MODELLING OF A VISCOSE-FIBRE DRYING PROCESS

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Abstract. A dynamic model of a Through-Air-Drying process for viscose staple fibres was established. In this process fibres are transported through a convective dryer which consists of numerous rotating drum sieves. Finally the fibres pass through two remoistening drums. The structure of the model is modular and scalable, where one drum is one module. By considering one module to be a unique discrete place, the system of partial differential equations (conservation of mass and energy) turns into a system of ordinary differential equations. Therefore, mean values of parameters and states, also as simulation results, are calculated. Drying rates and heat transfer rates are calculated using phenomenological equations for heat and mass transfer. Kinetics of drying is separated into three stages, where viscose fibres are hygroscopic. For sorption behaviour of the fibres the PEK model is applied. The process model is able to simulate transient behaviour of the dryer like changes of the incoming fibre moisture, changes of the drying air temperature and humidity, and changes of the thickness of the fibre layer on the drums. Simulation results of the longitudinal fibre moisture distribution along the dryer show good accordance with measurement data at different operating points e.g. different temperature profiles.

1 Introduction

Convective Through-Air Drying is a highly efficient state-of-the-art drying technology in the paper and textile industry. This technique is applied in processes to remove moisture from materials which can be passed through by air, e.g. porous media like paper or fabric and bulk goods like granulate or fibres. It features an intense contact between drying air and the good to be dried. Therefore, high rates of the simultaneous heat and mass transfer can be obtained.

The goal of this investigation was to construct a mathematical model of an industrial drying process for viscose staple fibres which is suitable for a Model Predictive Controller (MPC). In this thermal process a belt of fibrous web is carried on the surface of so called rotating drum sieves through the dryer. Due to this dryer construction the transportation path of the web has the form like a meander. While carried through the dryer, heated air is sucked through the web by means of a ventilator. After passing the web at each drum the drying air is heated up again by heat exchangers which are fed with vapour or hot water. There are various heating zones, which consist of 3 or 4 drying drums. Therefore, it is possible to expose the good to be dried to a desired temperature profile in order to obtain an optimal product quality and moisture setting.

This type of dryer can consist of numerous drums up to a number of 20 and even more. In this case the loose fibre flakes enter the predryer (8 sieve drums) forming the fibrous web followed by the main dryer (16 sieve drums). Both the predryer and the main dryer are operated in counter current flow with separated air feeds. This means that each of the two parts of the dryer are fed with fresh air, which is not conditioned, from the factory buiding. Figure 1 shows a scheme of the dryer and indicates the mass flow of fibres and air. At the end of the process the fibre belt passes two remoistening drums, where humid air flows through the fibre web, and so a sorption equilibrium between the fibres and the humid air is established. The procedure of slightly remoistening the fibres is used to obtain a higher homogeneity of the desired moisture at the end of the process. After remoistening the fibres they are transported pneumatically. This also can influence the fibre moisture setting noticeable depending on the relative humidity of the transportation air, which neither is conditioned.

There exist a lot of publications about Through-Air Drying. Most of them refer to paper drying and modelling of this process e.g. [1] and [2]. Ghazanfari [3] introduced a drying model for flax fibres using Fick's second law but with no special application. To summarize, there is no literature about modelling drying processes for viscose fibres with distributed drum sieves which leads to a system with distributed parameters

2 Modelling

2.1 Model structure and equations

The structure of the desired model is modular and scalable. This means that a model of a single drum sieve dryer is established in which it is possible to adapt parameters like geometrical values and process or plant parameters. By joining several of these modules it is possible to model the whole drying process. The main equations of the model are balance equations of mass and energy which generally leads to partial differential equations (system

