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Cfd analysis and airflow measurements to approach large industrial halls energy efficiency: A case study of a cardboard mill hall

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ABSTRACT

This paper deals with numerical methods for predicting air flow patterns in large industrial halls. Some major findings of the investigation of the airflow patterns in paper machine hall of Umka Cardboard Mill are presented in the paper. The main reason for the interest in this problem is to find optimal locations for extract air intake connections of the ventilation system connected to the exhausted air waste heat utilization. Previous studies have shown that the amount of heat released from the cardboard machine to the surrounding air in the hall and extracted by the series of ceiling mount axial fans was almost 30% of the total waste heat from the paper machine's drying section. These results have indicated the need for the waste heat utilization, but also for the optimization of the ventilation system. CFD simulation for predicting of air flow patterns was applied. The accuracy of the simulation was evaluated by comparing its results with the results of field measurements. Simulation results served well for qualitative analysis, gave better insight in general air movements inside the hall and indicated the extract air intake locations. By utilizing the waste heat from proposed optimal locations, fuel savings of 5% and reduction of 1140 t/year in CO_2 emissions can be achieved.

1. Introduction

Within the National Program of Energy Efficiency, which was initiated in 2002 by The Ministry of Science and Technological Development of the Republic of Serbia, numerous projects have been introduced in order to improve energy efficiency in industry. The project entitled "Utilization of solid waste and waste heat in process industry" was carried out in the period 2006–2009. The project involved Faculty of Mechanical Engineering, University of Belgrade as a research institution and Umka Cardboard Mill as a process industry representative. The aims of the project were defining potentials of waste heat that is generated in the cardboard making process and proposing solutions for its utilization. The first step in the analysis was calculation of the cardboard machine heat and mass balances. Methodology and results of the balances are presented in other papers [1,2]. The results of the heat balance have shown that large quantity of waste heat was released during cardboard manufacturing. The three glass tube heat exchanges of the existing waste heat recovery system utilize only 7.5% of the waste heat from machine's drying section. The amount of 14,400 kW was released with air discharged to the atmosphere. The results also indicated that 4430 kW of heat was released from the cardboard machine to the surrounding air in the production hall. Warm and humid air is accumulated below the ceiling. It is extracted by the series of axial fans mounted along the ceiling of the hall.

The utilization of low-temperature waste heat from the top of the hall was proposed for preheating of fresh air that is used in cardboard machine's drying section. Application of very efficient regenerative pebble-bed heat exchangers was considered [3]. It is estimated that the application of pebble-bed heat exchanger with optimized positions of ventilation extract air intake connections can save approx 610 kW of energy used for heating of fresh air for cardboard drying section (calculated for the summer conditions). In that way, savings of 5% in steam and fuel consumption of the cardboard machine can be achieved [3]. Another benefit is reduction of 1140 t/year in CO_2 emissions. It should be noted that even bigger savings may be expected in winter conditions.

In order to maximize the waste heat utilization, it is necessary to determine temperature profiles, air flow and the proper positions of ventilation extract air intake connections for pebble-bed regenerative heat exchanger in the hall of the cardboard machine.

