WASTE HEAT POTENTIALS IN THE DRYING SECTION OF THE PAPER MACHINE IN UMKA CARDBOARD MILL

by

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This paper deals with methods for calculation of potentials of waste heat generated in paper/board production process. For that purpose, the material and heat balance of the cardboard machine at Umka Cardboard Mill has been determined. Field measurements were conducted in order to define the unknown values of process parameters used for calculation in the balance equations and modelling. The focus was given to the cardboard drying section, which consumes most of the energy supplied to the machine. Additional aim of the work presented in the paper was to evaluate the specific energy consumption and the thermal efficiency of all individual energy units within the machine's drying section. The results indicate two main sources of waste heat: waste heat released to the atmosphere with the discharge air from the present waste heat recovery system (14,380 kW), and waste heat released in the hall from the machine and extracted by the hall ventilation system (4,430 kW). Waste heat from both sources is characterized by fairly low temperatures 58-75 °C and fairly high moisture content (30-40 g/kg).

The specific heat consumption and specific steam consumption (consumption per tonne of produced cardboard) of the machine was 1,490 kWh/t and 1.4 t/t, respectively. The thermal efficiency of drying section and coating drying section was 55.6% and 33.6%, respectively. All these figures imply necessity for further waste heat utilization with the aim of improving the efficiency of energy use.

Key words: *cardboard machine, waste heat potentials, field measurements,*
material balance, heat balance

Introduction

The pulp and paper industry is the fourth largest industrial energy user. With 6.4 EJ in 2005 it is responsible for about 6% of total world industrial energy use [1]. Since energy prices have risen drastically by around 40% between 2004 and 2007 in Europe [1], energy has become one of the key cost components of the pulp and paper sector. Energy accounted for 19% of total operating costs of the European pulp and paper industry in 2005, compared to 15% in 2001. In 2008, the share of energy in the total production costs was up to 30% for some mills [1].

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In that sense this industry is considered to be energy-intensive and suitable for applying technical innovations in order to improve energy efficiency. By far the largest share of energy use in a paper mill is in the drying sections (close to 50%). Thermal drying is often responsible for more than 80% of the total steam use [1]. The paper machine drying section and its operating principal have remained almost unchanged since their initial development; contact drying with steam heated cylinders is still the dominant method for drying paper and board. Therefore this section of the paper machine has been a subject of numerous energy efficiency studies [1-4]. The former and press sections of the cardboard machine consume much less thermal energy (up to 17%) [1] and therefore are not subject of the investigation.

The higher efficiency in end-use of energy in industry has been one of priorities of the National Energy Efficiency Program of the Republic of Serbia (NEEP) in period 2006-2008 and beyond [5]. In that sense the main objective of this study is defining the sources and amounts of waste heat generated in the drying section of the cardboard machine at Umka Cardboard Mill. Additional objectives of the study are to estimate specific energy consumption and evaluate the thermal efficiency of all individual energy units within the machine's drying section. Material and heat balance of the cardboard machine has been calculated to achieve this objectives. Before calculating the balance equations, it was necessary to conduct field measurements which included measurements of process parameters of the cardboard machine and measurements of air temperature and humidity inside the production hall. Methodology and results of the measurements are also presented in this paper.

Energy balancing and auditing are widely used method for determination of waste heat potentials not only in paper/board industry but also in other industrial sectors [6].

Problem description

The Umka Cardboard Mill is located 15 km from Belgrade, on the right bank of the Sava river. After machine reconstruction in 2006, mill's production capacity has been increased up to 75,000 t/year. Recycled wastepaper fibres are used as a raw material for stock preparation. Dry saturated steam is a basic secondary energy source in the production process. The steam is produced in natural gas-fired boilers at two pressure levels (*i. e.*, 3 and 12 bar). Drying cylinders and steam-air heat exchangers are supplied with the steam at 3 and 12 bar, respectively. On the average, machine's steam load is 16 t/h.

Specific consumption of electrical energy in *Umka Cardboard Mill* was 680 kWh/t in 2006, while specific consumption of thermal energy was 2,230 kWh/t. Compared to other similar mills in Western Europe it can be concluded that there are certain potentials for the reduction of thermal energy consumption [7]. Since the drying section of the cardboard machine is a major consumer of both electrical and thermal energy, it is believed that significant energy savings can be achieved in this section.

The drying section of the cardboard machine can be divided into five individual energy units enclosed by the boundaries chosen in such a way that all relevant flows cross-them.

Following individual energy units have been recognized:

- drying section hood,
- recuperative heat exchanger No. 1,
- recuperative heat exchanger No. 2,
- recuperative heat exchanger No. 3, and
- coating drying section.

