Dynamic Modeling and Control Strategies for Retention and Formation on a Paper Machine using a Microparticulate Retention Aid System

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요약

제지 기계의 습부 공정을 안정화시키고, 또한 종이의 지필도에 악영향을 끼치지 않으면서 종이의 기계방향 물성의 변이를 줄이기 위해서, 보류도와 지필도 공정을 동시에 제어하기 위한 제어전략들이 개발되었다.

보류도와 지필도에 미치는 주 변수들에 관한 연구를 양이온성팜(CPAM)/벤토나이트 보류제와 파일럿 제지 기계를 사용하여 수행하였다. 마이크로파티클 보류제 첨가량이 보류도와 지필도에 미치는 영향을 설명하기 위해서 deposition efficiency 모델과 bridging strength 모델을 개발하였다.

제지 기계 보류 공정의 동특성 모델을 질량수지분석을 사용해서 개발하였다. 지료화학 변수의 효과를 모델에 포함하기 위해서, 보류도를 작업조건들에 의존하는 변수로 모델에 포함시켰다. 또한 지필도의 실험적 모델을 개발하고 보류공정을 위한 동특성 모델들과 연계해서 지필도의 동특성을 모사하였다.

여러 제어 전략들이 시뮬레이션상에서 실험되어졌다. 평량과 종이의 회분율 대신에 종이내의 펄프 질량과 충전제 질량을 제어하면 decouper를 사용하지 않고도 두 제어루프간 상호작용을 줄일 수 있음을 보였다. 지필도의 제어를 위해서, 헤드박스 펄프 농도제어와 폴리머유량과 벤토나이트 유량의 비율제어를 제안하였다. 지종 변경시 백수농도의 설정값을 계산하는 문제를 해결하였다. 또한, 평량, 회분율, 백수농도 및 헤드박스 펄프 농도의 다변수제어가 논의되었다.

1.Introduction

Current trends in the papermaking industry involve many process perturbations [1, 2]. At the same time, the market requests higher paper quality at lower cost. Optimization and control of a papermaking process provide a key solution to improve paper quality and production efficiency at the same time. Especially, the control of the wet end of a paper machine has received much attention due to the profound effect on product quality and process efficiency.

In recent years, several on-line sensors for the wet end have been developed, making it possible to measure some of the variables that should be controlled. Several control strategies for the wet end have been suggested and tested [3-7].

However, no satisfying control strategy concerning formation has been suggested yet. Concerning microparticulate retention aids, some fundamental questions have not been clearly answered yet. Most of the existing wet end control strategies utilize a black box approach to model and to control the wet end of papermaking. Although several control strategies suggested to integrate wet end and dry end, no robust strategy is available for simultaneously controlling retention and formation processes. The challenge is to control the machine direction properties of paper without deteriorating formation of paper. The objective of this research was to develop control strategies for the wet end of a papermaking process utilizing a microparticulate retention aid system, focusing on retention and formation processes.

2.Experimental

Experiments were performed on a pilot paper machine (Centre Spécialisé en Pâtes et Papiers, CEGEP in Trois-Rivières, QC, Canada), which is a Fourdrinier paper machine, 76 cm wide, operating typically at a velocity of 40 m/min with a maximum speed of 90m/min. Two types of furnishes were used: softwood bleached kraft pulp (SwBKP), and a mixture of hardwood bleached kraft pulps (HwBKP) and SwBKP (70:30), refined to a freeness of 360 mL CSF. The pH of the furnish was adjusted to 7.5 by adding sodium hydroxide to the stock chests. Precipitated calcium carbonate, PCC, (30 % slurry, Albacar HO) was mixed with pulp at the blend chest (17.5 % filler content in thick stock) for SwBKP. For the mixture of HwBKP and SwBKP, the PCC slurry was diluted to 10 % and injected at the fan pump. A microparticulate retention aid system consisting of a cationic poly(acrylamide)(CPAM) and bentonite was used. CPAM (Allied colloids, Percol 292) of high molecular weight (~5 x 10^6) and with a degree of substitution of 25 mole % was used as received. The CPAM solution was injected at the inlet of the pressure screen and the bentonite solution was added at the screen outlet.

