{a) } \eta = \frac{\text{Actual evaporated water per production}}{\text{Theoretical evaporated water per production}} \tag{25}$$

or

$$\text{b) } \eta = \frac{(\dot{m}_f C_f + \dot{m}_{w,out} C_w)(T_{p,out} - T_{p,in}) + \dot{m}_{ev} \lambda}{\dot{m}_s h_s} \tag{26}$$

### *2.8. Machine specifications and physical properties*

The studied paper machine (PM2) is located in the Mazandaran Wood and Paper Industry (MWPI), in northern Iran, which produces fluting paper. The machine was built by Voith Company in 1998 and its production capacity is about 300 metric tons per day. The paper furnish contains about 70% neutral sulfite semi-chemical (NSSC) pulp processed from virgin wood and 30% recycled paper. The dryer section has 35 cylinders and it contains three steam groups. Group 3 in this dryer section is the main steam group. The condensate and blow-through steam of each group are fed into the condensate tank, where blow-through steam is fed further to the condenser. Steam group 1 consists of the first seven dryer cylinders. Dryer cylinders 8-18 and 19-35 belong to steam groups 2 and 3, respectively. The cylinders have a diameter of 1.5 m. The inlet steam absolute pressure to the machine is 6.5 bars. The dryers are equipped with rotary siphons and closed hoods. The scheme of the considered drying section is shown in Fig. 1.
As shown, there are two axial exhaust air fans and two centrifugal supply air fans in the PM2 dryer section. This machine has two air-to-air heat exchangers, at the wet end and at the dry end. The supply air is heated in the heat exchangers with hood exhaust air, then with steam in the air heating system to the desired temperature. Typical paper properties in the studied machine are presented in Table 1. In the considered machine, the dryness of the web inlet to the forming and press sections was 1% and 20%, respectively.
The sheet moisture content at the end of the press section was 40% (1.5 kg water/kg fiber), and the sheet has been dried to a 9% moisture target (0.099 kg water/kg fiber).

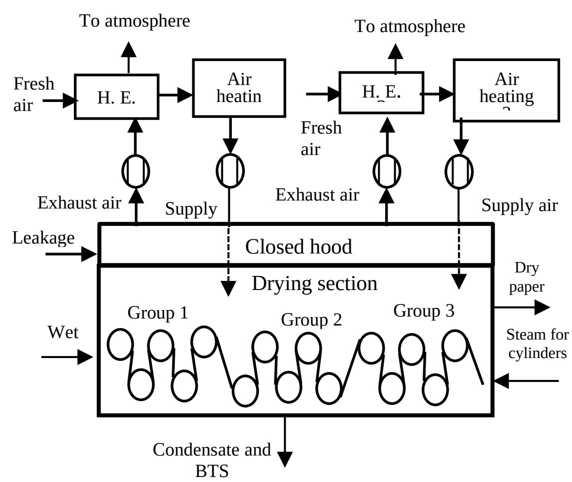


**Fig. 1.** The studied drying section and its heat recovery system.

**Table 1.** Properties of the paper in drying section.

| Parameter | Value |
|---|---|
| Paper basis weight (g/m$^2$) | 113-140 |
| Inlet dryness to drying section (%) | 40-43 |
| Inlet temperature (°C) | 35-45 |
| Final product moisture (%) | 7-11 |
| Paper width in drying section (m) | 4.47 |

Despite the high energy consumption in the drying section, it can be easily demonstrated that only a small percentage of the water content of the original web is removed in the drying section [14].

Table 2 shows the proportion of water removed in each of the three sections of the studied machine. As can be seen, the dryer section of the PM2 removes almost 1.27 kg of water per kg of paper, but the water removal in the press and forming sections is about 2.27 kg and 86.4, respectively. This is about 1.4% of the total water contained in the original stock. Average data for the considered paper machine in a given period are presented in Table 3. The exhaust hood air is a mixture of the supply air (76%) used as pocket ventilation air and leakage air (24%) which is infiltrated into the hood due to the poor tightness or improper condition of the hood.

**Table 2**. Proportion of water removed in forming, press and drying sections of paper machine.

| Parameter | Forming | Press | Dryer | Machine |
|---|---|---|---|---|
| Water removal per inlet pulp (kg $H_2O$/ton pulp) | 950 | 25 | 14 | 989 |
| Water removal per produced paper (ton $H_2O$/ton paper) | 86.4 | 2.27 | 1.27 | 89.94 |
| Water removal (%) | 96.1 | 2.5 | 1.4 | 100 |

**Table 3.** The properties of the studied paper machine.

| Parameter | Value |
|---|---|
| Average basis weight (g/m$^2$) | 127.8 |
| Average web speed (m/min) | 440 |
| Average inlet paper dryness (%) | 40 |
| Average inlet web temp. (°C) | 45 |
| Production rate (ton/hr) | 15.1 |
| Product moisture target (%) | 9 |
| Supply air flow rate (kg dry air/s) | 23.5 |
| Hood balance (kg supply air/kg exhaust air) | 0.76 |
| Leakage air flow rate (kg dry air/s) | 7.4 |
| Exhaust air flow rate (kg dry air/s) | 30.9 |

The proportion between the supply air and exhaust air amount means hood balance.

Based on the technical report of the process ventilation survey in the studied paper machine, the supply air amount compared to the exhaust air seems to be enough to keep the hood air balance at the correct level [15]. The properties of air used in the modeling are represented in Table 4.