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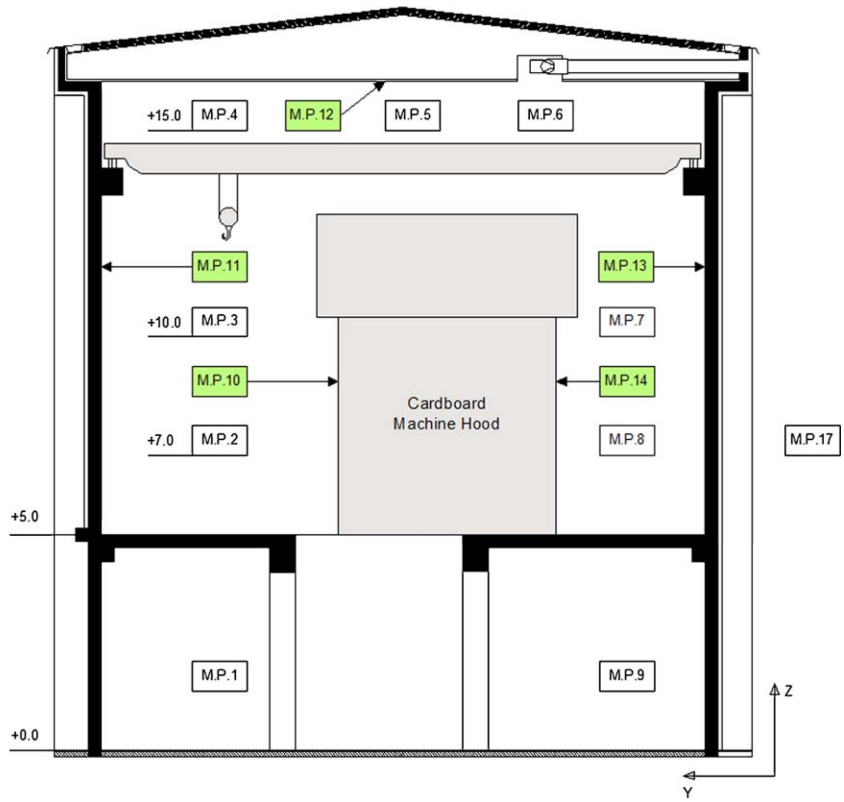

Fig. 1. Locations of the measuring points across one characteristic cross-section of the cardboard machine hall.

Table 1
Characteristics of measuring instruments.

Measuring instrument	Type	Measuring range	Accuracy
Thermo-hygrometer	Electronic	Temperature: −40 to 120 °C Relative humidity: 0 to 99%	Temperature: ±0.5 °C Relative humidity: ± 1%
Thermovision camera	FLIR ThermaCam E65	−20 to 250 °C	± 1 °C
Vane anemometer	Kestrel 4000 Nielsen-Kellerman	0.4 to 60 m/s −45 to 125 °C	0.1 m/s 0.1 °C
Hot-wire anemometer	Testo	0 to 20 m/s	0.01 m/s

Table 2
Results of measurements in smoothing cylinder section.

Measuring point	Temperature (°C)	Relative humidity (%)	Measuring point	Temperature (°C)	Relative humidity (%)
M.P.1	30	58	M.M.9	36.5	46
M.P.2	37	35	M.P.10	40–70	–
M.P.3	48	47	M.P.11	38–54	–
M.P.4	62.5	38	M.M.12	57–64	–
M.P.5	65.5	36	M.M.13	55–60	–
M.P.6	66	32	M.M.14	60–70	–
M.P.7	45	39	M.M.17	27	54
M.P.8	38.5	43			

Table 3
Characteristics of air inflow.

	Opening								
	#1	#2	#3	#4	#5	#6	#7	Windows	Total
Opening area (m^2)	33	8	125	5	5	5	30	2.35	213
Temperature (°C)	25	50	26.7	26.8	25.8	16.5	26.5	4	–
Relative humidity (%)	33	35	38.6	32	35	65	33	78	–
Velocity (m/s)	0.05	0.45	0.3	0.04	0.08	0.34	0.12	3	–