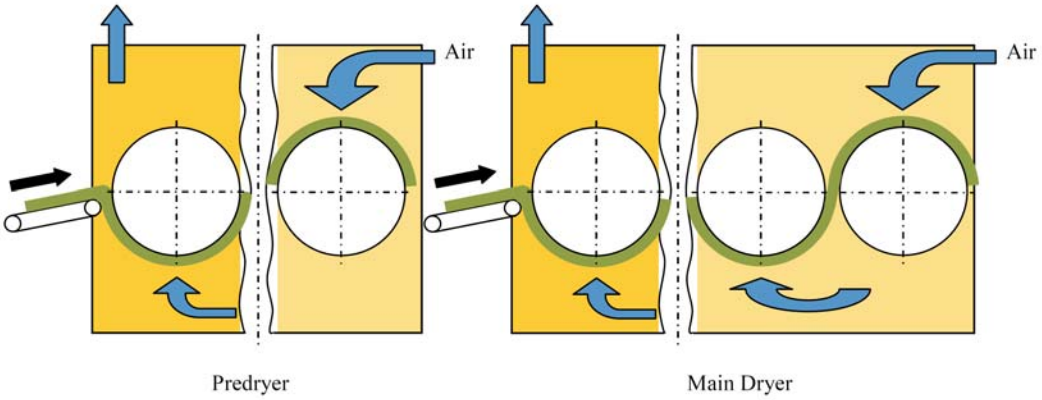

Figure 1: Scheme of the dryer; the transportation path of the fibre belt and the flow directions of the drying air are indicated

with distributed parameters). In order to obtain a system with lumped parameters the model is being discretised. This ensures that the equations turn into common differential equations which can be solved numerically, on the other hand that for calculations always mean parameter and input values are used, and therefore, also the results are mean values for the discrete place. Equation (1) is an example for the ordinary differential equation of the mass balance of water in the fibres. This equation is a nonlinear differential equation, since the term $\dot{m}_D$ is dependent on the actual moisture setting X of the fibres, like shown in equations (4) and (5), and it is also nonlinear in the parameters, because the properties of all media are temperature dependent.

$$\frac{dX}{dt} = \frac{1}{m_F} \cdot [\dot{m}_F \cdot (X_e - X) - \dot{m}_D] \tag{1}$$

In (1) X $[kg \cdot kg^{-1}]$ is the actual state of moisture setting in one discrete place, X_e $[kg \cdot kg^{-1}]$ is the incoming moisture setting of the fibres, m_F $[kg]$ is the mass of fibres in one discrete place, $\dot{m}_F$ $[kg \cdot s^{-1}]$ the mass flow of fibres and $\dot{m}_D$ $[kg \cdot s^{-1}]$ the actual mass flow of evaporating water.

In the actual model one module corresponds to a unique discrete place. This implies that each state of every module has to be passed with correct time delay (dead time) to the next module. Because of this processing time, which the fibre belt needs to pass over one drying drum, for some parameters e.g. the web thickness, an average value, which has to be used as constant for each discrete module (there exists no spacious distribution) for one simulation step, has to be computed.

Therefore, some arrangements have to be made: If there occurs a step of web thickness at the entrance of one module, it is not suitable to pass this new value directly to the mass balance equations which calculate a mean value for outgoing fibre moisture, because this would lead to an immediate step of fibre mass in the drum and therefore to an immediate rise of fibre moisture at the outlet of the drying drum. For that reason an average value for web thickness which passes from the old value to the new value like a ramp function is evaluated. This happens in exactly the processing time τ in which the fibres passes one drum, so it is possible to compute more meaningful fibre moisture values at the drum outlet. Dead time and processing time depend on the belt speed. Figure 2 shows how the new web thickness is calculated by the model. Because of the small web thickness, it is suitable and reasonable to assume the surface of the drum to be flat.