## 3. Results and discussion

The main results applying the applied model are illustrated in Figs. 2-4 [15]. Temperatures of the paper web and cylinder surfaces, according to the modeling results, are presented in Fig. 2. The specific drying rate and dryness variations of the paper web are presented in Fig. 3, as well. As illustrated in Figs. 2 and 3, the model determines the temperature and dryness of the web and evaporation rate variations of each cylinder. Also, Fig. 4 shows the variations in the humidity and temperature of pocket dryers in the drying section. In addition, the developed model tracks the operating data with appropriate accuracy [15]. The mass balance results for the drying section were tabulated in Table 5, based on the applied model.

**Table 4**. Properties of air in drying section.

| Parameter | Average Temperature (°C) | Humidity (g water/kg dry air) |
|---|---|---|
| Supply and leakage air | 35 | 16 |
| Preheated supply air | 65 | 16 |
| Supply air blown to the pocket dryers | 125 | 16 |

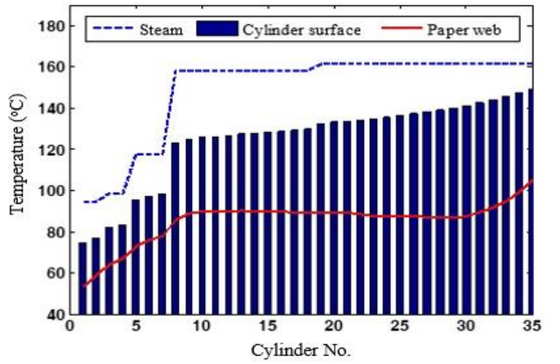


**Fig. 2.** Temperature variations of the paper web and cylinder surface (modeling results).

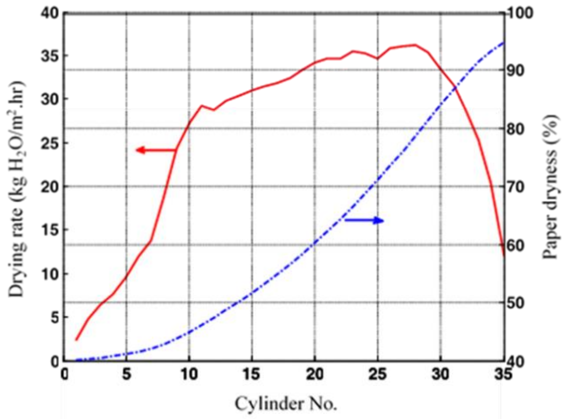


**Fig. 3.** Drying rate and dryness variations of paper web through paper length.

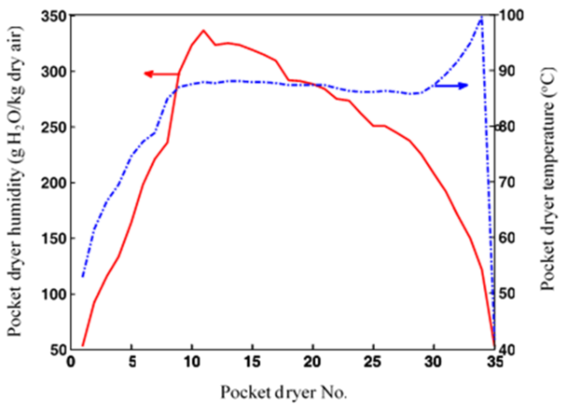


**Fig. 4.** Temperature and humidity variations of drying pocket dryers.

**Table 5**. The modeling results of mass balance for drying section.

| Parameter | Value |
|---|---|
| Outlet paper temperature (°C) | 105 |
| Outlet exhaust air temperature (°C) | 94 |
| Web mass rate to the dryer (ton/hr) | 34.3 |
| Fiber mass rate (ton/hr) | 13.7 |
| Inlet water mass rate (ton/hr) | 20.60 |
| Outlet water mass rate (ton/hr) | 1.37 |
| Average humidity of exhaust air | 192 |
| Water contained in inlet air (ton/hr) | 1.78 |
| Water contained in exhaust air (ton/hr) | 20.20 |
| Required steam to the dryer (ton/hr) | 25.8 |
| Total outlet condensate mass rate (ton/hr) | 22.7 |
| Total BTS mass rate (ton/hr) | 3.1 |

Table 6 compares the evaporation rate computed by different methods for the represented properties. Tab. 6 also represents indices of steam utilization for the studied drying region.

**Table 6**. The evaporation rate and steam utilization indices in the studied drying section.

| Parameter | | Value |
|---|---|---|
| Evaporation rate based on water balance | | 5.34 |
| Evaporation rate based on operating air | | 5.12 |
| Evaporation rate based on TAPPI method | | 5.33 |
| Evaporation rate based on modeling result | | 5.44 |
| Modeling inaccuracy (%) | | 2 |
| Steam consumption (ton/hr) | Steam group 1 | 3.5 |
| | Steam group 2 | 9.3 |
| | Steam group 3 | 10.5 |
| | Air heating | 2.5 |
| | Total | 25.8 |
| Evaporated water per production (ton/ton) | | 1.27 |
| $SSC_{paper}$ (kg steam/kg paper) | | 1.71 |
| $SSC_{water}$ (kg steam/kg water evap.) | | 1.34 |

As shown in Table 6, the specific steam usage per production ($SSC_{paper}$) and per evaporated water ($SSC_{water}$) were estimated to be 1.71 kg steam/kg paper and 1.34 kg steam/kg water, respectively. In the literature, the $SSC_{paper}$ for newsprint paper drying in Canadian mill ranges from 1.2 to 3.0 tons of steam per ton of paper, with an average of 2.0 tons of steam per ton of paper [3]. However, the value of these indices varies from mill to mill.

