International Drying Symposium (IDS'04), Sao Paulo, Brazil, August 2004

HEAT PUMP DRYING OF SULPHATE AND SULPHITE CELLULOSE

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Keywords: Cellulose, tensile index, water retention value, heat pump

ABSTRACT

Today, heat pumps are used in industrial drying of materials of biological origin, like food and wood. For heat sensitive materials, improved product quality can be achieved with this technology due to low drying temperatures and independency of the outdoor air. Also, energy consumption is reduced due to the high coefficient of performance of the heat pump and the high thermal efficiency of the dryer when properly designed. In this way heat pumps used in drying operations satisfy important requirements in industrial drying with respect to product quality control, low energy utilization and reduced environmental impact.

This paper presents heat pump drying of sulphate and sulphite cellulose at drying temperatures from –15^{o}C to 20^{o}C. Drying tests have been performed at constant and "step up" air inlet temperatures, which is done by initial freeze drying and final drying above the material freezing point. Key quality parameters like the tensile index (TI) and water retention value (WRV) have been measured. A considerable improvement in TI and WRV was achieved at –15^{o}C and 20^{o}C compared to conventionally industrial dried cellulose. The loss in WRV is reduced by 50% to 70% while the loss in tensile index is reduced with about 50%. The sorption isotherm for sulphate and sulphite cellulose was successfully modeled by the GAB and the BET equations.

INDUSTRIAL DRYING OF SULPHATE AND SULPHITE CELLULOSE

The dewatering of cellulose pulp starts normally with a suspension of fibers with about 1% dry matter. The fibers are distributed over a continuously running filter web (wire section) using a so-called head box. Water is drained off while the fibers are left on the wire until the dry matter fraction reaches about 10%. As a result a continuous pulp web is formed, and it moves to a press section where the dry matter is brought up to about 45 to 55%. This is the normal dry matter when the pulp enters the drying section, where water is removed and market pulp is produced at 90% dry matter.

There are basically three different dryer designs: the air dryer, the cylinder dryer and the flash drier. In the air dryer the web is air borne, which is inserted in the top of the drying chamber, flows through several horizontal passes back and forth in the chamber and leaves the drier at approximately 90% dry matter. The drying air enters at the bottom of the drier and moist air exits at the top of the drier with typically 70^{o}C to 90^{o}C and 70% to 80% relative humidity. In the cylinder drier the energy is transferred to the pulp through steam-heated cylinders in contact with the pulp. Regenerating air is also directly fed into the drying camber. The flash drier is mainly designed for thermomechanical and chemithermomechanical pulps which is dried in particulate form. The pulp is fragmented by a fluffer and dispersed into the air and dried as the air stream acts as the drying or heating media an transport the fibers and water vapor [Larsson and Karlsson, 2000].

Usually these industrial drying methods are associated with a reduction in quality of the cellulose pulps quality. According to Jayme [1944], this phenomenon is called hornification, which is characterized by a reduction in the water retention value (fiber swelling). Since then numerous researchers have studied the changes in the fiber quality caused by drying. Another well known negative effect, caused by drying, is the loss in tensile strength [e.g. Gurnagul and Page 2001].

When calculated based on mill data, the SMER number for pulp drying from 50% to 90 % dry matter matter is typically between 1.2 and 1.4 kg/kWh. SMER number for flash drier was reported to be 1.3 kg/kWh [Larsson and Karlsson 2000].

HEAT PUMP DRYING – ADIABATIC AND NON-ADIABATIC

Heat pump dryers are attractive for the processing of heat sensitive materials since the drying conditions are easily controlled. Aside from being able to save energy this dryer design is based on an environmentally friendly technology. In Norway it has been applied industrially for the drying of fish and apples. Additional successfully dried products are fish, fish residues, fruits, vegetables, dairy products, biological and other active or heat sensitive materials. The drying modes can be adjusted in accordance to the material sensitivity and implies a high final product quality as indicated bymeasured parameters such as hardness, porosity, density, rehydration, colour, aroma and other properties.