In the drying section hood shown in fig. 1 cardboard is being dried by hot air supplied from the steam-air heat exchangers and 61 hollow rotating cylinders within which steam is being condensed. Cardboard surfaces are being smoothed while passing between Yankee cylinder heated by steam and supporting surface heated by flue gases from a natural gas burner. Process is enclosed by insulated hood made of corrugated aluminium plates. The waste humid air is being discharged from the hood by ventilation system to the heat recovery system. The basic functions of the hood ventilation system are to blow hot air on the cardboard web and extract humid air from the hood providing controlled indoor atmosphere suitable for cardboard drying. Proper ventilation and air distribution inside the hood should provide required drying capacity and even moisture profile across the cardboard web.

Waste heat recovery system consists of three recuperative glass tube heat exchangers which have to recover heat of the humid air extracted from different points of the hood and to preheat fresh ambient air. Fresh air is then additionally heated in the steam-air heat exchangers and distributed to the drying section hood. The fresh air preheated in recuperative heat exchanger No. 2, as shown in fig. 1, is blown into the space gap between the roof and ceiling construction in order to warm the ceiling surface in winter conditions and prevent moisture from condensing on it. In summer conditions fresh air fans of heat exchanger No. 2 operate in opposite direction sucking the warm humid air out of the hall.

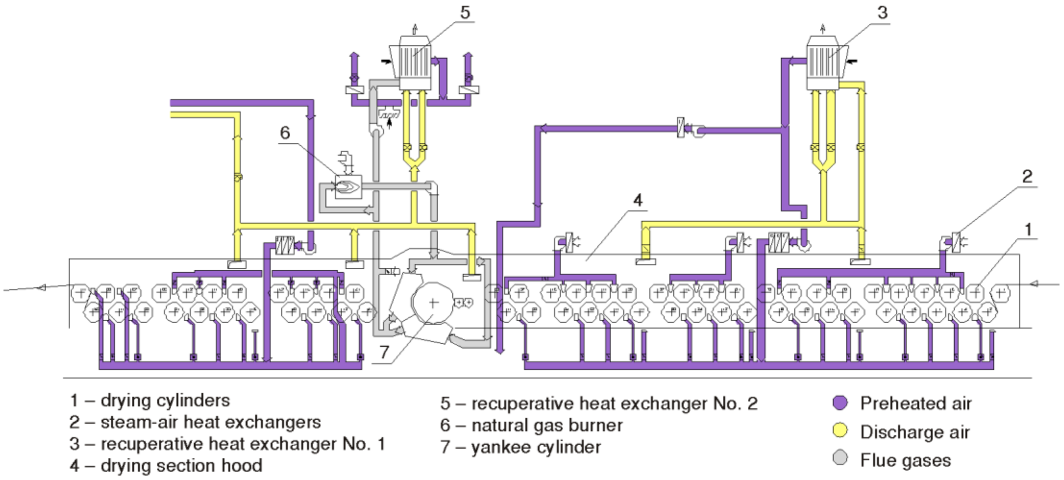

Figure 1. Overall view of the cardboard machine drying section

Four layers of coating are added in the coating drying section both to the top and to the reverse side of the cardboard web in order to improve its surface for printing. After each layer addition cardboard is heated and dried by a combination of infra-red and hot gas impingement dryers as shown in fig. 2. Hot gas for dryers is produced by the natural gas burners placed on the hall annex and coupled with the heat recovery system. This section of the machine is not enclosed by a hood and therefore represents significant source of waste heat inside the hall.

Several types of cardboard with a wide range of grades and weights are produced in the Umka Cardboard Mill. In time of the collection of process parameters data, the machine was operating in summer conditions continually producing 314 cm wide cardboard web with a weight of 250 g/m^2.