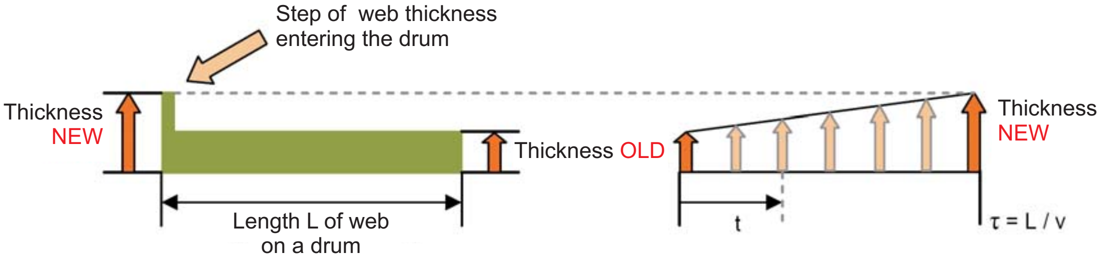

Figure 2: Calculation of changing web thickness; τ is the processing time $[s]$, t $[s]$ the actual time, and v the transport velocity $[m \cdot s^{-1}]$

2.2 Through-Flow Model

To be able to describe the airflow through the web qualitatively and to calculate important dimensionless characteristic numbers (Reynolds, Nusselt, Sherwood) a model of the airflow is necessary. The fibres are described as bulk material with a certain porosity and specific surface. If the porosity is known the velocity of flow can be computed immediately. As an example, with a given porosity of 0,9 the flow rate increases by 1/0,9 in comparison if air would have the completely free space to flow.

The actual drying and heat transfer rates are calculated by phenomenological equations for heat and mass transfer [4]. Gnielinski [5] introduced an equation which enables the calculation of the Nusselt number of a through-flown packed sphere bed by multiplying the Nusselt number of a single sphere with a factor. In mechanical process engineering generally there is a way of calculating an equivalent sphere diameter for goods of other shape [6], where mostly the ratio of length to width of this shape is taken into account. Because of the extremely large ratio of length to diameter (width) of the viscose fibres it seems not reasonable to use such an equivalent sphere diameter and therefore it is not applied to the model. Therefore it is assumed that the drying air passes the fibre web in flow channels or pores with an average diameter, which can be described as a pipe flow. For this reason the Reynolds number can be calculated easily.

2.3 Drying Kinetics

The Sherwood number Sh [-] used in the model for drying from liquid surfaces is given by [7] and shown in Formula (2), where Re [-] is the Reynolds number and Sc [-] is the Schmidt number.

$$Sh = 0.332 \cdot Re^{0.5} \cdot Sc^{0.33} \tag{2}$$

From this result for the Sherwood number it is now possible to evaluate the mass transfer coefficient β $[m \cdot s^{-1}]$ with formula (3), which is then used to calculate the drying rate (see fornula (4)).

$$\beta = \frac{Sh \cdot D}{l} \tag{3}$$

In (3) l is a characteristic length [m], the channel diameter, and D is the the diffusion coefficient $[m^2 \cdot s^{-1}]$.

Viscose fibres are hygroscopic, so generally three different parts of drying kinetics are distinguished [8]. In the first stage of drying, superficial water that evaporates from the surface of the fibres is assumed to be present. In this case the drying rate is expressed as in formula (4).

$$\dot{m}_D = \frac{A \cdot M_w}{R \cdot T} \cdot \beta \cdot p \cdot \ln \frac{p - p_{DL}}{p - p_{DO}} \tag{4}$$

In (4) $\dot{m}_D$ is the actual mass flow rate $[kg \cdot s^{-1}]$ of evaporating water, A the surface $[m^2]$ of the fibres, M_w the molar mass of water $[kg \cdot mol^{-1}]$, R the universal gas constant $[J \cdot K^{-1} \cdot mol^{-1}]$, T the average temperature $[K]$ of the gas layer, β the mass transfer coefficient $[m \cdot s^{-1}]$, p the absolute pressure $[Pa]$, p_{DL} the partial pressure of vapour $[Pa]$ in the drying air, and p_{DO} the partial pressure $[Pa]$ of vapour in the boundary layer to the fibre. p_{DO} depends on the surface temperature of the fibre. Therefore, this temperature is significant for the partial pressure gradient between air and the fibre surface and therefore strongly affects the mass transfer rate. Because of its dependency on air temperature and humidity this so called "wet bulb" temperature is implemented as a two-dimensional look-up table which data (approximate values) are obtained from the Mollier chart. All other data of media are implemented temperature-dependent as well.