A schematic layout of a continuous industrial heat pump dryer is shown in Figure 1. The advantages of the heat pump dryers are low energy consumption due to a high SMER that is expressed by:

$$SMER = COP/(dh/dx) \quad (1)$$

$$COP = Q_o / W \quad (2)$$

Typical SMER values are in the order of 2 to 5 depending on the drying conditions. The drying temperature can be regulated in a wide range from –20°C to 110°C. The product quality parameters can be controlled due to the low temperatures and the possibility for partly freeze drying. Additionally, this technology is environmentally friendly due to recirculation of the drying air and the high thermal efficiency of the dryer.

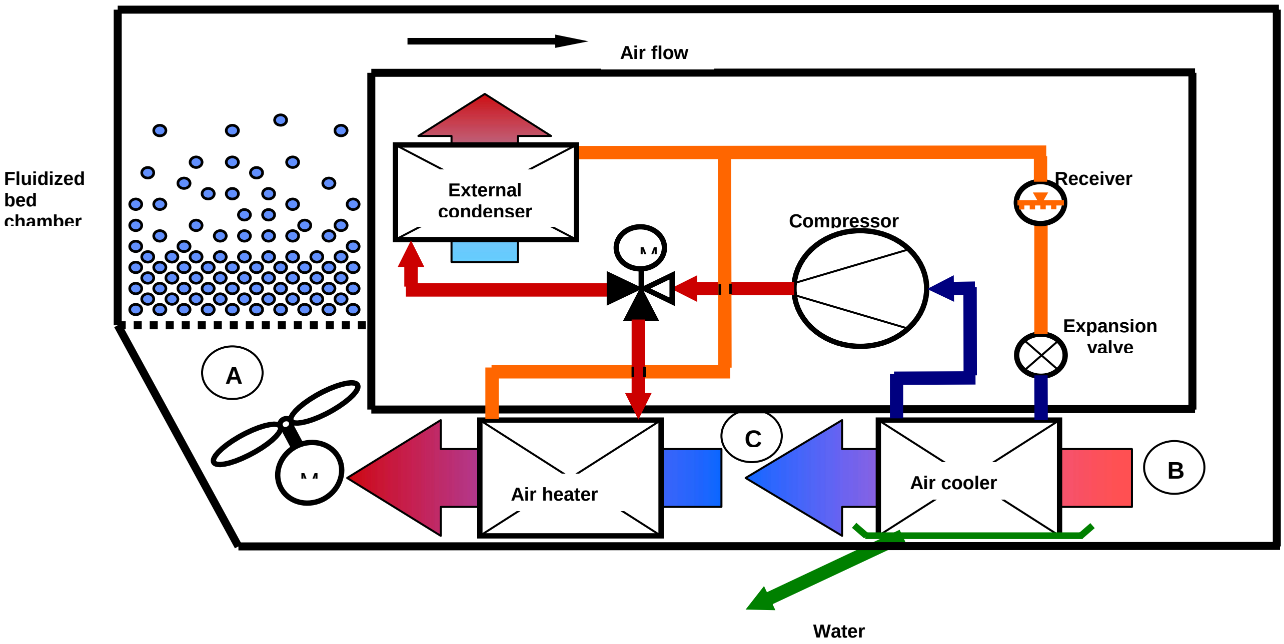

Figure 1 – Schematic layout of a heat pump fluidized bed dryer

Limitations with the adiabatic heat pump dryers are reduction in dryer capacity due to the cooling of drying air. At the Norwegian University of Science and Technology and SINTEF a non-adiabatic, two stages, plug-flow fluidised bed heat pump dryer using ammonia as refrigerant was constructed [Jonassen 1994, Strømmen 2000]. A capacity increase of 380% compared to an adiabatic design was achieved in this dryer and the measured maximum SMER was 4.7 kg H_2O/kWh. The drying chamber inlet air temperature was above 100°C in these experiments and measurements where done with herring meal under continuous operation of the dryer.