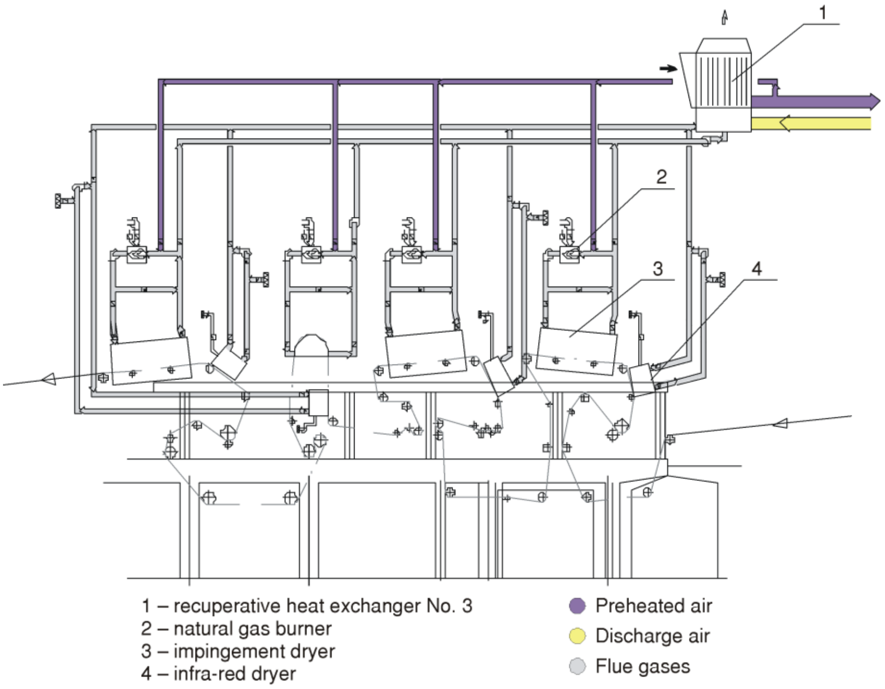

Figure 2. Overall view of the cardboard machine coating drying section

Determination of waste heat amounts

As the use of waste heat is very important for energy efficiency improvement in cardboard production process, the material and heat balances of the cardboard machine at Umka Cardboard Mill were determined. Field measurements were conducted in order to define the unknown values of process parameters used for calculation in the balance equations and modelling.

Results of material and heat balances of the cardboard machine are shown in this paper, but the development of the analytical and numerical models of energy flows in the machine hall and the results of modelling were shown elsewhere [8, 9].

Individual energy units for which the equations of material and heat balances have been derived are drying section hood, each of three heat exchangers and coating drying section.

Equations of material and heat balances for drying section hood

The material and heat balances of the drying section hood are defined by eq. (1) and (2), respectively.

$$\dot{m}_{\mathrm{CI}} + \dot{m}_{\mathrm{SA}} + \dot{m}_{\mathrm{PA}} + \dot{m}_{\mathrm{S}} + \dot{m}_{\mathrm{F}} + \dot{m}_{\mathrm{WI}} = \dot{m}_{\mathrm{CO}} + \dot{m}_{\mathrm{DA}} + \dot{m}_{\mathrm{FG}} + \dot{m}_{\mathrm{C}} + \dot{m}_{\mathrm{WO}} \tag{1}$$

$$\begin{aligned}
&(\dot{m}_{\mathrm{DCI}} c_{\mathrm{P_{DCI}}} + \dot{m}_{\mathrm{WCI}} c_{\mathrm{P_{WCI}}}) T_{\mathrm{CI}} + \dot{m}_{\mathrm{SA}} h_{\mathrm{SA}} + \dot{m}_{\mathrm{PA}} h_{\mathrm{PA}} + \dot{m}_{\mathrm{F}} h_{\mathrm{F}} + \\
&+ \dot{m}_{\mathrm{S3}} h_{\mathrm{S3}} + \dot{m}_{\mathrm{S12}} h_{\mathrm{S12}} + \dot{m}_{\mathrm{WI}} c_{\mathrm{P_{WI}}} T_{\mathrm{WI}} + \dot{Q}_{\mathrm{SUR}} = \\
&= (\dot{m}_{\mathrm{DCO}} c_{\mathrm{P_{DCO}}} + \dot{m}_{\mathrm{WCO}} c_{\mathrm{P_{WCO}}}) T_{\mathrm{CO}} + \dot{m}_{\mathrm{DA}} h_{\mathrm{DA}} + \\
&+ \dot{m}_{\mathrm{FG}} c_{\mathrm{P_{FG}}} T_{\mathrm{FG}} + \dot{m}_{\mathrm{C}} h_{\mathrm{C}} + \dot{m}_{\mathrm{WO}} c_{\mathrm{P_{WCO}}} T_{\mathrm{WO}} + \dot{Q}_{\mathrm{LOSS}}
\end{aligned} \tag{2}$$

Equations of material and heat balances for recuperative heat exchangers

The material and heat balances of the recuperative heat exchangers are defined by eqs. (3) and (4), respectively. The eqs. (3) and (4) are written in general form and can be applied for each of three recuperative heat exchangers (i = 1, 2, 3).

