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Simultaneous Water and Energy Optimization for a Pulp and Paper Mill

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In this paper, simultaneous water and energy reduction in a brown stock washing system (BSWS) for an existing pulp and paper mill is analyzed. In the BSWS, seven counter-current washers are used for pulp cleaning, where the dissolved solid (DS) contents in the pulp liquor is reduced prior sending to the bleach plant. Meanwhile, hot steam is consumed in black liquor heating and treatment, as well as delignification process in the oxygen (O_2) reactor. The mass and energy balances of the water network for the BSWS is first simulated with Cadsim, and adopted as the base case of the study. Next, a non-linear programming (NLP) optimization model is proposed to minimize the water and energy consumptions through wash water reuse/recycle. The NLP model is solved using LINGO optimization software. The proposed optimization approach reduces both energy and water consumption requirements in the BSWS significantly. A new water network configuration which achieved the abovementioned utility savings is proposed in this paper.

1. Introduction

In recent decades, the large-scale exploitation of resources i.e. energy and water by the process industries has exacerbated the imbalance between economic growth and environmental protection (OECD, 2008). Being one of the biggest consumers of these resources, the industrial practitioners are urged to adopt sustainable resource management strategies to minimize overexploitation and pollution (UNEP 2009).
Energy is widely used to heat/cool water in the process plants. Energy that is embedded in water creates an inextricable link between both resources in which the conservation of water will directly translate into energy savings (Tellinghuisen, 2009). Process integration technique has been regarded as an effective approach in the context of resource conservation (El-Halwagi, 1997; Smith, 2005). Significant advances were achieved in various process integration techniques such as pinch analysis and mathematical optimization. Several overviews presented recently confirmed the further extensions and developments (Friedler, 2009 and 2010, Klemeš et al 2010). However,

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they have been some important issues to be considered by formulating the problem and implementing the results (Klemeš and Varbanov, 2010).

Previous research has been focused on the development of methodology to integrate heat (Linnhoff, 1993) and water (Bagajewicz, 2000; Foo, 2009) systems separately. Lately, the work is expanded to address simultaneous energy and water minimization for maximum cost reduction. Various works are reported in the application of process integration techniques for simultaneous energy and water reduction in pulp and paper mill. Wising et al. (2005) identify the excess heat in the mill by plotting hybrid curve from grand composite curve. On the other hand, Nordman and Berntsson (2006) introduce "tank curve" to identify the maximum excess heat in the mill using visual basic coding. The most recent work for water and energy efficiency improvements are reported by Alva-Argáez et al. (2008 and 2009), Savulescu and Alva-Argáez (2008). In this work, the water network at the brown stock washing system (BSWS) of an existing pulp and paper mill is optimized. A non-linear program (NLP) is proposed to minimize the total energy and water consumption in the BSWS.

2. Problem Statement

Given a set of washers with fixed flowrates and displacement ratio (DR), it is required to synthesize an optimum washing system by effectively reuse/recycle the filtrate streams in the showers and in the dilution of pulp inlet stream.

An existing BSWS is first simulated on Cadsim and the optimized configuration is served as the base case of this study. Table 1 tabulates the wash water flowrates and displacement ratio obtained from the Cadsim simulation (Bonhivers and Stuart, 2007). As shown in Table 1, there are total of seven washers, which include an extended modified continuous cooking (EMCC) washer, two diffusion washers, decker washer, washer 1, washer 2 and PreDO washer. Note that all washers are arranged in counter-current mode.

Table 1: Washers flowrates and displacement ratio (DR)

Washers	DR	Water flowrates, (kg/t pulp)			
		Pulp inlet D_k	Shower S_k	Filtrate F_k	Pulp outlet P_{k-1}
EMCC	0.65	9457	4998	10505	3950
Diffusion 1	0.90	7612	12494	12852	7254
Diffusion 2	0.90	7254	12494	12494	7254
Decker	0.75	57439	9500	59803	7136
Washer 1	0.70	61981	4500	60681	5800
Washer 2	0.72	71662	6000	70869	6793
PreDO	0.70	71662	6000	71614	6048

3. Mathematical Model

Figure 1 shows the configuration of two washers. Each washer consists of two inlet streams, i.e. shower (with flowrate S_k and concentration C_k^S) and pulp inlet (D_k, C_k^D); as well as two outlet streams, i.e. filtrate (F_k, C_k^F) and pulp outlet (P_k, C_k^P). As shown, filtrate stream of washer k is sent for reuse/recycle in washer k', at shower (point 1) and pulp dilution (point 2). Note that fresh water, *j* is used to make up for shower, $F_{k,j}^{FWS}$ and pulp dilution, $F_{k,j}^{FWD}$.