EXPERIMENTAL

The heat pump dryer has been used for drying of chemical pulps by applying low and moderate temperatures with the aim to enhance the product quality. The drying temperature was chosen to be –15ºC, which is below the pulp freezing point for the pulps and finishing the process at +20ºC. The dried pulp quality parameters assessed were fiber swelling, and tensile strength. The heat pump dried pulps have been compared to non-dried and mill dried pulps. As mentioned before, the water retention value (WRV) is a measure of the fibers ability to swell and it is an empirical measure of a sample of pulp fibers ability to retain water. The WRV value (g/g) corresponds to the amount of water that is present in the pulp after centrifugation with a specified centrifugal force (3000 ± 50 g) and a definite period of time (15 minutes). The swelling is often assessed by plot of a beating curve, in which the measured WRV is described as a function of the degree of beating, given as revolutions in a PFI mill[1]. The WRV value increases directly with the degree of beating due to internal and external fibrillation and delamination of the fiber wall. The tensile strength is the maximum tensile force per unit width that paper and board will withstand before breaking under the conditions defined in the standard test method. The tensile index is used to quantify the strength of a paper and is defined as the tensile strength divided by grammage (which is g/m^2). A test piece of given dimensions (width 15 mm ± 0.1 mm, test length 180 ± 1 mm) is stretched to rupture at a constant rate of elongation using a tensile-testing apparatus that measure the tensile force. The tensile index is used to quantify the strength of a paper. The weak link in paper is not the fiber itself, but the bonds between the fibers, which implies that the tensile index is a measure of the joint strength of fiber or fiber bonding.

The samples were disintegrated before characterization to enabled changes to occur after water removal and reswelling. The laboratory sheets were made according to SCAN-CM 26:99 and the tensile index and water retention values measured according to the methods SCAN P 16:76 and SCAN C 62:00 respectively. The three important parameters in atmospheric freeze-drying are the water activity as a function of water content, sorption isotherm and the specific enthalpy. The water activity was measured using an AQUA LAB cx2 instrument having a small sample test-chamber. The chamber psychrometric conditions are adjusted by rising or reducing the temperature of an aluminum mirror, located above the sample, until the vapor over the mirror surface evaporates or condenses. The specific enthalpy and the initial freezing point were measured with a differential scanning calorimetry, DSC, Perkin Elmer Thermal Analyzing [DSC-7].

RESULTS

Figure 2 and 3 [Heum 2003] shows the plot for water retention value and the tensile index as a function of revolutions in a PFI-mill. The mill-dried pulp has the lowest tensile index value while the non-dried pulp has the highest value in all cases, and represents the reference for quality. The mill dried pulp has the lowest values. The differences between those represent the quality loss with the present drying technology. The intermediate curves represents the new drying technology using two different temperatures (not optimized). Both water retention value and tensile index is increased substantially compared to drying with the present technology. The loss in WRV is reduced by 50% to 70% while the loss in tensile index is reduced with about 50%.

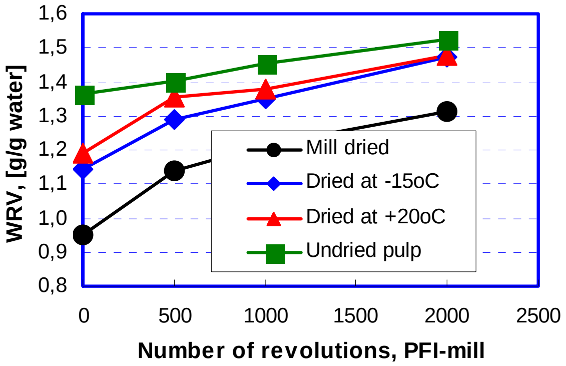

Figure 2 - Water retention value as a function of revolutions in a PFI mill. The heat pump dried pulps are compared to mill dried and never dried pulps.

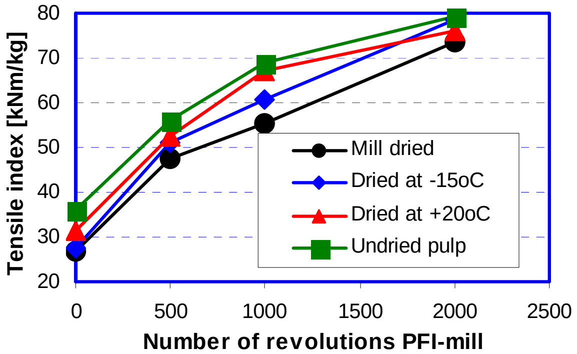

Figure 3 - Tensile index as a function of revolutions in a PFI mill. The heat pump dried pulps are compared to mill dried and never dried pulps.