$$\dot{m}_{\mathrm{AAR}i} + \dot{m}_{\mathrm{PPAR}i} + \dot{m}_{\mathrm{FGR}i} = \dot{m}_{\mathrm{DAR}i} + \dot{m}_{\mathrm{PAR}i}\,, \quad i = 1,\ 2,\ 3 \tag{3}$$

$$\dot{m}_{\mathrm{AAR}i} h_{\mathrm{AAR}i} + \dot{m}_{\mathrm{PPAR}i} h_{\mathrm{PPAR}i} + \dot{m}_{\mathrm{FGR}i} c_{\mathrm{P_{FGR\mathit{i}}}} T_{\mathrm{FGR}i} = \dot{m}_{\mathrm{DAR}i} h_{\mathrm{DAR}i} + \dot{m}_{\mathrm{PAR}i} h_{\mathrm{PAR}i} + \dot{Q}_{\mathrm{LOSS}} \tag{4}$$

Due to lack of data on flue gases flows and absence of measurements of natural gas consumption in the coating drying section, it was possible to derive only equations for material and heat balance of cardboard web.

Field measurements – methodology and results

The cardboard machine is very well covered by process data measurement integrated in supervisory control and data acquisition system (SCADA). The data needed to calculate energy and mass flows covered by SCADA are the following: speed of cardboard web, humidity of cardboard web before and after the drying section, flow rate and pressure of steam, flow rate and temperature of supply air, flow rate, temperature, and humidity of discharge air, flow rate, temperature, and humidity of preheated air, heat capacity of natural gas burner, flow rate and temperature of flue gases in drying section, and flow rate and temperature of condenser cooling water.

Additional field measurements have covered data connected to the waste heat streams, heat transfer and energy flows in the machine hall, in order to complete all data necessary to calculate heat balances and waste heat losses according to eqs. (1)-(4). These goals have determined the measurement method to be used.

For that purpose, the following different types of measurements were conducted:

(1) temperature and relative humidity of room air in nine points (M.P.1 to M.P.9) across a cross-section of the hall,
(2) temperature profiles on the inner surfaces of side (M.P.11 and M.P.13), front (M.P.15) and back (M.P.16) walls,
(3) temperature profile of the cardboard machine hood (M.P.10 and M.P.14),
(4) temperature profile of the hall ceiling (M.P.12),
(5) temperature and relative humidity of ambient air (M.P.17), and
(6) temperature of cardboard web before and after drying section.

All of these measurements were conducted in 6 characteristic cross-sections, matching 6 different sections of the machine, each with a different technological process: former, pre-drying, smoothing, after-drying, coating drying, and handling section. The characteristic cross-section of cardboard machine hall and locations of the measuring points are shown in fig. 3. The characteristics of measuring instruments are presented in tab. 1.

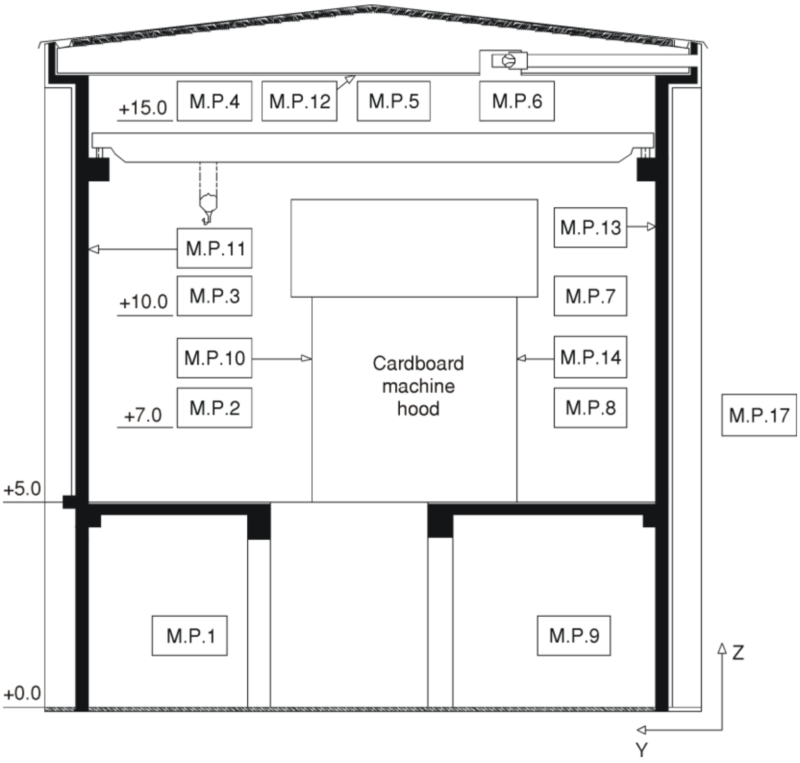

Figure 3. Locations of the measuring points across the cross-section of the cardboard machine hall

Table 1. Characteristics of measuring instruments

Measuring instrument	Type	Measuring range	Accuracy
Thermo-hygrometer	Electronic	Temperature: –40-120 °C Relative humidity: 0-99%	Temperature: ±0.5 °C Relative humidity: ±1%
Thermovision camera	FLIR ThermaCam E65	–20-250 °C	±1 °C

All measurements were carried out manually. In order to reach measuring points M.P.3 to M.P.7 the sensor of measuring device was fixed to the crane hook. Signals from the sensor were transmitted to the data logger, displayed, and recorded. The sensor was not moved to the next measuring point until the values were stable.