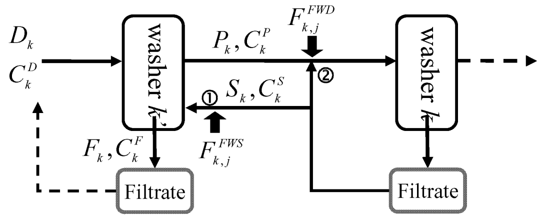

Figure 1: Counter-current washers (flowrate in kg/t pulp; concentration in wt%)

The mathematical model for BSWS optimization is formulated as follows: The objective function is set to minimize the total cost, obj_{COST} as shown in Equation (1). This includes the total fresh water (first term) and energy (second term) costs. It is assumed that the unit cost for fresh water, FW_{COST} is \$ 0.15/m^3 and the unit cost for energy, E_{COST} is \$ 5/GJ.

$$\min obj_{\text{COST}} = \left(F_{\text{FW}} \times FW_{\text{COST}}\right) + \left[\left(H_{\text{Evap}} + H_{\text{Reactor}} + H_{\text{BL}}\right) \times E_{\text{COST}}\right] \quad (1)$$

3.1 Washers Mass Balances

Equations (2) – (5) stated the flowrate balances for shower, dilution point and filtrate, respectively, while Equation (6) is the overall flowrate balance at washer *k*.

$$S_k = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWS} + F_{k',k}^{S} + R_k^S \qquad k, k' \in K \quad (2)$$

$$D_k = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWD} + F_{k',k}^{D} + R_k^D + P_{k-1} \qquad k, k' \in K \quad (3)$$

$$F_k = R_k^D + R_k^S + F_{k,k'}^{D} + F_{k,k'}^{S} + W_k + W_k^R \qquad k, k' \in K \quad (4)$$

$$D_k + S_k = P_k + F_k \qquad k \in K \quad (5)$$

where variables $F_{k',k}^{S}$ and $F_{k',k}^{D}$ denoted reused filtrate in shower and pulp dilution point; variables R_k^S and R_k^D denoted the recycled filtrate which are re-circulated within washer *k*, at shower and dilution point; flowrate variable P_{k-1} represents the pulp liquor from previous washer *k*-1 entering into the next washer *k*; variables W_k and W_k^R indicate the distribution of black liquor from filtrate to evaporator and EMCC washer; variables $F_{k,j}^{FWS}$ and $F_{k,j}^{FWD}$ denoted fresh water *j* that makes up shower and pulp dilution point.

On the other hand, dissolved solid (DS) balances for the shower stream and pulp dilution point are stated in Equations (6) – (7).

$$S_k C_k^S = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWS} + F_{k',k}^{S} C_{k'}^{F} + R_k^S C_k^F \qquad k, k' \in K \quad (6)$$

$$D_k C_k^D = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWD} C_{k,j}^{FWD} + F_{k',k}^{D} C_{k'}^{F} + R_k^D C_k^F + P_{k-1} C_{k-1}^{P} \qquad k, k' \in K \quad (7)$$

Note that the fresh water, *j* is assumed to be free of DS throughout this work.

3.2 Twin Roll Press (TRP) Mass Balance
Pressate from TRP is sent for reuse/recycle and Equations (9) and (10) stated the unit's flowrate and DS balances. The total flow rate of fresh water *j* is given in Equation (11).

$$D_{\mathrm{T}} = \sum_{j \in J} F_j^{FWT} + R_{\mathrm{T}}^{D} + P_{\mathrm{T}}^{in} \tag{9}$$

$$D_{\mathrm{T}} C_{\mathrm{T}} = \sum_{j \in J} F_j^{FWT} + R_{\mathrm{T}}^{D} + P_{\mathrm{T}}^{in} \tag{10}$$

$$F_{\mathrm{FW}} = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWD} + \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWS} + \sum_{j \in J} F_j^{FWT} \tag{11}$$

where variable F_j^{FWT} denoted the fresh water flowrates at TRP.

3.3 Heat Balances
Energy is used to generate hot steam. Hot steam is required for BL treatment at evaporator (H_{Evap}), delignification process at O_2 reactor (H_{React}) and also for BL heating, H_{BL} , as shown in Equations (12) - (14).

$$H_{\mathrm{Evap}} = \left(\sum_{k \in K} W_k - 2900 \right) \times 2200 \div 4 \qquad k \in K \tag{12}$$

$$H_{\mathrm{React}} = F_{\mathrm{R}} \times C_{\mathrm{P}}^{\mathrm{R}} \left(115 - T_R \right) \qquad k \in K \tag{13}$$

$$H_{\mathrm{BL}} = W_k \times C_{\mathrm{P}}^{\mathrm{BL}} \left(100 - T_k^F \right) \qquad k = \text{Diff. washer 1} \tag{14}$$

where variable F_{R} denoted the O_2 reactor flowrate; variables T_{R} and T_k^F denoted the reactor and filtrate temperature. In this work, heat capacity for pulp mat in reactor, $C_{\mathrm{P}}^{\mathrm{R}}$ is assumed 4kJ/kg°C, while heat capacity for black liquor, $C_{\mathrm{P}}^{\mathrm{BL}}$ is assumed 3.5 kJ/kg°C.