The second stage of drying starts when superficial humidity is removed from the good and the water surface draws back into the capillaries of the fibres. The velocity of retraction of the water surface is assumed to be constant. In the mathematical formulation (5) this is regarded with an additional term which describes an extra resistance which vapour has to overcome by diffusion, where s is the length $[m]$ of the actual water free capillary, μ a diffusion resistance coefficient $[-]$, and D the diffusion coefficient $[m^2 \cdot s^{-1}]$.

$$\dot{m}_D = \frac{A \cdot M_w}{R \cdot T} \cdot \frac{1}{\frac{1}{\beta} + \frac{s \cdot \mu}{D}} \cdot p \cdot \ln \frac{p - p_{DL}}{p - p_{DO}} \tag{5}$$

Hygroscopic materials like the viscose fibres have a third stage of drying kinetics, where equilibrium of humidity is established between the good and the surrounding air. In this case, the PEK-model (Parallel Exponential Kinetics) is applied to model the kinetics of sorption [9]. This model (6) assumes the existence of two exponential mechanisms of sorption, a fast and a slow one, which are superposed. The process of remoistening the fibres with humid air and the pneumatic transportation pipes can also be modelled by this sorption model. M_t is the change of mass [%] at any time, M_{inf} the mass change at equilibrium [%], τ the characteristic time constant $[s]$, and t the time $[s]$.

$$M_t = M_{inf1} \cdot (1 - e^{-t/\tau 1}) + M_{inf2} \cdot (1 - e^{-t/\tau 2}) \tag{6}$$

Due to moisture inhomogeneity in the fibrous web, it is not suitable to separate the three stages of drying kinetics exactly. Therefore, they are applied into the drying process model with overlapping sections. The second stage starts when the fibre moisture reaches 85 %. This is the point when viscose fibres are supposed to have no more moisture on the surface, because they swell due to humidity and can absorb up to 85 % water in terms of weight. At approximately 20 % fibre moisture the second stage of drying kinetics begins to fade away and terminates at 10 % fibre moisture. While the second stage is fading away linearly, the third stage, the sorption model, becomes more influence. This is performed due to physical reasons (see above: moisture inhomogeneity) and in order to get a smooth change from the second to the third kinetics model, which is also fitting better the measurement data.

2.4 Model inputs, output and parameters

The following relevant process values are included and therefore regarded in the model of a drum module and are denominated as follows:

1. Input values
    - Moisture setting oft the incoming fibres
    - Mass flow of the fibres
    - Temperature of the incoming drying air
    - Humidity of the incoming drying air
2. Output values
    - Moisture setting oft the leaving fibres
    - Temperature of the leaving drying air
    - Humidity of the leaving drying air
3. Process parameters
    - Volume flow of the drying air (constant, because the engine speed of the ventilator cannot be changed)
    - Carrying speed of the drying drum
    - Geometrical dimensions of the drying drum
    - Porosity of the fibre material
    - Specific surface of the fibre
    - General data of the fibres
    - Data of water
    - Data of air

The classification of the process values to input values, output values, and process parameters is more or less arbitrarily. Both input values and process parameters are data that need to be known in order to be able to simulate the drying process. In this case, the input values are process values that are likely to change during the drying process and therefore of special interest for investigations. They are visible and easily changeable in the graphical surface of the model's software implementation to perform simulations with different setups. Input values are also inputs to the real process so they have a great influence to the drying behaviour and can also be considered to be used as control variables.

The drying model is able to simulate transient behaviour of the process like changes of the incoming fibre moisture, changes of the drying air temperature and humidity, and changes of the thickness of the web of viscose fibres. In (Figure 3) simulation results of such transient procedures for the predryer consisting of 8 drying drums are shown. In the diagram each curve corresponds to the progression of fibre moisture setting over time for one drum.