The measurements were conducted during the summer day in July 2008. It took three hours to complete all measurements. Time spent on measurements was negligible comparing to the production process period which lasted for few days. Moreover, significant fluctuations of ambient air conditions and machine operating conditions were not registered in time of the measurements. Under these circumstances, it can be assumed that measured properties were not changed in time of the measurements.

Some representative results of measurements done by thermovision camera are shown in figs. 4 and 5. Only the air properties measured in after-drying section of the hall are given in this paper and presented in tab. 2.

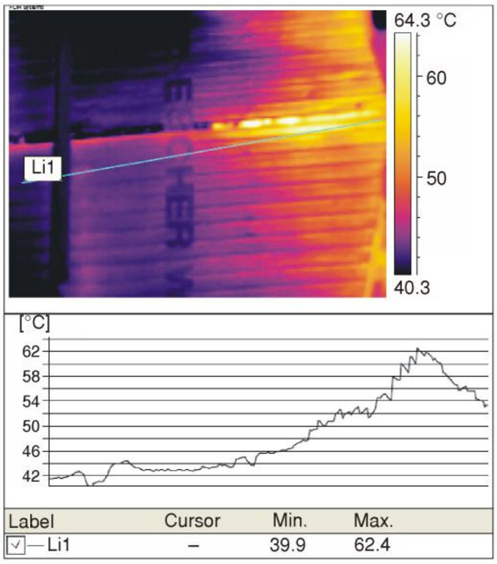

Figure 4. Temperature of cardboard machine hood
(color image see on our web site)

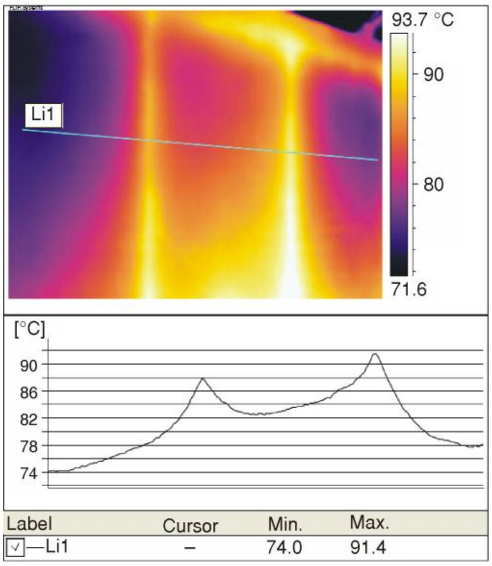

Figure 5. Temperature of impingement dryer in coating drying section
(color image see on our web site)

Table 2. Results of measurements in after-drying section

Measuring point	Temperature [°C]	Relative humidity [%]	Measuring point	Temperature [°C]	Relative humidity [%]
M.P.1	30	62	M.P.9	32.2	46.6
M.P.2	32.6	46	M.P.10	42-48	–
M.P.3	39.4	73.1	M.P.11	36-55	–
M.P.4	66.7	24.6	M.P.12	58-61	–
M.P.5	70	23.5	M.P.13	43-58	–
M.P.6	68.2	24.7	M.P.14	50-56	–
M.P.7	40.9	53.7	M.P.17	26.8	54.5

From the presented results and the results obtained in other sections it can be concluded that air temperature distribution varies considerably from section to section. Vertical temperature distribution is characterized by large temperature gradient and noticeable temperature stratification. Air temperature is slightly higher on the southern side of the hall due to the presence of additional heat sources such as machine drives and motors as well as steam pipes and discharge air ducts. As expected, the highest air temperature of 74.5 °C were recorded at the ceiling level of coating drying section.

There is a close correlation between the air temperatures and the surrounding surface temperatures. The highest values of surface temperatures (above 100 °C for infra-red and hot gas impingement dryers) were recorded also in the coating drying section. Leakage of hot humid air and flue gases was observed from the impingement dryers and from some parts of drying hood. Consequently, air temperatures at ceiling level were higher than temperatures of drying hood and heat exchangers surfaces in most cases.