Heat balances for showers and pulp dilution point are shown in Equations (15) – (16). Equation (17) states the overall washer flowrate balance. Equations (18) and (19) state the DR parameters in relationship with temperature and DS concentration.

$$S_k T_k^S = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWS} T_j + F_{k',k}^{S} T_{k'}^{F} + R_k^S T_k^F \qquad k, k' \in K; j \in J \tag{15}$$

$$D_k T_k^D = \sum_{j \in J} \sum_{k \in K} F_{k,j}^{FWD} T_j + F_{k',k}^{D} T_{k'}^{F} + R_k^D T_k^F + P_{k-1} T_{k-1}^{P} \qquad k, k' \in K; j \in J \tag{16}$$

$$D_k T_k^D + S_k T_k^S = D_k T_k^D + F_k T_k^F \qquad k \in K \tag{17}$$

$$\mathrm{DR} = \left(T_k^D - T_k^P \right) / \left(T_k^D - T_k^S \right) \qquad k \in K \tag{18}$$

$$\mathrm{DR} = \left(C_k^D - C_k^P \right) / \left(C_k^D - C_k^S \right) \qquad k \in K \tag{19}$$

where variables T_k^S , T_k^D , T_k^F and T_j denoted the stream temperature at shower, pulp dilution point, filtrate and fresh water *j*, respectively.

Note that the fresh water is supplied at two different temperature levels, i.e. 45 °C, 70 °C. Meanwhile, maximum DS concentration is preset at 094 % while temperature of the pulp liquor entering to bleach plant is fixed at 66 °C. Objective function in Equation (1) is solved subjects to the constraints in Equations (2)–(19), which constitute an NLP model. The mathematical model was solved using LINGO Global solver v10.

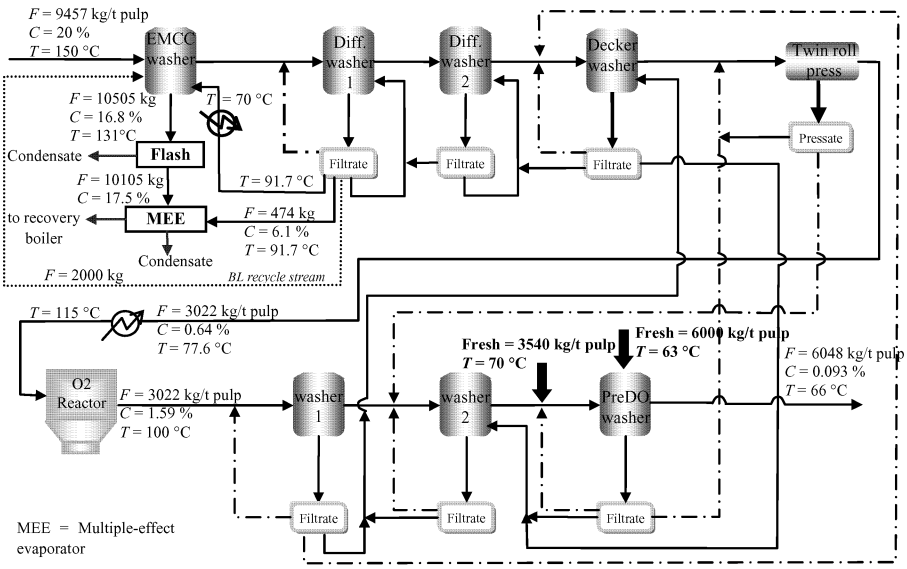

Figure 2: BSWS optimal water network configuration

Optimization results show water and energy reductions of 23 % and 17 %, respectively as compared to the base case. Figure 2 shows one of the possible optimal water network configurations for the BSWS with symbols *F*, *C* and *T* each represent flowrate, DS concentration and temperature. As shown in Figure 2, fresh water is consumed in the final washer (PreDO) at its shower stream (6000 kg/t pulp at 63 °C) and pulp dilution point (3540 kg/t pulp at 70 °C).

4. Conclusions

In this paper, an NLP optimization model is proposed to minimize the water and energy consumptions through wash water reuse/recycle. The optimization result shows that both energy and water consumption requirements of the BSWS are reduced significantly. Future consideration should include the piping cost which takes into account of the distance among the washers.

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