[1] A PFI mill is a standardized laboratory mill, used to assess effects of milling by the pulp and paper industry worldwide.

In this case the highest WRV and tensile index are achieved at 20ºC drying temperature and not a combined mode drying but the process is still not optimized at this condition. Further experiments will be performed to study the mechanisms linked to improvement of water retention value and tensile index when the chemical pulp is dried at low temperatures. [Lauritzen, 2003]

The sorption isotherm for sulphate and sulphite cellulose is shown in Figure 4.

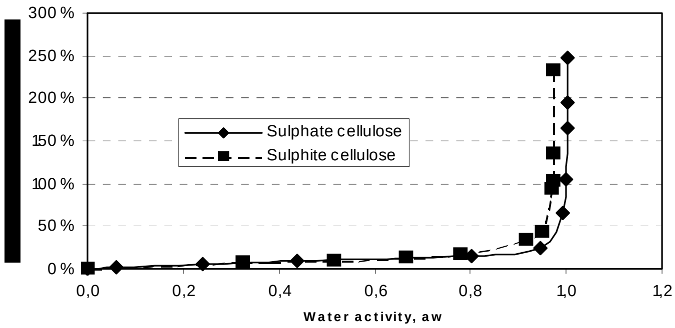

Figure 4 - Sorption isotherms for sulphate and sulphite cellulose

Figures 5 and 6 show the enthalpy curves for sulphate and sulphite cellulose with different levels of moisture content and exposed to temperatures between –30ºC to +30ºC.

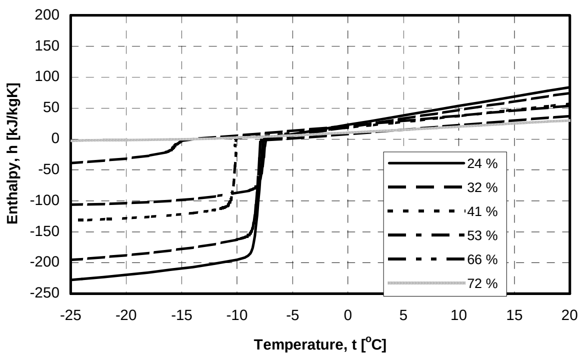

Figure 5 - Specific enthalpy of sulphate cellulose at different water content on wet basis

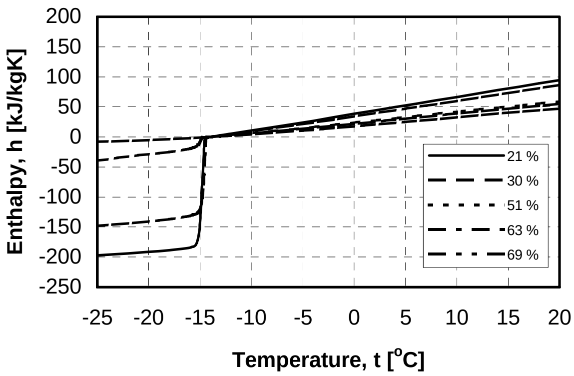

Figure 6 - Specific enthalpy of sulphite cellulose at different water content on wet basis

These figures also present the latent heat of fusion and freezing for both cellulose materials. Figure 5 shows that the freezing points for sulphate cellulose vary between –16ºC to – 9ºC depending on the moisture content. Figure 6 indicates that the freezing point for sulphite cellulose appers to be at –15ºC with negligible depression and nearly independent of moisture content.