Results of material and heat balance calculations

Drying section hood

Results of material and heat balance calculations are obtained by the use of eq. (1) and (2) and presented in tab. 3. The measurement has shown that the temperature of cardboard web entering the drying section hood was 32 °C while water mass content was 53%. By the end of this section the temperature of web was 80 °C and humidity 11%.

Table 3. The results of material and heat balance for drying section hood

	Input		Output		Difference	
	kg/s	kW	kg/s	kW	kg/s	kW
Cardboard	6.07	568	3.2	462	2.87	106
Humid air	52.7	3,942	63.3	14,519	−10.6	−10,577
Flue gases	4.58	1,200	4.58	276	0	924
Steam and condensate	4.53	12,421	4.39	1,857	0.14	10,564
Condenser cooling water	15	1,689	15	2,189	0	–500
Sum	–	19,820	–	19,303	–	**517**

Recuperative heat exchangers

Assuming the temperature of flue gases from infra-red dryers and neglecting the heat losses through the exchanger envelope, the two unknowns from eq. (3) and (4) for each heat exchanger namely $\dot{m}_{\mathrm{DAR}i}$ and $h_{\mathrm{DAR}i}$ can be calculated. The results of material and heat balance for recuperative heat exchangers are presented in tab. 4.

Coating drying section

The results of material and heat balance of cardboard in coating drying section are presented in tab. 5. Specific heat capacity of coating was 2.97 kJ/kgK, with a non-volatile content of 35% and input temperature of 30 °C.

Table 4. The results of material and heat balance for recuperative heat exchangers

	Input		Output		Difference	
	kg/s	kW	kg/s	kW	kg/s	kW
Heat exchanger No. 1						
Humid air from drying section/Discharge air	31.4	5,889	31.4	5,708	0	181
Fresh air/Preheated air	21.1	1,329	21.1	1,510	0	−181
Heat exchanger No. 2						
Humid air from drying section and flue gases/Discharge air and flue gases	31.2	7,488	31.2	6,854	0	634
Fresh air/Preheated air	29	1,850	29	2,484	0	−634
Heat exchanger No. 3						
Humid air from coating drying section and flue gases/Discharge air and flue gases	9.67	2,169	9.67	1,820	0	349
Fresh air/Preheated air	20.3	1,295	20.3	1,644	0	−349

Table 5. The results of cardboard material and heat balance in coating drying section

	Input	Output	Difference
Temperature, [°C]	80	59	21
Humidity, [%]	11	6.6	–
Mass flow rate of dry cardboard, [kgs^{-1}]	2.85	3.07	−0.22
Specific heat capacity of dry cardboard, [kJkg^{-1}K^{-1}]	1.51	1.51	–
Mass flow rate of moist cardboard, [kgs^{-1}]	3.2	3.29	−0.09
Specific heat capacity of water contained in cardboard, [kJkg^{-1}K^{-1}]	4.195	4.179	–
Heat flow rate, [kW]	462	328	134

Discussion

Considering that the mass of dry cardboard was not changed in the drying section, it can be concluded from tab. 3 that 2.87 kg/s of water evaporated from the cardboard. The mass flow rate of supply and preheated air was lower than the mass flow rate of discharge air. According to the calculations 10.6 kg/s of surrounding air was drawn in the hood due to under pressure inside of it. The air was drawn in the hood from the lower levels of the hall (measuring points M.P.1 and M.P.9) through the openings in hood's floor. One part of condensate, approx 0.14 kg/s, was not returned to the boiler house but spent in the press section. The results of heat balance show that 517 kW of heat was emitted to the surroundings through the hood envelope.

The total heat flow rate supplied to the hood by steam and flue gases was 13,621 kW. The heat flow rate needed for evaporation of 2.87 kg/s of water from the cardboard was 7,300 kW. Furthermore, 277 kW was consumed for heating the cardboard from 32 °C to 80 °C resulting the total amount of energy used for cardboard heating and drying of 7,577 kW. As a result, the thermal efficiency of drying section was approx 55.6%. Based on the results the specific thermal energy consumption of drying section of 4.75 $\mathrm{MJ/kg_{H_2O}}$ was calculated. For similar conventional drying systems specific thermal energy consumptions of 2.8-4 $\mathrm{MJ/kg_{H_2O}}$ [1] and 3.5-5 $\mathrm{MJ/kg_{H_2O}}$ [10] are reported, so it can be concluded that there are fairly large potentials for energy efficiency improvement.

From tab. 4 it can be concluded that present waste heat recovery system has utilized in total 1,164 kW of waste heat for preheating the fresh ambient air. Heat exchanger No. 2 has recovered the highest amount of waste heat (634 kW) with highest flow rate of preheated air (29 kg/s).