3.ResultsandDiscussion

3.1. Parameters affecting retention

3.1.1. Deposition efficiency

A deposition efficiency model relating filler retention to the dosages of retention aids was developed. The collision efficiency model was extended for a microparticulate retention aid system in term of the deposition efficiency to include the effect of bimodal particles (i.e., fibre and filler) and the polymer transfer from fibre to filler. The deposition efficiency, E_{dep}, is defined as [8]:

$$\begin{aligned} E_{dep} = {} & \gamma_{inh}(1-\theta_{i,F}-\theta_{i,D})(1-\theta_{j,F}-\theta_{j,T})+\gamma_{pol}(1-\theta_{i,F}-\theta_{i,D})(\theta_{j,F}+\theta_{j,T})(1-\mu_j) \\ & +\gamma_{pol}(\theta_{i,F}+\theta_{i,D})(1-\mu_i)(1-\theta_{j,F}-\theta_{j,T})+\mu_i(\theta_{i,F}+\theta_{i,D})(\theta_{j,F}+\theta_{j,T})(1-\mu_j) \end{aligned} \quad (1)$$

where, θ is the surface coverage of polymer, μ is the surface coverage of microparticles on the polymer covered sites, γ_{inh} is the relative bond strength of the interaction between bare fibre and bare filler surfaces compared to that of the microparticle bridging, γ_{pol} is the relative bond strength of the polymer bridging to the microparticle bridging, the subscript i is for the bigger particle (fibre), j is for the smaller particle (filler or fines), $\theta_{i,F}$ is the surface coverage of fresh polymer covered sites on fibre, $\theta_{i,D}$ is the surface coverage of depleted polymer covered sites on fibre, and $\theta_{j,T}$ is the surface coverage of transferred polymer layer on filler. The first part of the equation expresses the inherent interaction between the bare fibre surface and the bare filler surface; the second and the third parts are for the polymer bridging; and the fourth part represents the microparticle bridging.

3.1.2 Effect of deposition efficiency on filler retention

Fig. 1 represents the influence of CPAM on filler retention. When the dosage of CPAM was increased at a bentonite dosage of 3 mg/g (HwBKP + SwBKP), the filler retention linearly increased. In case of SwBKP, the filler retention initially increased with CPAM and then leveled-off after 0.5 mg/g of CPAM at a lower bentonite dosage (1 mg/g), while it slightly increased at a higher bentonite dosage (5 mg/g).

The increase in the filler retention with CPAM for a SwBKP furnish is caused by the increase in the deposition efficiency (compare Figs. 1 and 2). At a bentonite dosage of 1 mg/g, the increase in the deposition efficiency with CPAM dosage is mainly due to the increase in the polymer bridging. At a bentonite dosage of 5 mg/g, the major interaction is the interaction between the bentonite covered fibre surface and the transferred polymer covered filler surface.

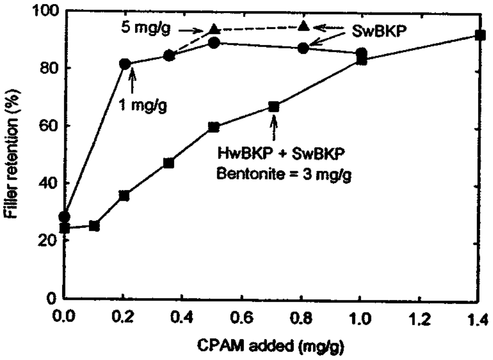

Fig. 1. Effect of CPAM dosage on the filler retention for various bentonite dosages shown in the figure for two different furnishes.

