Paper drying
A simulation model to optimize the energy consumption
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The drying process is a highly cost intensive part in paper production as up to 75% of the overall thermal energy are applied there. Due to the fact that energy is getting more and more expensive, a project has been started by the Institute for Pulp, Paper and Fibre Technology, Graz University of Technology, Austria to optimise the drying section in terms of energy consumption.

For each paper machine a physical simulation model of the drying group is developed. The models include the drying cylinders, IR and impingement dryers, heat recovery, condensate and steam system. Fundamentals of paper drying and the simulation model were discussed in an earlier publication in 1. The whole drying process can be divided in several steps as shown in Figure 1.

The graph shows the heat up phase (A-B), the first drying phase with a more or less constant drying rate (B-C), the section (C-D) with decreasing drying and the third drying phase (D-E) above about 80% dry content. The drying rate is decreasing rapidly in this third phase due to hydrogen bonding and capillary effects, which bond the water to the fibre surface. Additional evaporation energy is necessary to overcome these effects and this additional energy is called sorption enthalpy 3, the graph is shown in Figure 2. Water has a latent heat of 2,308,05 kJ/kg at 80°C 4, this is equivalent to the heat of vaporization up to an equilibrium moisture content (EMC) of about EMC = 0.3 g/g. At higher dry contents the vaporization energy is increased by the heat of sorption, at e.g. 97% dry content (EMC-0.03) the necessary heat for evaporation is about 2,900 kJ/kg instead of 2,300 kJ/kg. This equals to the heat of sorption of 600 kJ/kg water. The integrated heat of sorption (shaded area) represent up to 3% of the vaporisation energy of pure water, meaning that for drying paper up to a dry content of 97% the total heat of vaporization is about 3 % higher than the latent heat of water.

Based on the energy demand for evaporating the water (depending on the furnish mix) the drying process is simulated. To optimize a specific drying section depth knowledge on the process parameter is necessary. A mass and heat balance of the existing drying section, the heat recovery system, steam and condensate system is calculated as a basis for simulating.

Simulation Model
Based on the accurate heat/mass balance and pulp parameters the physical simulation model is developed. The model is validated based on online DCS measurements and manual control measurements of for example temperature, air moisture and air flow at various positions. The model is optimised and validated to a maximum deviation (between model and DCS values) of lower than 5%.

The simulation model includes the following parameters:
- All paper machine parameters like machine speed, grammage, machine width and paper web
- Air condition in the hood (moisture, temperature, etc.)
- Drying equipment like steam cylinder, impingement dryers, IR-dryers
- Heat recovery system with heat exchanger, fans and flow volume
- The steam and condensate system for each drying group
- All relevant paper parameters in terms of drying (fibre mix, filler content, dry content before and after drying section)
- All the necessary equations for the heat and mass transfer during the drying process in the drying hood and heat recovery system
The main advantages for using such a simulation model are: Testing of different machine settings for energy optimisation can be done under safe conditions. Promising settings found in the simulation can later on be tested in machine trials. Additional equipment can be added to the model fairly easy, like additional heat exchangers, additional impingement hoods etc. The model can be used to calculate different scenarios for machine rebuilds and investments for new equipment. The model can be applied as a training tool for operators and also create an increased cost awareness of operators. True costs for energy (gas, fuel, steam) can be integrated in the model and thus true cost results are obtained directly from the simulation. MD-profiles for evaporation rate, paper temperature etc. can be obtained.

**Application case studies**

Three project case studies to save energy are discussed in this chapter: The first one considered the influence of supply air temperature on a Yankee machine. Considering the Stefan equation there are two possibilities to influence the evaporation rate of a paper web (see Formula 1).