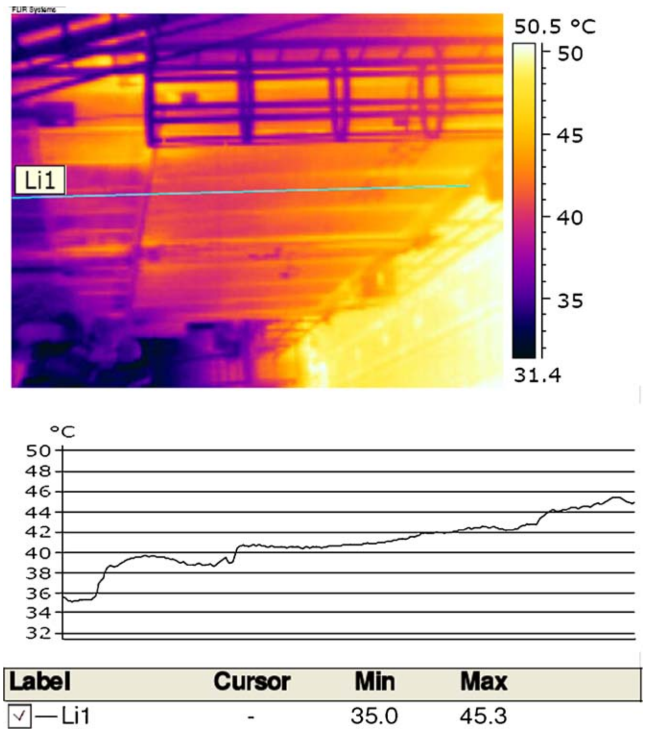

Fig. 2. Temperature of cardboard machine hood (M.P.10) in pre-drying section; temperature increases with hood height.

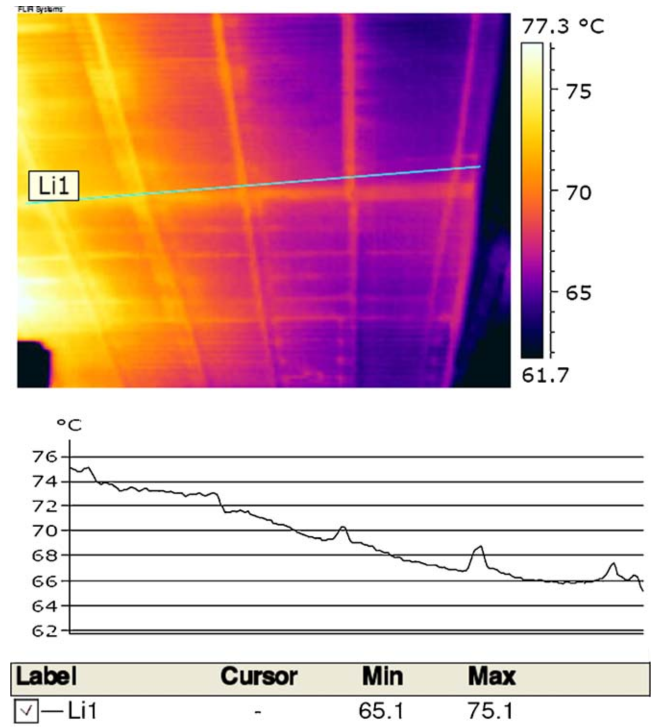

Fig. 3. Ceiling temperature (M.P.12) in coating drying section; temperature increases from northern to southern side of the hall.

For that purpose, a CFD simulation and field measurements have been carried out and the results are presented in this paper.

2. Methodology-field measurements and Cfd simulation

2.1. Problem description

The Umka Cardboard Mill is located 15 km from Belgrade, on the right bank of the Sava River. After the 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 in stock preparation process. 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 steam at 3 and 12 bar, respectively. The machine's steam load is on average 16 t/h.

The temperature and moisture distribution inside the Umka Cardboard Mill hall vary significantly with space and depend on outdoor atmospheric conditions. In order to determine the properties of air inside the hall and estimate waste heat potentials, field measurements have been conducted in real operating conditions.

Considering the size of the hall (196 m long, 15 m wide and 11 m high) and vast number of factors that influence thermo-physical properties of air, it is difficult to optimize the waste heat recovery system using only analytical calculations and point to point measurements in the hall. The results of previous studies and field measurements have given overall features of air temperature, pressure and velocity fields inside the hall.

Additional information is required in order to find the most favourable locations for heat exchangers' intake connections. A CFD simulation for predicting of air flow patterns was applied and presented in the paper. CFD simulation is appropriate in cases where the detailed flow field is of interest in a configuration with mostly known and steady-state boundary conditions. It is becoming a more popular method since it provides more comprehensive solution; it is less expensive and requires less time than some other methods such as field experiments. The accuracy of the simulation was evaluated by comparing its results with the results of field measurements.

The approach of using a CFD simulation results and site measurements for retrofitting the air-conditioning system in process industry in a large malt house has successfully been applied and presented by Wang and Zhu [4]. Some other methods for predicting airflow patterns such as laser Doppler anemometry (LDA) and particle image velocimetry (PIV) have been presented and compared with three-dimensional numerical simulations (CFD) by Posner et al. [5].