MODELLING OF SORPTION ISOTHERMS

The BET and the GAB models are represented in equations (1) and (2). The used models represents well the sorption isotherm for sulphate and sulphite cellulose, respectively.
The BET-equation is given by:

$$\frac{a_w}{(1-a_w)X} = \frac{1}{X_m C} + \frac{a_w (C-1)}{X_m C} \qquad (1)$$

The GAB-equation can be expressed as:

$$X = \frac{X_m C_g a_w}{(1 - K a_w) * (1 + (C_g - 1) K a_w)} \quad (2)$$

Table 1: Constants for the BET and GAB equations:

	BET		GAB		
	X_m	**C**	**X_m**	**C**	**K**
Sulphate	0,0323	55	0,0464	40	0,8503
Sulphite	0,0271	55	0,0238	79	1,004

The measured data and results are plotted in Figure 7 and 8. Figure 7 indicates that there were good agreement between measured data and both BET and GAB models, but GAB equation had a slightly better prediction for the sorption isotherm for sulphate cellulose, especially at moisture content below 20%db. The plots in Figure 7 show similar results using both models, but BET the equation describe better the whole range of sorption isotherm for sulphate cellulose.

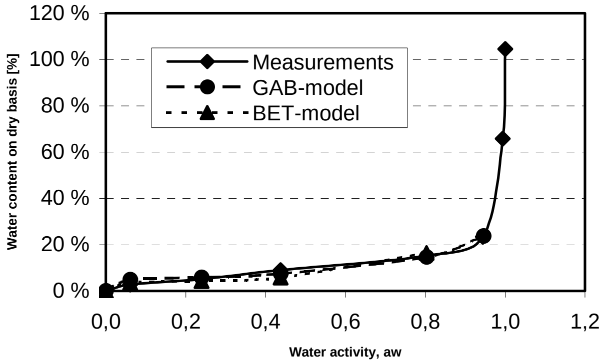

Figure 7 - Experimental and GAB/BET model sorption isotherm for sulphate

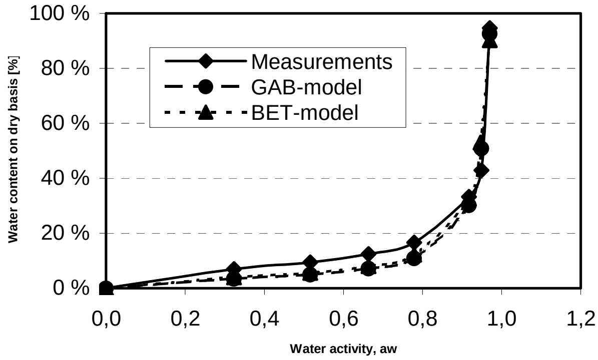

Figure 8 - Experimental and GAB/BET model sorption isotherm for sulphite

DESIGN OF HEAT PUMP DRYING IN COMBINED DRYING MODE WITH DRYING TEMPERATURE BELOW AND ABOVE THE FREEZING POINT

To achieve as high SMER as possible an industrial fluidised bed heat pump dryers should be designed according to the following “design rules”:

- Drying operation with optimum bed height to attain a higher relative humidity at the dryer outlet
- Stable fluidisation due to the sorption characteristics of the material being dried
- Continuous drying process to attain higher capacity and thermal efficiency, behaviour to batch process
- As high inlet air temperature in the dryer as possible for improved thermal efficiency and capacity
- As low refrigeration capacity as possible, as long as the desired production is achieved since over-sizing increases dh/dx and reduces SMER)
- The choice of evaporating and condensing temperature of the heat pump should be a combination that provides the best combination of COP and dh/dx (an optimum might exist).

The energy consumption in a continuous heat pump dryer operated in a combined drying mode at temperatures at -15^{o}C in the first stage and at 20^{o}C in the second stage can be calculated from the following equation:

$$SMER = (COP_{LT}/(dh/dx)_{LT}) * (\tau_{LT}/ \tau_{tot}) + (COP_{HT}/(dh/dx)_{HT}) * (\tau_{HT}/ \tau_{tot}) \quad (3)$$

The calculations were done based on the reference process points obtained in Mollier humid air diagram listed in Table 2.