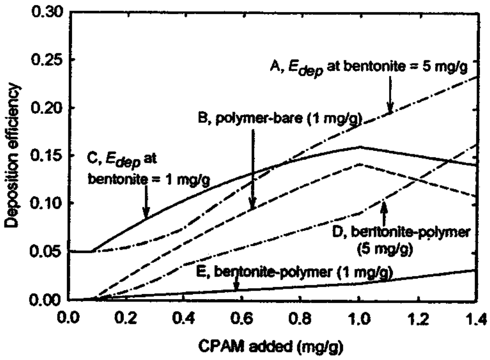

Fig. 2. Effect of CPAM dosage on the deposition efficiency for two bentonite dosages. γ_{inh}=0.05, γ_{pol}=0.2, t_r=0.5 and the maximum coverage by bentonite = 12.5 mg/m^2.

3.2. Parameters affecting formation

3.2.1. Bridging strength

The degree of flocculation is determined by how easily a single fibre can be entrapped inside a floc and how easily a fibre can escape from a floc. Chemical flocculants, consisting of a cationic polymer and a microparticle, provide sticky sites on fiber surfaces and hence increase the bond strength at the fiber-fiber contacts [9]. To relate the dosages of retention aids to the fibre floc strength, a bridging strength model was developed based on interactions between a single fibre and neighbouring fibres in a fibre network. The bridging strength (S_b) is defined as [8]:

$$S_b = \alpha_{inh}(1-\theta_i)^2 + 2\alpha_{pol}\theta_i(1-\theta_i)(1-\mu_i) + 2\theta_i^2\mu_i(1-\mu_i) \qquad (2)$$

where, α_{inh} is the relative bond strength of the interaction between bare surfaces compared to that of a microparticle bridge and α_{pol} is the relative bond strength of the polymer bridge to the microparticle bridge. The first part of the equation 2 expresses the inherent interaction between bare fibre surfaces, the second part describes the polymer bridging and third part the microparticle bridging.

3.2.2. Effect of bridging strength on formation

Fig. 3 shows the influence of bentonite dosage on the formation index (ROD) for various CPAM dosages. At a CPAM dosage of 0.35 mg/g, the formation index (ROD) initially increased with increasing bentonite concentration and then slightly decreased after 1 mg/g of bentonite. At a CPAM dosage of 0.5 mg/g, the formation index also slightly decreased with bentonite. However, at a CPAM dosage of 0.8 mg/g. the formation index significantly increased when the bentonite dosage was increased.

Fig. 4 shows the effect of bentonite on the bridging strength. At CPAM dosages of 0.35 and 0.5 mg/g, the bridging strength decreases with an increase in bentonite dosage. This is mainly due to the decrease in the interaction between bare fiber surfaces and polymer covered sites. At a CPAM dosage of 0.8 mg/g,

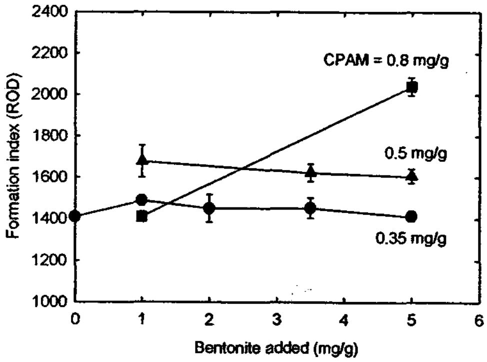

Fig. 3. Efffect of bentonite dosage on formation for various CPAM dosages shown in the figure.

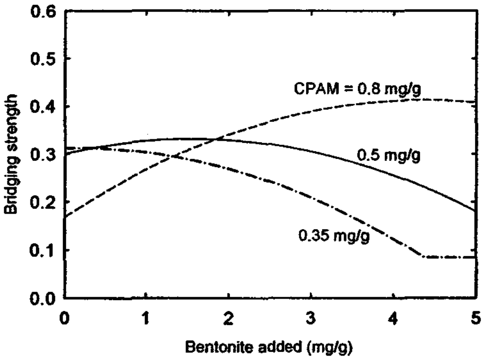

Fig. 4. Effect of the bentonite dosage on the bridging strength for various CPAM dosages indicated in the figure. $\alpha_{inh}=0.2$ and $\alpha_{tol}=0.5$.

most of the fibers are covered with polymer ($\theta_i=0.8$). When the bentonite dosage is increased, there is a significant increase in interactions between polymer covered sites and bentonite covered sites, which contribute to the increase in the bridging strength. At a bentonite dosage of 5 mg/g, the surface coverage of bentonite on polymer covered sites is 0.5 ($\mu_i=0.5$), which provides a maximum interaction by bentonite bridging.