2.2. Field measurements

2.2.1. Methodology and description

The goals of the final quantities to be obtained determine the method or measurement procedure to be used. It is essential to define what values are going to be measured, type of equipment that is to be used and time schedule of a measurement according to the information required. In this case, the temperature, velocity and humidity fields in the hall of the cardboard machine were point of interest. Since the measurements should serve as a supplement to CFD simulation (boundary conditions and validation of results), the temperatures of cardboard machine hood and inner walls of the hall were important to be measured.

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 ceiling (M.P.12),

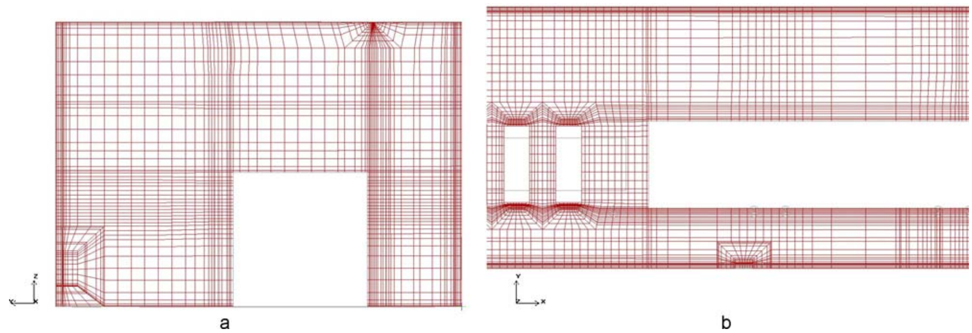

Fig. 4. Mesh configuration in former section; (a) vertical; (b) horizontal.

5. Temperature and relative humidity of ambient air (M.P.17) and
6. Temperature, humidity and velocity of air that flows into the hall through openings and windows.

Fig. 1 shows a characteristic cross-section of cardboard machine hall and locations of the measuring points. The cardboard machine of the Umka Cardboard Mill is accommodated in a 196 m long, 15 m wide and 11 m high production hall. The architectural features of the hall can be considered as a single volume of 32,000 m^3, with a base area of 3000 m^2. The 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 characteristics of measuring instruments are shown in Table 1.

All measurements were carried out manually. Measuring points were located at the constant distances from the floor and side walls as shown in Fig. 1. 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.

Considering the size of the hall, relatively small number of measuring points (54 in the whole space) and the fact that air properties vary with respect to space and time and depend on many factors such as type of cardboard being produced, outdoor climate conditions, status of doors and windows, machine running mode etc., high accuracy of the results was not required. Still the method being used and the measurement results are reliable enough and sufficient for qualitative analysis.

It took 3 h 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 stated that measurements were performed under steady state conditions. These measurements should provide information on summer conditions in the hall since they were carried out during the 18th of July 2008, except for the air inflow measurements that are conducted additionally in winter conditions and used only for validation of the CFD model.

2.2.2. Main results

Some representative results of measurements done by thermovision camera are shown in Figs. 2 and 3. The air properties measured in smoothing section of the hall are given in Table 2. The results of air inflow measurements are given in Table 3.

The results show that air temperature distribution varies considerably from section to section along the hall. 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 temperatures were recorded at the ceiling level of after-drying section (70 °C) and coating drying section (74.5 °C).

There is a close correlation between the air temperatures and the surrounding surface temperatures. This is explained by the fact that the highest values of surface temperatures were also recorded in coating drying section. The temperature distribution on the inner side of the walls was characterized by high temperature gradient, likewise the air temperature distribution. On the other hand, hood temperatures were quite uneven with respect to the side and the section of the machine. The ceiling temperatures also differed considerably from section to section, with higher values recorded on the southern side of the hall.

Based on these results it can be assumed that the hottest and the highest thermal plume is formed over the coating drying section of the machine. Consequently, the space above this section should be the best location for heat exchangers' intake connections. The results of CFD simulation discussed later in this paper should confirm this assumption.