The variation of evaporation rate and steam demand depending on various paper basis weights for constant web speed and initial web dryness are shown in Fig. 5. As shown, if the paper grammage is raised from 100 to 140 g/m$^2$, the evaporation rate should be increased from 4.18 to 5.85 kg/s to get the desired paper moisture target.

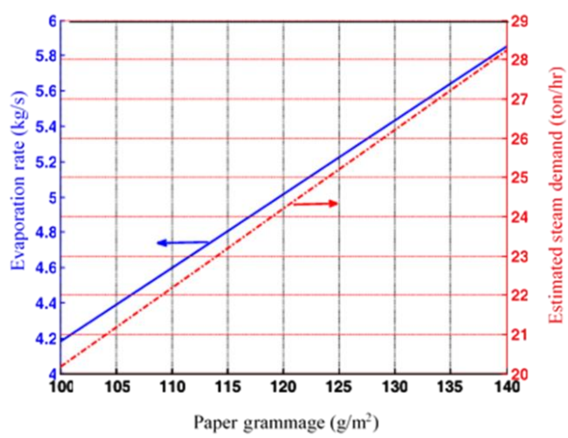


**Fig. 5.** Evaporation rate and steam demand for drying section vs. paper grammage.

The steam demand for the considered drying section with 40% initial dryness and 9% moisture target was about 25.8 tons/hr. Also, as shown in Fig. 5, if the paper basis weight is increased from 100 to 140 g/m$^2$, the required steam will be increased linearly from 20 to 28 tons/hr. It can be easily calculated that steam consumption will be reduced by about 1% for a 1% reduction in original consistency or web basis weight.

Decreasing the web basis weight at the same conditions also enables the machine speed to increase. Fig. 6 demonstrates the web speed variation depending on the paper grammage for 40% web dryness in the dryer and 9% final paper moisture.

As illustrated in Fig. 6, machine speed will be about 560 m/min for the grammage of 100 g/m$^2$, and it should be reduced to about 400 m/min for the grammage of 140 g/m$^2$ to achieve the desired moisture target at same conditions of Table 3.

Table 7 represents the water removal from the web in various sheet moistures to the dryer for the original 1 kg of stock inlet to the forming section. As seen, if the web moisture in the dryer is decreased by 5%, the water removed will be reduced from about 14 to 11.2 g. Therefore, a 5% reduction in the inlet web moisture content to the dryer leads to a 20% saving in dryer load and steam use. On the other hand, as mentioned in most popular literature, it can be easily confirmed that a 1% increase in the inlet sheet dryness results in a reduction in the dryer steam demand of about 4%.

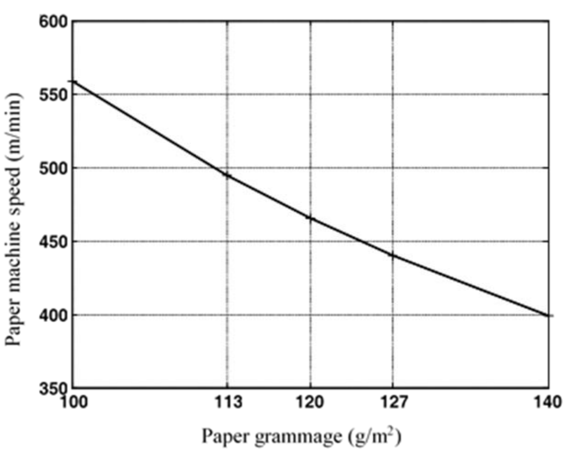


**Fig. 6.** Paper machine speed variation vs. paper grammage.

The required energy for different initial dryness of the web is also represented in Table 7. As shown, when the initial dryness of the web in the drying section is increased from 40 to 45%, heat utilization per produced paper can be reduced by around 17%.

For the same steam usage, the paper machine speed can be increased by raising the inlet web dryness to the dryer. Accordingly, the changes in web speed against the initial web dryness for grade 127 g/m$^2$ are depicted in Fig. 7. It can be found that if the initial paper dryness is raised by 5%, web speed can be increased by about 25% to achieve 9% moisture target, at the same conditions of Table 3.

The SSC changes based on different initial web dryness for web basis weight 127 g/m$^2$ are also illustrated in Fig. 7. As demonstrated, increasing the initial paper dryness by 1% corresponds to an SSC reduction by about 4%.

The required steam in the drying section at different initial web dryness is presented in Fig. 8. As shown in Fig. 8, by increasing the inlet web dryness from 37.5 to 45%, the total required steam can be reduced from about 27.6 tons/hr to around 22.5 tons/hr.

**Table 7.** Water removal and required energy for various initial dryness of web.

| Inlet web dryness to dryer (%) | 40 | 45 |
|---|---|---|
| Final moisture (%) | 9 | 9 |
| Contained water in inlet web (g) | 15 | 12.2 |
| Water removal in drying section (g) | 14 | 11.2 |
| Evaporation rate (kg/s) | 5.33 | 4.28 |
| Steam use reduction (%) | - | 20 |
| $SHC_{water}$ (GJ/ton evap.) | 3.7 | 3.7 |
| $SHC_{paper}$ (GJ/ton paper) | 4.7 | 3.9 |