Table 2: Process conditions for the heat pump dryer operated at combined drying mode

	LT	HT
Air inlet drying temperature	-15 ^oC	20 ^oC
Air inlet relative humidity	40%	40%
Air outlet relative humidity	80%	80%
Surface temperature of air cooler	t_{dp} - 5^oC	t_{dp} - 5^oC
Heat pump evaporating temperature	air cooler surface temperature – 2^oC	air cooler surface temperature – 2^oC
Heat pump condensing temperature	air inlet drying temperature + 5^oC	air inlet drying temperature + 5^oC
Heat pump refrigerant	NH_3	NH_3

The calculations were done and the results are shown in the Figures 9 and 10. Drying at –15^oC for 7 hours will result in 14,4 times higher energy consumptions per kg dry matter compared to drying at +20^oC only and the SMER will be reduced from 4,05 to 0,28 kg water per kWh.

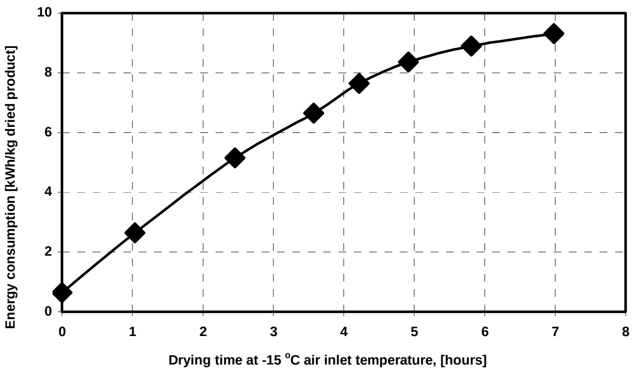

Figure 9 – Dryer energy consumption per kg dried sulphate cellulose with increasing drying time at low temperature

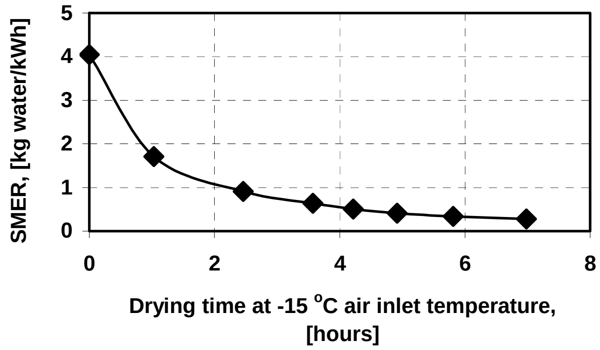

Figure 10 – SMER for dried sulphate cellulose with increasing drying time at low temperature

CONCLUSIONS

The heat pump drying technology was successful applied for drying trials of sulphate and sulphite cellulose using single temperatures of –15^oC and 20^oC. The key quality parameters such as tensile index (TI) and water retention value (WRV) have been measured. A considerable improvement in TI and WRV was achieved at –15^oC and 20^oC compared to industrial dried cellulose. The loss in WRV is reduced by 50% to 70% while the loss in tensile index is reduced with about 50%. The sorption isotherm for sulphate and sulphite cellulose well described by the BET and the GAB models. Step-up temperature drying mode was used to estimate the energy consumption in drying at –15^oC for 7 hours and a final drying at 20^oC will be approximately 14.5 times higher than drying at 20^oC only, with SMER numbers of 4.05 kg/kWh and 0.28 kg/kWh respectively.

NOTATION

a_w	Water activity	[-]
C	Constant	[-]
C_g	Constant	[-]

COP	Coefficient of performance	[-]
dh/dx	Dryer thermal efficiency	[kJ/kg]
K	Constant	[-]
SMER	Specific Moisture Extraction Rate	[kg water/kWh]
Q_o	Energy from air in the cooler	[kW]
W	Work	[kW]
X	Water content	[kg/kg dry matter]
X_m	Water content of monolayer	[kg/kg dry matter]
τ_{tot}	Total drying time	[hours]
τ_{HT}	Drying time at high temperature	[hours]
τ_{LT}	Drying time at low temperature	[hours]

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Calculated from mill data (two different mills)

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SCAN C 62:00, Chemical pulp – Water Retention Value.