3 Results and Discussion

The primary goal was to simulate the longitudinal progression of fibre water content through the dryer, knowing the main influence factors on the process like incoming humidity of fibres and drying air as well as the drying temperature distribution along the dryer. Simulation results generally show good accordance with the measured data. In Figure 4 and Figure 5 some measurement data compared to the simulation results are plotted.

For validation of the model it was necessary to make some extra measurements at the real plant. Because there are no online sensors for fibre humidity, samples of fibres were taken from the dryer and their moisture setting was determined gravimetrically. For this reason only a validation of the stationary process has been made, but for different operating points e.g. different fibre types with different drying temperature profile. One uncertainty is that the results of the measurements can vary up to five percent in terms of absolute moisture setting. In the moistener the fibre is remoistened by humid air, which means mass transfer via the gas phase. In this case the sorption model

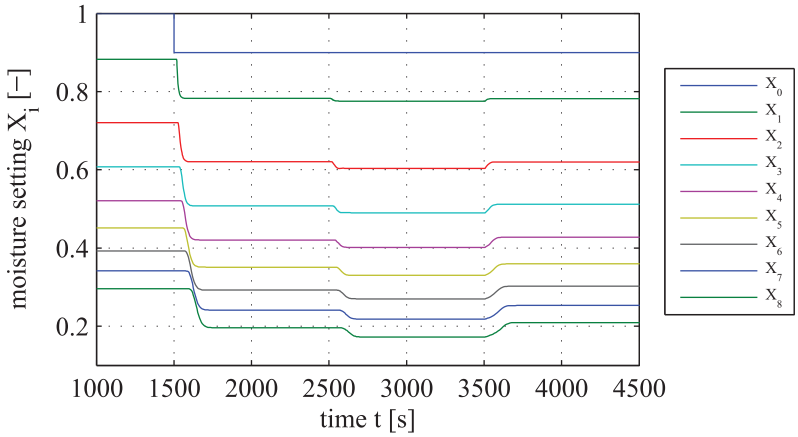

Figure 3: Simulation of transient behaviour; X_0 is the incoming moisture setting of the fibres, X_1 until X_8 is the moisture setting at each drum. At t=1500 s X_0 takes a step to $X_0 = 0.9$, at t=2500 s the fibrous web becomes thinner, and at t=3500 s temperature of drying air decreases by 5 °C at every drum. Moisture settings X_i are normalised.