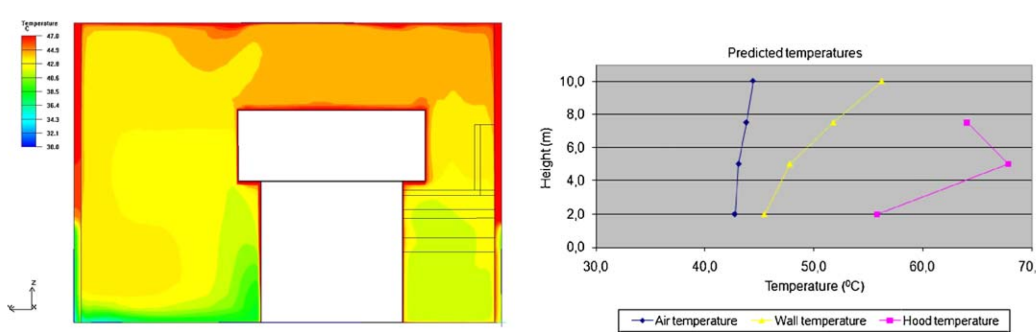

Fig. 5. Simulated temperature distribution in smoothing cylinder section.

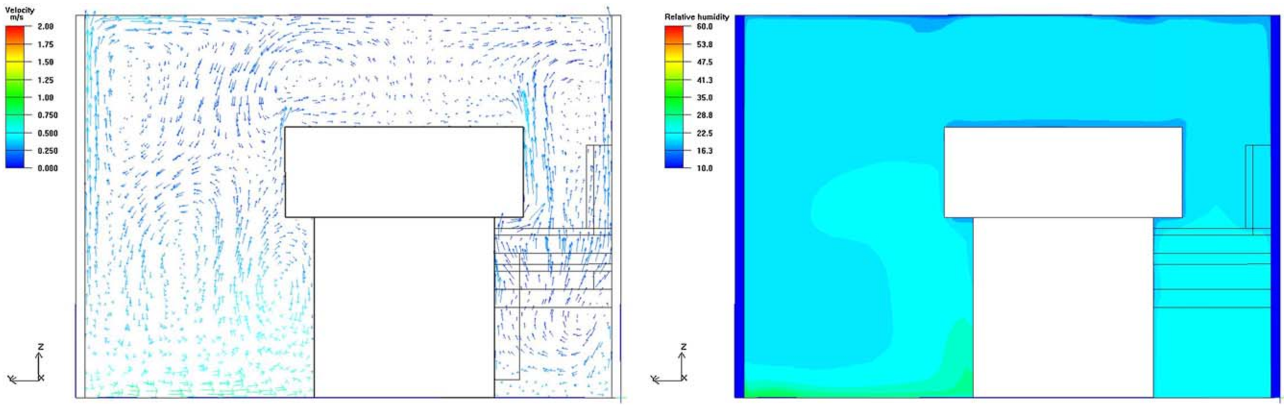

Fig. 6. Simulated velocity distribution and relative humidity in smoothing cylinder section.

2.3. *CFD simulation*

2.3.1. *Simulation outline and methodology*

As mentioned before, the CFD simulation is carried out for the purpose of predicting of the air flow patterns in the hall. The main interest was to gain additional information on air movements in the hall in order to optimize the ventilation waste heat recovery system. Due to the large size of the hall and complexity of the cardboard production process this seemed to be the appropriate method.

The fresh air is supplied to the hall through the several openings located on the floor and side walls and randomly opened windows. All the supply openings are located mostly at the lower levels of the hall (1–2 m above the floor). The cold air from the floor is heated by the hot machine surfaces. It rises due to buoyancy, settles at some level or reaches the ceiling, where it is extracted by the hall's ventilation system. The ventilation system consists of a series of axial fans that extract the hot and moisture air through 43 exhaust openings located in the ceiling. In a room like this the airflow patterns should be governed by vertical convection flows, due to buoyancy and mechanical ventilation.