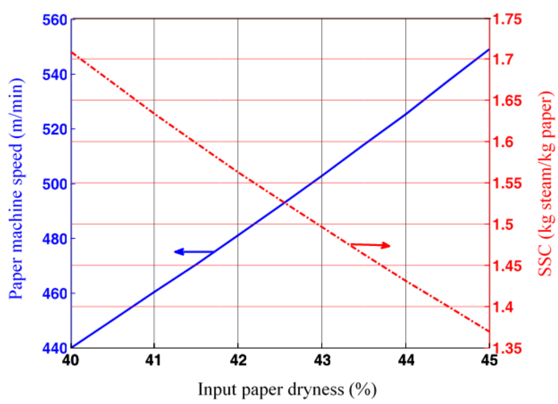


**Fig. 7.** Paper machine speed and SSC variation vs. web dryness to the dryer.

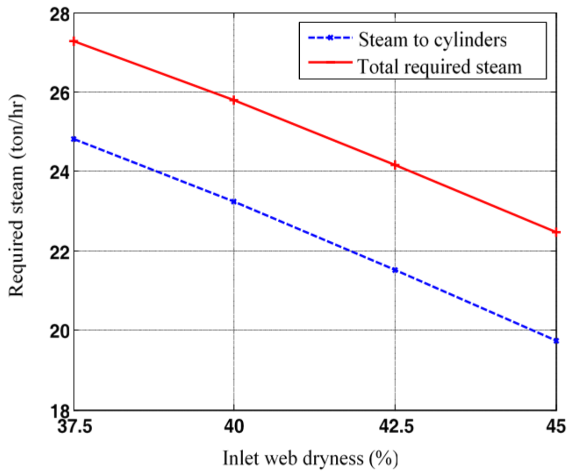


**Fig. 8.** Steam usage in drying section at various inlet web dryness.

Water content and water removed for increased moisture targets for 1 kg original stock and 40% initial dryness are shown in Table 8, as well. As represented in this table, due to raising the final moisture of the paper by 1%, the dryer steam demand can be reduced by about 0.8%. Correspondingly, when the initial dryness is assumed to be 45%, the dryer steam demand will be diminished by about 1.1% for a 1% increase in the moisture target. Similarly, calculations show that for a 50% initial web dryness, a 1% increase in the sheet moisture content can reduce the dryer steam use by about 1.34%.

## 4. Energy performance evaluation

According to the defined parameters and the modeling results, the amounts of energy consumption in the five divisions of the dryer are represented in Table 9. This table also shows the various indices of energy utilization for each studied drying region.

Specific heat consumption per production ($SHC_{paper}$) and per evaporated water ($SHC_{water}$) for the considered drying section were 4.7 and 3.7 GJ/ton, respectively.

**Table 8.** Water content and water removed for increased moisture target (for 1 kg original stock and 40% dryness into the dryer).

| Parameter | Value | |
|---|---|---|
| Sheet moisture target (%) | 9 | 10 |
| Contained water in sheet (g) | 0. 99 | 1.11 |
| Water removed in drying section (g) | 14.01 | 13.89 |

**Table 9**. The energy consumption in various sections of dryer.

| Energy | Value (kW) | $SHC_{paper}$ (kJ/kg paper) | $SHC_{water}$ (kJ/kg water evap.) | Percentage (%) |
|---|---|---|---|---|
| Sensible heat | 414 | 99 | 78 | 2.1 |
| Latent heat | 13511 | 3224 | 2535 | 68.5 |
| Supply air heating | 1444 | 345 | 271 | 7.3 |
| Leakage air heating | 3582 | 855 | 672 | 18.1 |
| Heat loss | 789 | 188 | 148 | 4.0 |
| Total | 19699 | 4711 | 3704 | 100 |

The value of $SHC_{paper}$ ranges from 3.5–6.7 GJ/ton in Canadian newsprint machines and 2.4–5.5 GJ/ton in Sweden [3]. However, reliable data for a similar fluting paper drying section is not accessible.

As mentioned, the steam used in the PM2 multi-cylinder drying section was determined from the model to be about 25.8 tons/hr or 1.71 tons/ton of produced paper. Steam is supplied at 6.5 bar and 162°C. Accordingly, each ton of steam supplied had about 1.22 times the enthalpy required to evaporate 1 ton of water. Therefore, 25.8 tons steam/hr can be used to evaporate about 8.74 kg $H_2O$/s or 2.1 kg water/kg paper. However, the actual evaporated water per production during the studied period was about 1.27 tons of water/ton of paper. The temperatures of the inlet and outlet paper in the drying section were 45 and 105°C, respectively. Thus, the dryer efficiency based on the two mentioned methods, was calculated to be around 61 and 63%, respectively. Given that, the PM2 dryer section operates somewhat more efficiently than other comparable machines [16]. The details of the energy balance for the entire drying section of the considered paper machine are represented in Table 10.

The Sankey diagram, in which the width of the arrows is shown proportionally to the flow quantity, is a significant aid in recognizing ineffectiveness and the saving potential of streams throughout the drying process. The energy distribution in the paper drying process can be demonstrated via this diagram [3]. Sankey diagrams put a visual emphasis on the main transfers or flows within a system. A Sankey diagram of PM2 is displayed in Fig. 9.