![Heat of vaporization of unbleached kraft pulp at 80°C as a function of equilibrium moisture content (EMC). The heat of sorption is the difference between the latent heat of water (2,308 kJ/kg) and the vaporization energy.](image)

**Formula 1:**

\[
\dot{m}_v = \frac{\beta \cdot p_0}{T_{Paper} \cdot R_v \cdot \ln \left( \frac{p_0 - p}{p_0 - p_{vp}} \right)} \cdot A_{contact}
\]

- \(\beta\): mass transfer coeff. [m/s]
- \(\dot{m}_v\): evaporation rate [kg/s]
- \(A_{contact}\): paper surface area [m²]
- \(p_0\): total pressure [Pa]
- \(p\): vapour partial pressure of air [Pa]
- \(p_{vp}\): vapour partial pressure of the paper web [Pa]
- \(T_{Paper}\): temperature of paper web [K]
- \(R_v\): gas constant of vapour [J/kgK]

In terms of a Yankee machine (project member application) we can increase the absorbed heat of the paper web by increasing the steam pressure (influencing \(p_{vp}\)) or by increasing the temperature of the air in the impingement hood (influencing \(T_{Paper}\)). The example below shows these two possibilities as used in the simulation model.

**Case A:** the impinging temperature is 175°C, cylinder steam pressure is 1.7 bar gauge

**Case B:** the impinging temperature is 150°C, cylinder steam pressure is 2.5 bar gauge

In both cases the heat absorption of the web and the drying performance are the same. The heat transfer via cylinder with higher steam pressure is more efficient than increased convection via impingement drying. The simulation model shows an energy advantage of about 1.8% for Case B. This effect is also confirmed by 4. In addition the energy costs for gas (heating of impingement air flow) is about 2.5 times higher than steam energy. So in total the cost advantage for Case B is about 5% of the total energy costs. This optimisation could be implemented without investment costs with a cost benefit of EUR 80,000/y.

![Example for a simulation model – graphical user interface for a board machine.](image)
The second project case study considered the possibilities to use exhaust air of infrared dryer. In some machines the exhaust air of an infrared dryer is not used in the heat recovery system. The amount of the exhaust air in our case study was close to 10,000 m³/h with a temperature of 165°C and a moisture content of 0.01 kg/kg. This corresponds to an energy amount of close to 4,000 MWh/yr compared to fresh air. This heated air with low moisture content can be used in impingement air hoods. This will lead to direct energy savings of 4,000 MWh/yr. Therefore the investment is just some piping and valves for redirecting the air stream, payback time for this investment is far below one year.

The third project case study considered the optimisation of leakage air and recirculated air. In another case study the mass balance of exhaust and supply air turned out to be incorrect during our measurements. The amount of leakage air was more than 50% of total air volume. One fan which is responsible for the supply air didn’t work properly because of destroyed fan plates. The heat exchanger in line with the fan was also contaminated. Because of these two effects the operation air flow of this fan was only 35% of the nominal air flow.

The heat exchanger was cleaned with water and steam, the fan plate was rebuilt and new pulleys and belts were installed to optimize the leakage air flow between supply air flow and exhaust air flow to a value of 20%.

With the decreased leakage airflow it was possible to reduce the supply airflow temperature dramatically. In the past a very high supply air temperature was necessary to avoid condensation effects in the hood because of the 30°C cold leakage air.

This lead to energy savings due to reduction of steam consumption for air heating and reduction of electric energy consumption from turning down the supply air fans. Without any major investment in machine infrastructure energy savings of about 4,000 MWh/yr (thermal and electric combined) were obtained.

Conclusion & outlook
Based on exact mass- and heat balance different approaches for energy optimization can be simulated and subsequently quantified using the developed model. Applicability and evaluation of different settings is easy because the simulation software uses the same graphical user interface as the computer screens for controlling the paper machine. The results from the simulations are directly displayed on the screen and additionally the financial results are shown.

Application of the simulation model in four paper machines revealed so far an energy optimisation potential of 2 to 8% of total drying energy consumption including only optimisations with payback time below two years. This leads to saving potentials between EUR 50,000 and 250,000/y for each mill.

Currently the optimizations obtained from the simulation are verified in machine trials at the participating companies. Results so far are in line with the predicted savings from the simulation.

References

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