Prediction of the airflow is based on a solution of fundamental flow equations, i.e. continuity, momentum and energy equation. During that process continuous problem domain has to be replaced with a discrete domain using a grid. In the discrete domain, each flow variable is defined only at the grid points. Solution exists only at the grid points while the values at other locations are determined by interpolating the values at the grid points. The discrete system is a large set of coupled algebraic equations in the discrete variables. Therefore, it is suitable for numerical solution [6].

Certain assumptions and simplifications of the real system or the process have to be made to enable modelling it on the computer. However, important flow features should be captured. The geometry was imported from CAD software and was considerably simplified. The Boussinesq approximation (treats air density as constant value in all solved equations, except for the buoyancy term in the momentum equation) was applied in order to get a faster convergence. The airflow patterns were simulated under steady state conditions using a commercial code FLUENT 6 (ANSIS Inc.) with AIRPAK version 3.0.16 (ANSIS Inc.) used for pre and post-processing. The air inside the hall was assumed to be free of solid particles (i.e. paper fibres). The cardboard machine hood was considered to be tight and without air leakages. Variations in indoor conditions due to the building thermo-physical behaviour, lighting and presence of workers were not taken into consideration. All materials were assumed to be isotropic and their properties were defined as constant.

The vertical (a), and horizontal (b) cross sections of the hall and of the cardboard machine are presented in Fig. 4, as well as the hexahedral unstructured mesh which was chosen in this study. The elements near boundary surfaces (e.g. machine surfaces, walls, windows, openings, fans etc.) were refined in order to reduce the turbulence and heat transfer modelling errors. Boundary conditions were specified according to the field measurements. The turbulence viscosity was modelled using the standard k–ε model.

2.3.2. *Results*

Before discussing temperature, velocity and vapour distribution in the hall attention is paid to the mass and heat balance. The difference between discharge and supply mass flow rate was 0.23 kg/s, which is considered to be negligible comparing to overall mass flow rate of 59 kg/s. For given hall dimensions, the air change rate of 5.4 per hour was calculated. On the other hand, the difference between discharge and supply heat flow rate was only 348 kW. This amount of heat should correspond to the heat released from heat sources inside the room.

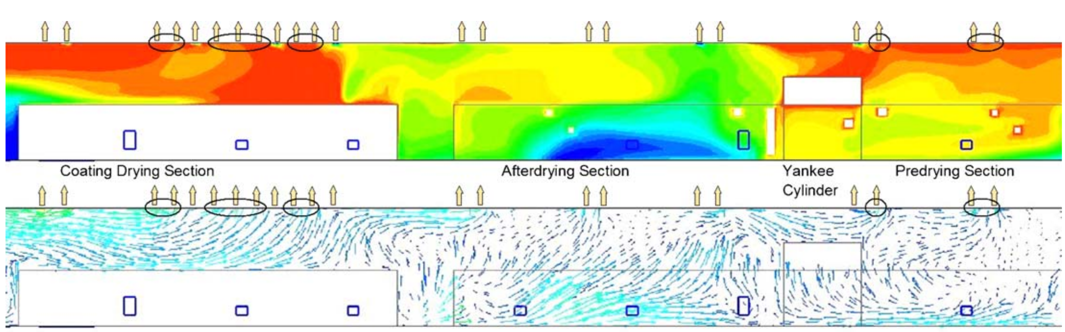

Fig. 7. Temperature and velocity field along the hall and the positions of optimal heat exchangers' intake connections.

The total heat flow rate from the machine surfaces was 202 kW, while the overall heat surplus was 615 kW. Since the air heat gain was 348 kW, it can be concluded that about 267 kW was lost through the building envelope.

Simulated temperature distribution in smoothing cylinder section is shown in Fig. 5, while the velocity and humidity distribution in the same section is shown in Fig. 6. The results for other sections do not differ noticeably and for that reason are not shown in the paper.

As it is presented in Fig. 5, the air temperature gradient from 2 to 10 m height is weak (2–3 °C), although wall and hood temperatures increase with height considerably (more than 10 °C). The results of simulation show that the highest air temperatures of 47 °C are at ceiling level and the lowest of 37 °C are at floor level. Velocity distribution shown in Fig. 6 is characterized by intensive air mixing with air velocities less than 1 m/s both in horizontal and vertical direction except in the vicinity of windows. Buoyancy driven flows along the hot hood and wall surfaces are also noticeable. Air humidity is in range of 20–30%, with higher values predicted at floor level.