**Table 10.** Detailed energy balance for paper machine drying section.

| Energy | Value (kW) | $SHC_{paper}$ (kJ/kg paper) | Percentage (%) |
|---|---|---|---|
| **Input energy** | | | |
| Input paper | 1340 | 320 | 5.7 |
| Steam to cylinders | 17881 | 4269 | 75.9 |
| Steam to heater | 1919 | 458 | 8.1 |
| Fresh Supply air | 1763 | 421 | 7.5 |
| Leakage air | 555 | 132 | 2.4 |
| Cold water to condenser | 84 | 20 | 0.4 |
| Total input energy | 23542 | 5620 | 100 |
| Output energy | | | |
| Output paper | 720 | 172 | 3.1 |
| Condensate from cylinders | 3419 | 817 | 14.6 |
| Condensate from heater | 476 | 114 | 2 |
| Condensate from H.E. | 84 | 20 | 0.4 |
| Exhaust air | 16286 | 3890 | 69.6 |
| Hot water from condenser | 290 | 69 | 1.2 |
| Heat loss of hood and H.E. | 2141 | 511 | 9.1 |
| Total output energy | 23416 | 5593 | 100 |
| Uncertainty percent | -0.6 % | | |

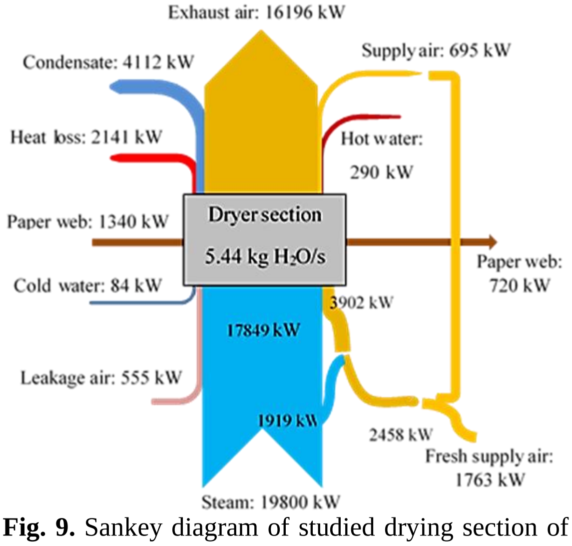


**Fig. 9.** Sankey diagram of studied drying section of fluting paper machine.

As shown in Fig. 9, a considerable amount of energy is utilized to heat the supply air and a significant amount of energy content in the hood air is exhausted to the atmosphere. The recovery efficiency of the heat recovery system is very low compared to the maximum available value. The simulation results for the mass and energy balance of the paper machine drying section are presented in Fig. 10.

The main characteristics, which have an important effect on the dryer's efficiency are the dryer hood type (open or closed hood), the pocket dryer dew point and the heat recovery performance. Dryers have the highest energy efficiency when they are equipped with a closed hood, the dew point of the pocket dryer is high and the heat recovery system performs efficiently [13].

The heat recovery systems have considerable potential for energy efficiency enhancement in the drying section. Hence, heat recovery systems are mostly used in modern paper machines to heat supply air, process water, and machine hall ventilation in the dryer section which leads to significant amounts of energy recovery [17]. The most common heat exchanger types in the heat recovery systems of a paper machine are air-air, air-water, or scrubber-type air-water, which can be run based on the operating conditions. Typically, the maximum heat recovery from air-to-air heat exchangers is less than 10%. Higher energy recovery levels can be available with air-to-water heat exchangers [15]. According to Fig. 1, in the studied drying section, the supply air was heated with hood exhaust air at the wet end and dry end section to 63 and 66°C, respectively. The final temperature was 128°C at the wet end and 122°C at the dry end sections. The total energy transferred to the supply air due to heat recovery can be calculated from enthalpy differences between the exhaust hood air and the supply air blown to the pocket dryers:

$$\Delta h_a = h_{ea} - h_{sa} \tag{27}$$

here $h_{ea}$ and $h_{sa}$ are the enthalpy of exhaust hood air and supply air blown into the pocket dryers, respectively.

*4.1. Energy performance of heat recovery system*

The theoretical and actual air usage for pocket ventilation can be obtained according to the inlet and outlet humidity:

$$m_{a,th} = \frac{1}{X_{ea} - X_{sa}} \tag{28}$$

$$m_{a,act} = \frac{\dot{m}_{ea}}{\dot{m}_{ev}} \tag{29}$$

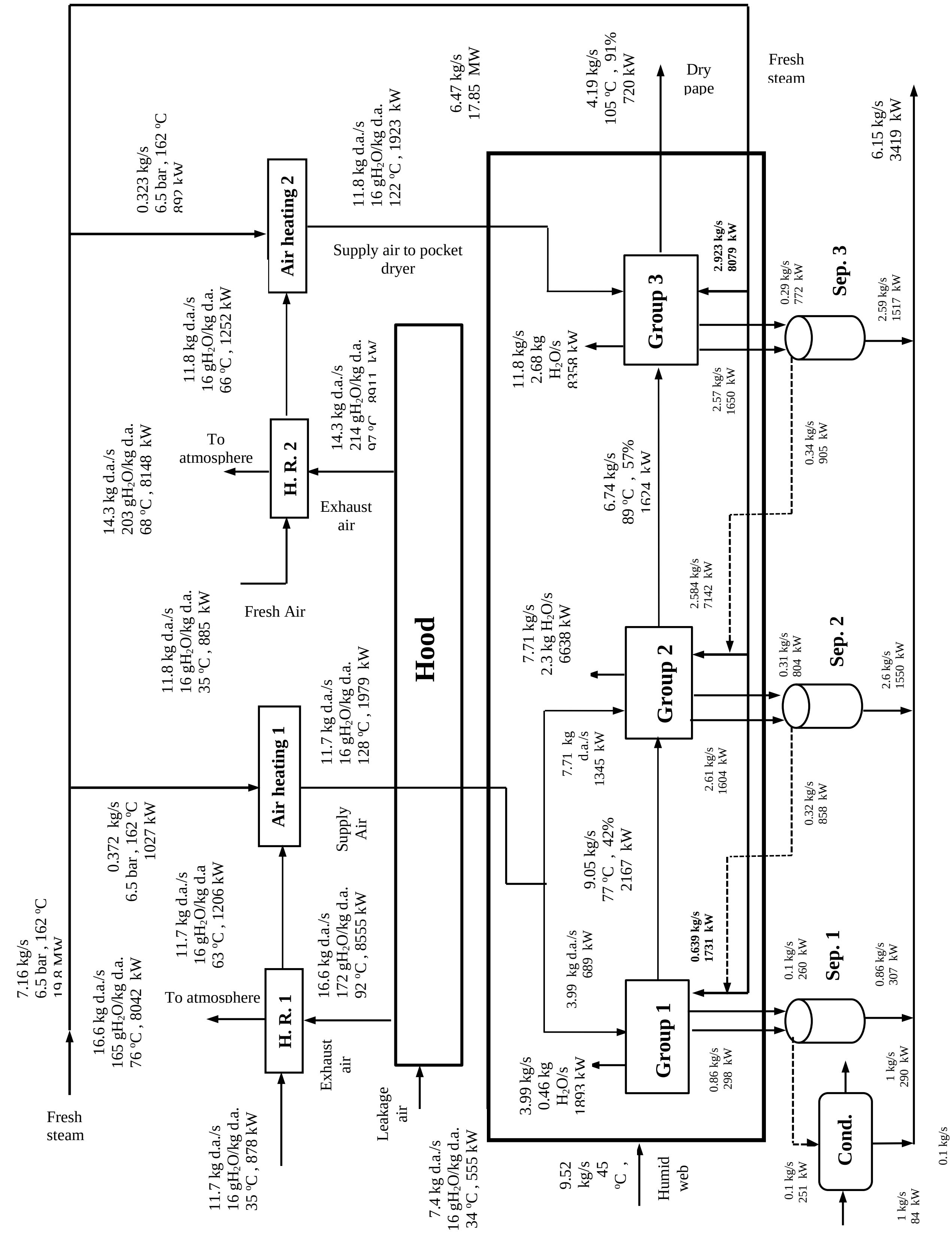


**Fig 10.** The simulation results for the mass and energy balance of paper machine drying section.

[Fig. 11] depicts the theoretical required supply of air and exhaust air for the studied drying section at various exhaust humidities. As can be seen, for the exhaust air humidity in the range of 130-250 g $H_2O$/kg dry air, the total airflow can be changed from about 9 to 4 kg dry air per evaporated water. [Fig. 12] also presents the theoretically required supply and exhaust air usage at different exhaust air humidity and hood balances.

Maintaining the hood at a higher amount of humidity can lead to a lower required energy of supply air and a higher heat recovery potential from the exhaust air, as presented in [Fig. 13].

Consequently, the specific heat consumption per evaporated water in the drying section at different exhaust air humidity is presented in [Fig. 14]. As shown, if the exhaust air humidity increases from 0.13 to 0.215 kg $H_2O$/kg dry air, the specific heat consumption in the drying section can be decreased from about 4 GJ to around 3.67 GJ per the evaporated water.