3.3. Dynamic modeling of the retention and formation processes

The mass balance technique was used to model the dynamics of material distribution in a paper machine after the paper machine was simplified to highlight the short circulation loop of white water. To describe the wet end chemistry effect, first-pass retention was included in the model as a parameter dependent on operating conditions. In addition, an empirical model for formation was developed as a function of the crowding number, the bridging strength and the filler fraction in headbox stock and implemented into the dynamic simulation models. The effect of the white water flow rate F_5 on the dynamics of a paper machine is shown in Fig. 5.

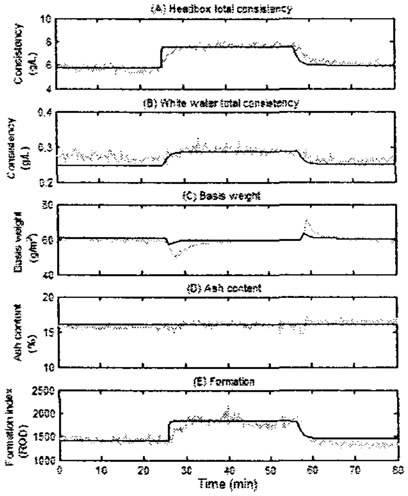

Fig. 5. Effect of white water flow rate on the dynamics of a paper. The black line represents the simulated data and the gray line, the experimental data.

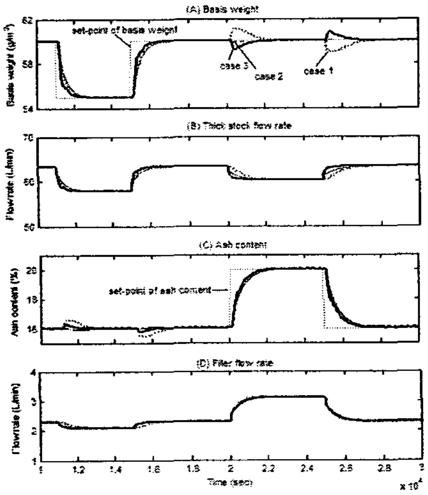

Fig. 6. Comparison of three control schemes for basis weight and paper ash content when the set-point of the basis weight and the ash content are step-changed.

3.4. Control of the retention and formation processes

Basis weight and paper ash content in machine direction (MD) are traditionally controlled by manipulating the thick stock flow rate and the filler slurry flow rate, respectively. Basis weight and ash content have strong cross effects. The interactions between the basis weight and the ash content control loops could be easily eliminated by choosing the pulp mass and the filler mass in paper as controlled variables instead of basis weight and ash content. Fig. 6 compares the responses of a paper machine for the three different control schemes when the set-points of basis weight and ash content are step-changed: (case 1) the basis weight and ash content control without a decoupler; (case 2) the basis weight and ash content control with a decoupler; (case 3) the pulp mass and filler mass control with a static feedforward control. The pulp mass and filler mass control system (case 3) responds slightly faster than the basis weight and ash content control system with a decoupler (case 2).

Fig. 7 compares the responses of a paper machine with a constant bentonite flow to that with a ratio controlled bentonite flow during the white water set-point changes. The only difference is the response of formation. Variations in formation are smaller when the bentonite flow rate is ratio controlled.