3. Comparison of results and discussion

The total heat flow rate from the machine surfaces, as a result of simulation, is of 202 kW. This value is negligible compared with the results of the machine heat balance, which imply 4430 kW of the total heat release from the heat sources in the hall. Consequently, the simulated air temperatures are much lower than measured especially in upper zones of the hall. Furthermore, resulting vertical temperature gradient in smoothing cylinder section is too weak although there is a good agreement between simulated surface temperatures and measured values. There is a big difference of the temperature stratification that have been observed and measured in real operating conditions in the hall and of that obtained by the simulation. Similar results which are not presented in this paper are obtained for other sections of the hall. This can be partially explained by intensive air mixing throughout space. The simulation has also shown that buoyancy driven flows along the hood and wall surfaces were noticeable, but not strong enough to create the temperature stratification observed by measurements. Simulated values of relative humidity were lower than measured, particularly at the lower zones of the hall.

Considering results, it appears that simulation could not provide reliable quantitative values. The reason for this may be the influence of the penetration of hot air from the machine to the hall which was neglected during the model simplification. Due to the complexity of production process and cardboard machine itself, it is difficult to determine or estimate the rate of hot air leakage and its influence on the overall airflow patterns in the hall. This has to be the subject of further research and model improvement.

However, the qualitative picture of airflow patterns has been obtained and is in good agreement with on site observations in the Umka Cardboard Mill hall. The results of temperature and velocity field along the hall are presented in Fig. 7. The results imply that the hottest and highest thermal plume is formed above the coating drying section. It reaches the ceiling level and spreads horizontally penetrating into the adjacent sections. The plume formed above the smoothing section (Yankee cylinder) also has noticeable waste heat potential. It is suggested that these two airflows are the most suitable for heat recovery. The airflows that are extracted from the 10 of 22 openings which are pointed out in Fig. 7 are the hottest and have the biggest waste heat potential. Therefore, these ten openings are proposed as optimal for heat exchangers' intake connections. This results of CFD simulation have largely confirmed the assumption previously indicated by the measurements.

4. Conclusions

The simulation results have shown that total heat flow rate from the cardboard machine was 202 kW. More than a half of this amount was released from the coating drying section of the machine (107 kW). These figures are not comparable to the results of the machine heat balance which imply 4430 kW of total heat release from the heat sources in the hall. Consequently, the simulated air temperatures were much lower than measured especially in upper parts of the hall.

From the results it appears that simulation could not provide reliable quantitative results since the resulting values differ significantly from measured values. However, simulation provides a qualitative picture of airflow patterns which is in good agreement with on site observations in the Umka Cardboard Mill hall. The method can be applied in other paper mills and similar industry premises where large flat machine surfaces and high halls are common.

Several conclusions are derived from numerical analysis as follows:

- Airflow patterns in the hall are governed by vertical convection flows due to buoyancy and mechanical ventilation. Leakage of hot air into the hall from some parts of the machine also alters thermal plumes created above the machine.
- Air velocities are fairy low (less than 1 m/s) both in horizontal and vertical direction except in the vicinity of windows.
- Investigation confirms the assumption that the plume formed above the heat exchangers in the coating drying section is the hottest and the highest with considerable high airflow rate. It reaches the ceiling level and spreads horizontally penetrating into nearby sections along the hall. Therefore, it is suggested that this airflow is the most suitable for heat recovery. By utilizing the waste heat from proposed optimal locations, fuel savings of 5% and reduction of 1140 t/year in CO_2 emissions can be achieved.

Besides utilizing the waste heat from the ventilation extract air in the hall, it is possible to lower energy losses from the production process by minimizing air leakages and improving insulation around the machine hood and heat exchangers. Additional measurements and analytical calculations are needed in order to determine the influence of air leakages on the overall airflow patterns in the hall. This has to be the subject of further research and model improvement.

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