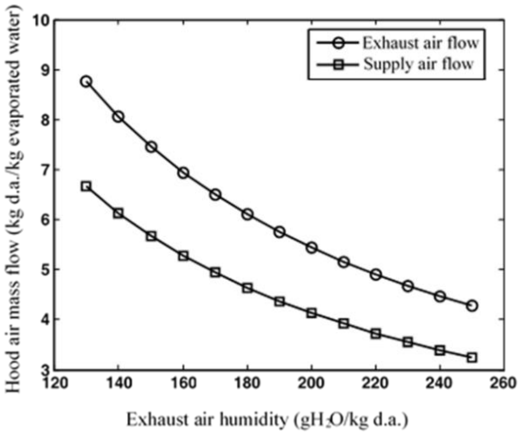


**Fig. 11.** Theoretical supply and exhaust air usage at various exhaust humidity.

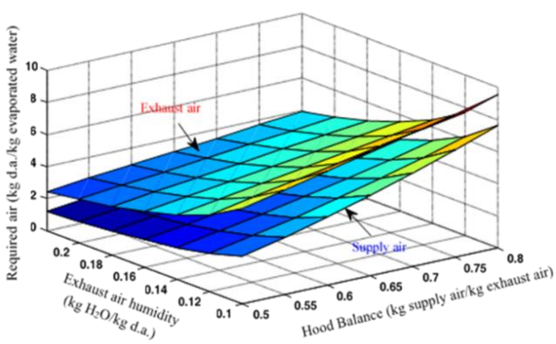


**Fig. 12.** Theoretical required air usage at various exhaust humidity and hood balance.

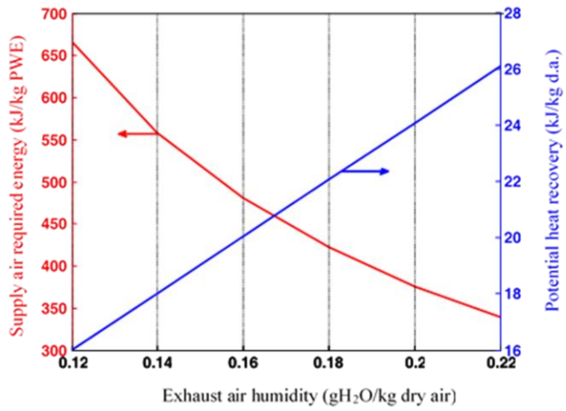


**Fig. 13.** Supply air energy and potential heat recovery at various supply air temperature.

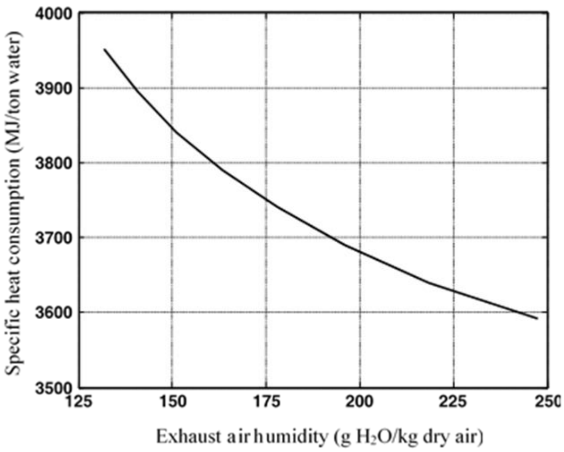


**Fig. 14.** $SHC_{water}$ at various exhaust humidity.

As shown, if the exhaust air humidity increases from 0.13 to 0.215 kg $H_2O$/kg dry air, the specific heat consumption in the drying section can be decreased from about 4 GJ to around 3.67 GJ per the evaporated water.

The optimal energy performance and condensation prevention in pocket dryers can be obtained at the higher humidity of the exhaust air. As a result, the maximum heat recovery in the drying section can be attained. However, concerning the limitation of the evaporation rate and the maximum permissible range of the surrounding and pocket dryers air humidities, the modeling results show that the maximum humidity and the optimal humidity levels for the exhaust air in the studied machine can be predicted to be about 0.2 kg $H_2O$/kg dry air and 0.15 kg$H_2O$/kg dry air, respectively [18, 19].

The temperature efficiency of the heat exchanger in the primary heat recovery system can be computed as follows [8]:

$$\eta_t = \frac{T_{sa,rec} - T_{sa,in}}{T_{ea} - T_{sa,in}} \tag{30}$$

where $\eta_t$ is the thermal efficiency and $T_{sa,rec}$ is the temperature of supply air out of the heat exchanger. $T_{sa,in}$ and $T_{ea}$ represent the fresh supply air and exhaust air temperature, respectively.

Also, the recovery efficiency of heat energy in the drying heat recovery section can be examined by the following equation:

$$\eta_{rec} = \frac{Q_{sa,rec} - Q_{sa,in}}{Q_{ea}} \tag{31}$$

here $\eta_{rec}$ is the recovery efficiency of the heat recovery section and $Q_{sa,rec}$ is the energy content of outlet supply air from the heat exchanger. $Q_{sa,in}$ and $Q_{ea}$ represent the fresh supply air and exhaust air energy content, respectively.

Table 11 shows the results of the heat recovery evaluation in the studied paper machine. The total recovered energy in the supply air was 695 kW (328 kW in the wet end and 367 kW in the dry end section) and average recovery efficiency has been obtained to be 4%. The temperature efficiency of the heat exchanger was estimated to be 50%.

**Table 11.** The results of drying heat recovery evaluation.

| Parameter | Value |
|---|---|
| Average fresh supply air enthalpy (kJ/kg) | 75 |
| Average exhaust air enthalpy (kJ/kg) | 570 |
| Average temp. of preheated air (ºC) | 64.5 |
| Average thermal efficiency of heat exchanger (%) | 50 |
| Total energy content of exhaust air to atmosphere (kW) | 16196 |
| Total energy content of inlet supply air (kW) | 1763 |
| Total energy content of preheated air (kW) | 2458 |
| Total recovered energy of exhaust air (kW) | 695 |
| Average recovery efficiency (%) | 4.1 |
| Theoretical air usage (kg d.a./kg evap.) | 5.65 |
| Actual air usage (kg d.a./kg evap.) | 5.8 |

The outlet temperatures of exhaust air after the primary heat recovery system were measured to be 76ºC at the wet end and 68ºC at the dry end [15]. Fig. 10 indicates the temperature and humidity of the exhaust hood air are considerable and it still has a lot of energy to be recovered. The exhaust air humidity is as high as possible; therefore, reducing the energy consumption in the drying section can be attained by decreasing the temperature of the supply air.

As demonstrated in Fig. 15, increasing the supply air temperature decreases the required ventilation air, but instead, the required steam will increase.

Fig. 16 shows the paper dryness profile based on the modeling results at various supply air temperatures.