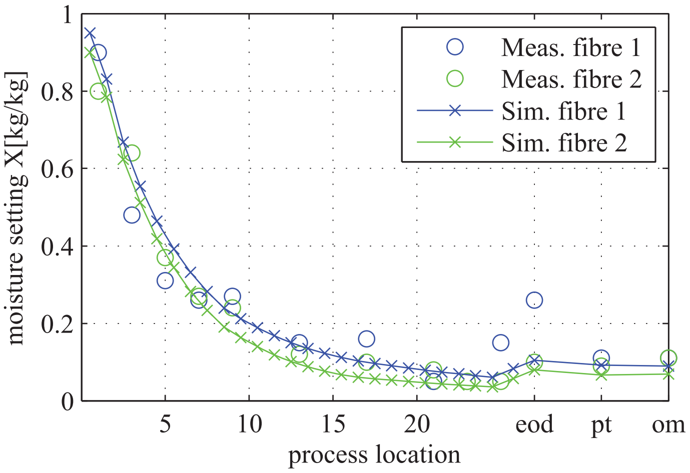

Figure 4: Validation with different fibre types at different operation points

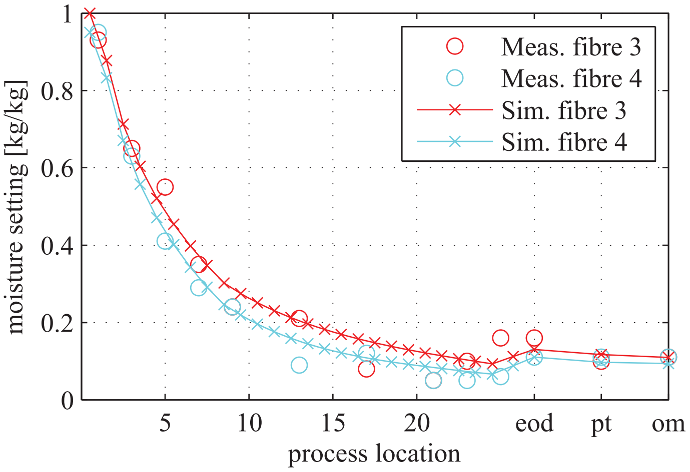

Figure 5: Validation with different fibre types at different operation points; the numbers at the axis "process location" are the numbers of the drums, "eod" means "end of dryer" (after the moistener), "pt" means "pneumatic transportation" , and "om" stands for "online measurement".

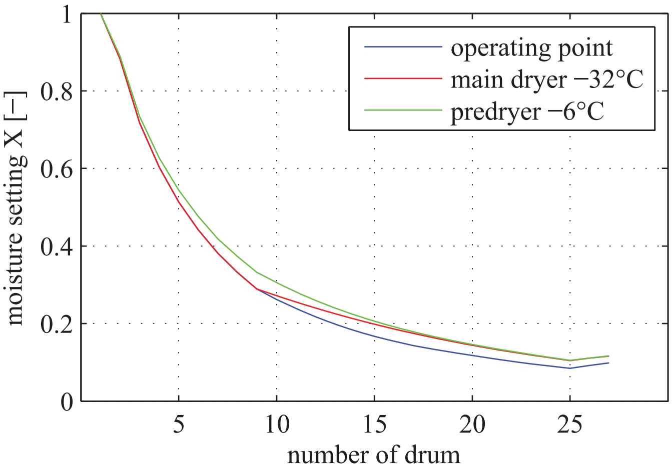

Figure 6: Sensitivity analysis of temperature levels in the dryer; the predryer consists of the drums 1 to 8, the main dryer of the drums 9 to 24.

calculates a light increase of fibre moisture. However, the measurements of the fibre samples generally show a higher moisture level, which in most cases is physically not reachable [10]. The simulation results indicate the possibility that the fibre setting doesn't only rise as expected by mechanism of sorption. One reason for this effect could be that some water in liquid phase goes directly onto the fibres or the flowmeter of the moistener is biased. In order to know more about the behaviour of the moistener some investigations on the plant are currently being performed.

Another result of simulations was a sensitivity analysis how the drying air temperature level has to be reduced in order to obtain 2 % higher moisture setting of the fibres at the end of the drying process. The temperature levels in the predryer and the main dryer were considered. The results are as follows: A decrease of the temperature level of 6 °C in the predryer (high drying rates) has the same effect on the fibre moisture like a decrease of the temperature level of 32 °C in the main dryer. This signifies that the temperature in the predryer has a much stronger influence on the fibre moisture than the temperature in the main dryer. In Figure 6 the different progressions of fibre moisture curves which finally end up with the same end value at drum 24 are depicted.

4 Conclusions

Based on theoretical and practical investigations, a dynamic model of a convective drying process, Through-Air-Drying of viscose staple fibres on sieve drums, was presented. Important properties of the drying drum model are its modularity and its scalability. The system is discretised, therefore the model equations are ordinary differential equations. For the air flow through the fibre web a pipe flow is assumed. Drying kinetics are separated into three stages with different mathematical formulations.

Simulation results of transient behaviour of the drying process and a sensitivity analysis of the drying air temperature level in the predryer and the main dryer are shown. Stationary validation at different operating points (different fibres, different temperature levels) of the process model generally gives a good accordance between the model simulation results and measured data. Due to the fact that measurements of the remoistening drums show an impossible high fibre moisture, this results have motivated that closer investigations in the plant are being performed in order to learn more about the remoistening behaviour of the process.

The established process model is going to be used for model predictions in an Model Predictive Control application. First the model will be liniarised an reduced of order to suit for a quadratic optimisation problem, later on the full nonlinear model will be used. This will turn the control problem into a nonlinear optimisation problem.

5 References

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