The results of cardboard balance in coating drying section shown in tab. 5 indicate that 0.54 kg/s of water evaporated from the cardboard in this section. On the other hand, 0.22 kg/s of non-volatile coating was added. Total heat capacity of gas burners in this section is 4,000 kW. The heat flow rate needed for evaporation of 0.54 kg/s of water and heating of 0.22 kg/s of non-volatile coating content from 30 °C to 59 °C was 1,346 kW. Under assumption that burners were operating at full capacity, calculated thermal efficiency of coating drying section was approx 33.6% while specific thermal energy consumption per 1 kg of evaporated water was 7.4 $\mathrm{MJ/kg_{H_2O}}$. Energy consumption of modern infra-red and impingement dryers is 5-8 $\mathrm{MJ/kg_{H_2O}}$ and 3-5 $\mathrm{MJ/kg_{H_2O}}$, respectively [1], which is considerable lower compared to the calculated value.

The results of heat balance are summarized in energy flow diagram of the process (Sankey diagram) that is shown in fig. 6. It is important to notice that the considerable amount of waste heat has been released to the atmosphere with discharge air because of the low efficiency of present waste heat recovery system. Total amount of waste heat in humid air and flue gases after the paper machine is 15,546 kW and after the recuperators in discharge air remains 14,382 kW. In addition, the greater part of waste heat from coating drying section is emitted to the surrounding air in the hall (3,913 kW). Driven by buoyancy the hot air rises to the upper levels of the hall where is extracted by hall’s ventilation system.

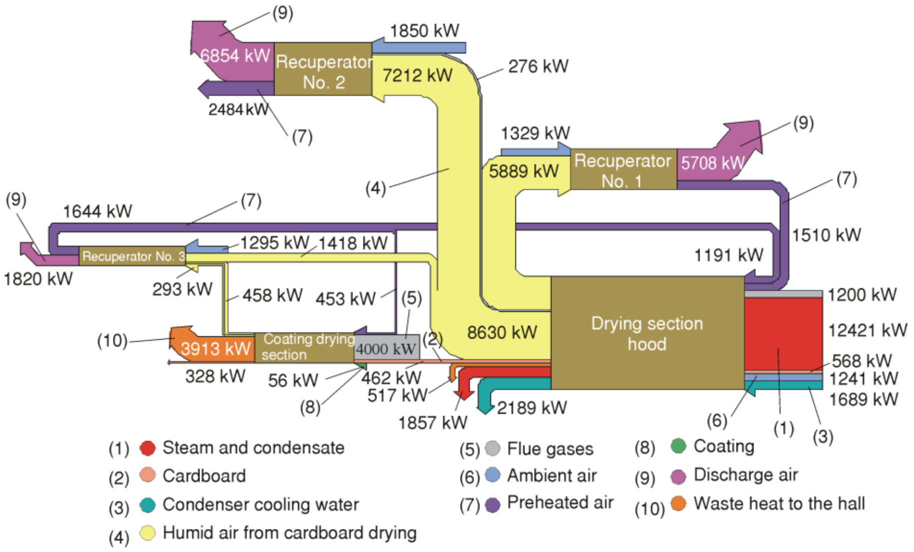

Figure 6. Sankey diagram for drying and coating dying section of the paper machine

Main characteristics of discharge air with waste heat flow rates are shown in tab. 6. Based on the results of heat balances the thermal and temperature efficiency of each heat exchanger is calculated and presented in tab. 6.

Table 6. Thermal and temperature efficiency of waste heat recovery system

Recuperative heat exchanger	Mass flow rate	Temperature	Waste heat flow rate	Thermal efficiency	Temperature efficiency
	kg/s	°C	kW	%	%
No. 1	31.4	58	5,708	3.9	27.4
No. 2	32.2	67	6,854	11.2	56.4
No. 3	9.67	74	1,820	39.9	21.7
Sum	**73.27**	-	**14,382**	**10.5**	-

The cardboard production in time of the measurement was in the normal operating regime. For this regime, specific thermal energy consumption of the machine's drying section was 1,490 kWh/t or 5.36 GJ/t and specific steam consumption was 1.4 t/t. The total amount of waste heat released to the atmosphere from waste heat recovery system was 14,382 kW. Moreover, the heat amount of 4,430 kW was released from the drying and coating drying sections to the surrounding air inside the cardboard machine hall.

The study carried out in similar paper mills, which are equipped with the latest technology, have shown that reference specific energy consumption of machine multi-cylinder drying section is close to 3.9 GJ/t [1]. With optimized dryer configuration the specific energy consumption can drop to 2.7 GJ/t [1], which is approximately two times lower than the specific energy consumption of 5.36 GJ/t calculated in this study.