During grade changes, the changes in the thick stock flow rate influence both the mass flow rate and the consistency of headbox stock. The variations in the headbox pulp consistency will influence the degree of fibre flocculation and then paper formation. Hence, it is required to keep a constant pulp consistency for a uniform formation while the mass flow rate of headbox stock is varied according to the changes in basis weight. Headbox pulp consistency control was tested through simulation (Fig. 8). In the control system, the headbox valve opening and hence the headbox flow rate is manipulated based on headbox pulp consistency measurements. The variations in formation are considerably reduced when the headbox pulp

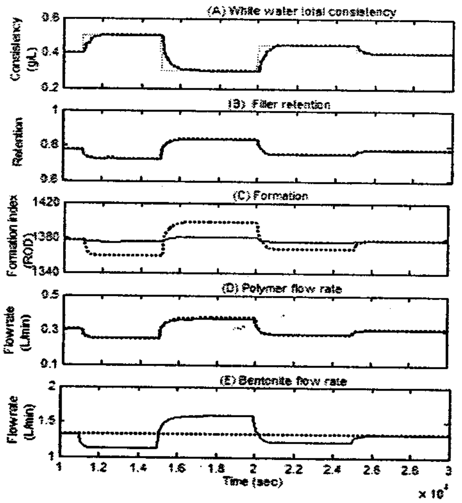

Fig. 7. Comparison between the white water total consistency control with a ratio controlled bentonite flow (solid line) and that with a constant bentonite flow (dotted line).

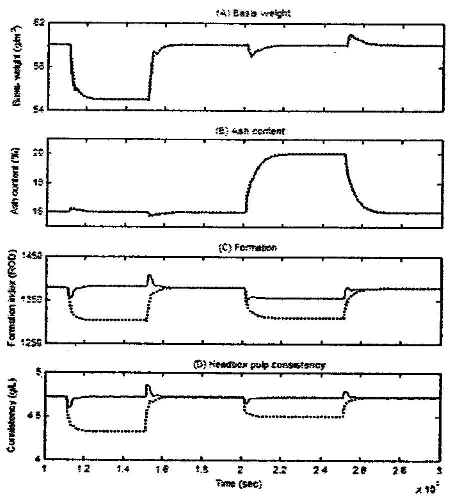

Fig. 8. Effect of the headbox pulp consistency control. Responses of a paper machine to the set-point changes of the basis weight and the ash content with (solid line) and without (dotted line) the headbox pulp consistency.

consistency is controlled.

4.Conclusions

The major parameter affecting first-pass retention is the dosage of cationic polyacrylamide (CPAM) followed by the dosage of bentonite. The effects of the dosages on first-pass retention can be explained by the deposition efficiency model. The two main parameters in the wet end affecting formation are the number of contacts between fibres and the bond strength at the contacts, which influence the fibre floc strength. The effects of the dosages of retention aids on the fibre floc strength and subsequently the formation can be explained by the bridging strength model. Increasing headbox fibre concentration results in the increased contact number between fibres, providing in a stronger fibre floc strength and consequently an impaired formation. A best formation can be achieved, at a given polymer dosage, when microparticles cover all of the polymer covered sites on fibre surface.

The dynamics of the retention process of a paper machine can be modeled from first-principles (mass balances). The effect of wet end chemistry on the retention process dynamics can be described by developing an empirical model for first-pass retention and including it as a parameter dependent on operating conditions. In addition, the dynamics of formation was simulated.

The control structure that controls the pulp mass and the filler mass in paper instead of basis weight and paper ash content can reduce the inherent interactions between basis weight and ash content control loops. Keeping a constant ratio between polymer flow rate and bentonite flow rate helps reducing the variations in formation, while the polymer flow rate is manipulated to control the white water consistency. The problem concerning the determination of the white water consistency set-point during grade changes can be solved by developing an empirical model for the white water consistency as a function of basis weight and ash content. Headbox pulp consistency control helps optimizing paper formation during grade changes. Multi-input multi-out (MIMO) control helps eliminating interactions in the white water consistency control. However, no distinctive advantage is found for the pulp mass and the filler mass control loops.

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