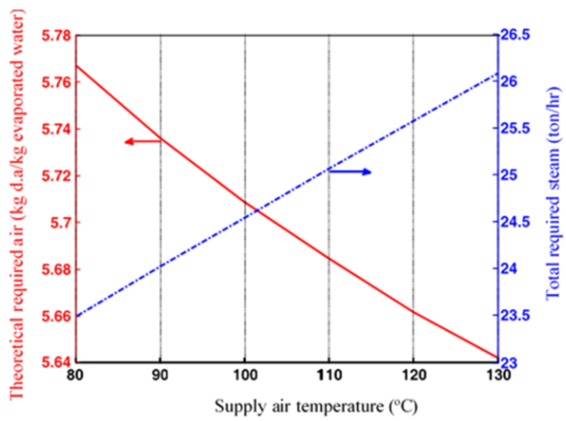


**Fig. 15.** Air and steam usage variation vs. various supply air temperature.

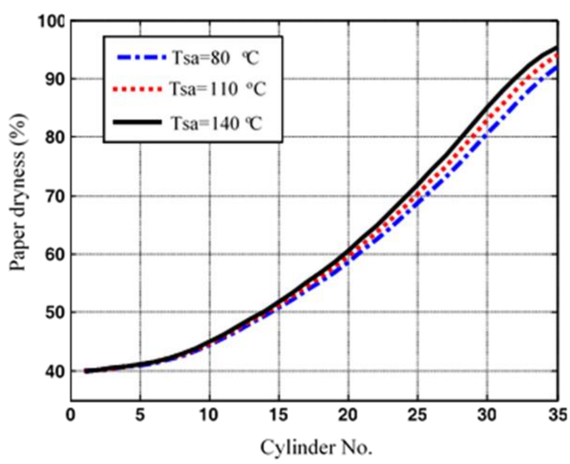


**Fig. 16.** Paper web dryness profile at various supply air temperature.

As shown in the figure, increasing the supply air temperature in the pocket dryers, although increasing the steam use, does not proportionately help in the paper drying process. In the earlier studies of the paper machine, it was observed that there was no observable rise in the evaporation rate with higher supply air temperature and would hence only be loss of energy [20].

Higher temperatures in the pocket dryers do not provide extra gain to the paper drying process [15]. Therefore, excessive increases in the supply and exhaust air temperature raises the energy usage in the drying section. The optimum range for the supply air temperature after the steam heater can be kept to 100-120°C. This guarantees a temperature level of the inlet supply air not less than 90-100°C in the pockets [15, 18].

The PM2 average supply temperature was 125ºC and the supply air was heated unnecessarily too hot. If the supply air temperature is assumed to be 100ºC, the Sankey diagram of PM2 is shown as Fig. 17. It can be seen that after decreasing the supply air temperature to 100 ºC, nearly 0.215 kg/s (0.77 tons/hr) of saturated steam with pressure 6.5 bars can be saved in the heat recovery section. Therefore, the total input energy can be reduced by about 4% and the total savings would be 335 and 265 kW for wet end and dry end, respectively.

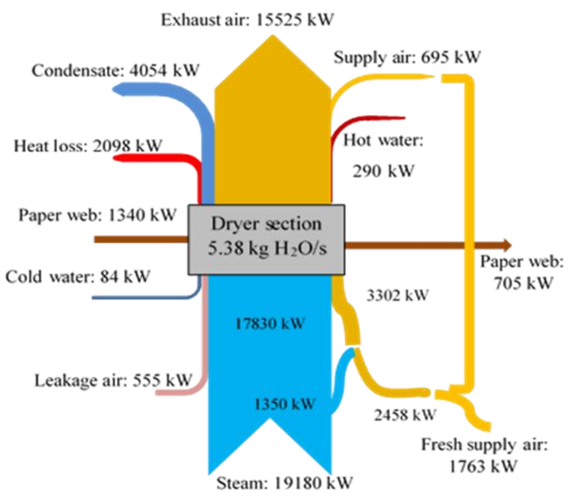


**Fig. 17.** Sankey diagram of studied drying section after optimization.

Consequently, for about 8000 hours in a year, the total amount is about 4800 MWh. The cost of steam generation in MWPI in 2016 was about 4.2 $ per ton. Thus with correct temperatures for supply air, the total money saved in the dryer section will be around 26,000 dollars every year. In addition, about 0.04 tons/hr steam can be saved in the cylinder dryers which causes a slight reduction in the evaporation rate. Although by decreasing the supply air temperature and reducing the evaporation rate, the dryness of the outlet paper can nearly reach the desired value, meanwhile the total energy supplied to the drying section could be decreased and the energy utilization for water evaporation almost remained constant, increasing energy efficiency. Accordingly, if the supply air temperature is set to 95ºC, about 0.95 tons/hr steam usage and 5.2% input energy can be decreased and the total savings would be about 31,000 $ per year. Also, the calculation shows that the dryer efficiency can be increased from 63% to about 67%. Furthermore, in MWPI nearly 65 $Nm^3$ of natural gas must be consumed to produce each ton of required steam. Hence, due to optimization in the heat recovery system, about 496,000 $Nm^3$ gas can be saved every year, which corresponds to a reduction of about 925 tons $CO_2$ per year.

## 5. Conclusions

In this study, a developed model has been applied to study the multi-cylinder fluting paper machine at Mazandaran Wood and Paper Industries (MWPI) in Iran. The modeling parameters have been utilized in inclusive mass and energy balances and heat use calculations and assessing of energy efficiency in the drying section. Also, the energy performance of the heat recovery system has been analyzed, depending on the energy balance calculations and modeling results.

The considered drying section removed about 1.4% of the total water contained in the original stock. Calculations show that for grade 127 gr/m$^2$, a 1% rise in initial web dryness results in a 4% decrease in dryer load and about a 6% web speed increase. Also, a 1% increase in moisture content corresponds approximately to a 1% reduction in dryer load.

The specific energy consumption per production unit ($SHC_{paper}$) and specific steam consumption per production ($SSC_{paper}$) were about 4.7 GJ/ton of paper and 1.71 tons of steam per ton of paper, respectively.
For 40% initial dryness and a 9% moisture target, steam consumption will be reduced by about 1% for a 1% reduction in web basis weight.
The dryer efficiency was calculated to be approximately 63%. The temperature efficiency of the heat exchanger was estimated to be 50% and the heat recovery system had nearly 4% efficiency. Energy use in the heat recovery system can be decreased by reducing the supply air temperature to the optimal value. Accordingly, by adjusting this temperature to about 95°C, about 0.95 tons/hr of steam consumption can be decreased, which can lead to approximately 31,000 $ savings per year and about a 4% rise in dryer efficiency. Also, calculation shows that the consumption of natural gas can be decreased by nearly 496,000 $Nm^3$ per year, resulting in a reduction of about 925 tons $CO_2$ emission every year.

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