Overall thermal efficiency of waste heat recovery system was found to be 10.5%. However, the performance of two bigger heat exchangers No. 1 and No. 2 with mass flow rates of 31.4 and 32.2 kg/s, respectively, was much lower than the performance of smaller heat exchanger No. 3. The reason for this may be the higher temperature and lower humidity of discharge air at heat exchanger No. 3 due to higher content of flue gases resulting in a smaller proportion of latent heat in the total amount of waste heat. On the other hand, due to high humidity of air from cardboard drying (up to 40 g/kg) latent heat makes more than 60% of total waste heat amount contained in discharge air at heat exchangers No. 1 and No. 2. Although vapour condensation significantly improves heat transfer coefficient [3] in this case latent heat could not be fully utilized since the humidity of preheated air has to be minimal. Besides, temperatures of discharge air are fairly low 58-74 °C, so that additional heating in steam-air heat exchangers is necessary. For this reason, the temperature efficiency has been calculated for each heat exchanger and presented in tab. 6.

Modern paper machines are equipped with multi units heat recovery systems that are able to recover over 50% of the energy used by the paper machine [3]. The recovered heat is used for the heating of drying section supply air, process water and machine hall ventilation. The humid exhaust air from the drying hood is first led to conventional heat recovery units, which recover heat to the dry supply air going into the hood. After this, heat is recovered in aqua heat recovery units to the circulation water of machine hall ventilation or process water in stock preparation, depending on the structure of the heat recovery system.

Considering the performance of present recovery system in the mill and significant amount of waste heat generated in the process, there are large potentials for it's further improvement and heat utilization.

In another study it is estimated that approx 1,610 kW of the waste heat can be recovered and utilized for preheating of drying section supply air in summer conditions by means of highly efficient regenerative pebble bed heat exchangers. The reduction of 12.9% in steam consumption can be achieved, referring to the total steam consumption of 4.53 kg/s. Even more savings may be expected in winter conditions [11].

Conclusions

The analysis of the mass and energy flows within the drying section of the cardboard machine has determined waste heat potentials. Considering the characteristics of production process, two main sources of waste heat were detected. The vast amount of waste heat, 14,382 kW, was released to the atmosphere with discharged air after the existing waste heat recovery system. Another part of 4,430 kW, was released to the cardboard machine hall and delivered to the atmosphere by the hall ventilation system. The waste heat amounts from both sources are significant, but characterized by fairly low temperatures (58-75 °C) and quite high moisture content (30-40 g/kg).

Thermal efficiency of waste heat recovery system was found to be very low (10.5%) while temperature efficiency was in range from 21.7 to 56.4%. On the other hand, modern paper machines are equipped with multi units heat recovery systems that are able to recover over 50% of the energy used by the paper machine [3].

Thermal efficiency of drying section and coating drying section was 55.6% and 33.6%, with specific thermal energy consumption of 4.75 $\mathrm{MJ/kg_{H_2O}}$ and 7.4 $\mathrm{MJ/kg_{H_2O}}$, respectively. Furthermore, it was calculated that 1,490 kWh (5.36 GJ) of heat was used in the drying section for production of 1 tonne of cardboard. Paper mills that are equipped with latest technology and with optimized dryer configuration, consume only 2.7 GJ/t [1] which makes them two times more efficient.

In order to improve efficiency and reduce energy consumption and production costs waste heat from both sources, of air discharged from paper machine drying section and of hall ventilation system, has to be recovered and utilized in the production process. Besides utilizing the waste heat, it is possible to reduce the energy losses by minimizing air leakages and by improving insulation around the machine hood and heat exchangers in coating drying section. The method described in this study can be successfully applied in other paper mills and similar industry sectors.

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Nomenclature

c_p – specific heat capacity, [kJkg^{-1}K^{-1}]
h – specific enthalpy, [kJkg^{-1}]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
$\dot{Q}$ – heat flow rate, [kJs^{-1}]
T – temperature, [K]

Subscripts

AAR – ambient air to recuperator
C – condensate
CI – cardboard incoming
CO – cardboard outgoing
DA – discharge air
DAR – discharge air from recuperator
DCI – dry cardboard incoming
DCO – dry cardboard outgoing
F – fuel
FG – flue gases
FGR – flue gases to recuperator
LOSS – losses
PA – preheated air
PAR – preheated air from recuperator
PPAR – air from production process to recuperator
S – steam
SA – supply air
SUR – surplus
S3 – steam at 3 bar pressure
S12 – steam at 12 bar pressure
WCI – water in cardboard incoming
WCO – water in cardboard outgoing
WI – water inlet
WO – water outlet

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