Energy Optimization of a High Consistency Refiner Process

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1. INTRODUCTION

A concept for energy optimization of a high consistency (HC) refining processes in the pulp and paper industry is presented. High consistency refining is an important stage in the production of Kraft paper as it is required to obtain the desired paper properties Brännvall (2004). Refiners as discussed here consist of one rotating disc and one static disc. The pulp is pressed through the narrow gap between both and processed.

Two kinds of models are used for the optimization - one describing the behavior inside the refining zone with an entropy based approach and the other is an empirical model connecting the specific energy to a pulp quality parameter given by the Gurley number. The latter model is also denoted as the quality parameter model.

This optimization uses the specific energy as manipulated variable which is defined as energy consumption per the mass flow rate in the refiner. Optimized variables that should stay close to their desired values are the outlet consistency and the Gurley number. The outlet consistency is defined as the solid fraction of the pulp after the refiner. Moreover, the Gurley number is a measure for the air resistance of the produced sack paper and is defined by the time required by 100 ml of air to flow through a test sample of paper with an area of 6.45 cm². Its model was provided by industrial partners based on experiments performed by Fridén et al. (2006). The outlet consistency is determined by using a refiner model which is based on the entropy model by Eriksson (2005). However, the model is extended for the current optimization. Under certain assumptions a predetermined temperature distribution in the refiner is used to calculate various thermodynamics properties like enthalpy, entropy, saturation pressure of steam.

The optimization permits to adjust the inlet consistency to a fixed value and getting the corresponding solution. While keeping the energy consumption as low as possible, it is still attempted to keep outlet consistency and Gurley number close to its desired value. An important parameter in the model is the temperature profile since it has a large influence on the steam creation in the refining zone as

presented by Höhn and Birk (2013). Here the temperature profile is generated by a cubic approximation between the inlet, maximum and outlet temperature for different radial positions. Discretizing the refining zone over the radius yields four algebraic equations for the mass flow rates of steam, water and fibers in each radial element.

2. OPTIMIZATION PROBLEM

A convex optimization procedure is used which involves a cost function with quadratic terms and takes squares of deviations from the desired quality parameters to minimize the specific energy. Its cost function is given below:

$$J = (SE)^2 + \bar{W}_1 \left(\frac{C(r_1)}{1 - C(r_1)K_1SE} - C_{SP} \right)^2 + \bar{W}_2 (K_2(SE - SE_0) + Gu_0 - Gu_{SP})^2 \quad (1)$$

The optimization problem has been solved using both analytical and numerical approaches. Analytically the solution can be obtained by using the first derivate of the cost function and equating it to zero. Respective expressions can be found below:

$$\frac{dJ}{dSE} = aSE^4 + bSE^3 + cSE^2 + dSE + e, \quad (2)$$

where the coefficients can be written as expressions of $C(r_1)$, C_{SP} , ΔGu , K_1 , K_2 , $\bar{W}_1$ and $\bar{W}_2$:

$$a = -2C(r_1)^3 K_1^3 (K_2^2 \bar{W}_2 + 1) \quad (3)$$

$$b = 2C(r_1)^2 K_1^2 (C(r_1) K_1 K_2^2 SE_0 \bar{W}_2 + 3K_2^2 \bar{W}_2 - C(r_1) \Delta Gu K_1 K_2 \bar{W}_2 + 3) \quad (4)$$

$$c = -6C(r_1) K_1 (C(r_1) K_1 K_2^2 SE_0 \bar{W}_2 + K_2^2 \bar{W}_2 - C(r_1) \Delta Gu K_1 K_2 \bar{W}_2 + 1) \quad (5)$$

$$d = 2(3C(r_1) K_1 K_2^2 SE_0 \bar{W}_2 + K_2^2 \bar{W}_2 - 3C(r_1) \Delta Gu K_1 K_2 \bar{W}_2 + C(r_1)^3 C_{SP} K_1^2 \bar{W}_1 + 1) \quad (6)$$

$$e = -2(K_2^2 SE_0 \bar{W}_2 - \Delta Gu K_2 \bar{W}_2 + C(r_1)^2 C_{SP} K_1 \bar{W}_1 - C(r_1)^3 K_1 \bar{W}_1) \quad (7)$$

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3. EXPLICIT AND NUMERICAL SOLUTION

The complete solution can then be determined by using the solution equation for a quartic function:

$$SE_{1,2} = -\frac{b}{4a} - S \pm \frac{1}{2} \sqrt{-4S^2 - 2p + \frac{q}{S}} \quad (8)$$

$$SE_{3,4} = -\frac{b}{4a} + S \pm \frac{1}{2} \sqrt{-4S^2 - 2p - \frac{q}{S}} \quad (9)$$

$$p = \frac{8ac - 3b^2}{8a^2} \quad (10)$$

$$q = \frac{b^3 - 4abc + 8a^2d}{8a^3} \quad (11)$$

$$S = \frac{1}{2} \sqrt{-\frac{2}{3}p + \frac{1}{3a} \left(Q + \frac{\Delta_0}{Q} \right)} \quad (12)$$

$$Q = \sqrt[3]{\frac{\Delta_1 + \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}} \quad (13)$$

$$\Delta_0 = c^2 - 3bd + 12ae \quad (14)$$

$$\Delta_1 = 2c^3 - 9bcd + 27b^2e + 27ad^2 - 72ace \quad (15)$$

Further analysis of the solution can be done using a gradient based approach. Among the four solutions only one gives a physical solution for specific energy, i.e. the other three solutions lie either outside a reasonable range or render in complex numbers. Evaluation of the solution shows that the used parameters in the solution have a higher influence compared to the introduced weighting factors. Among the two weights the value of W_1 has a very small impact on the solution compared to W_2 . The explicit solution is compared for distinct points to a numerical optimization using a global search algorithm and interior point method. Details of the utilized optimization algorithms can be found in publications by Glover (1998), Byrd et al. (1999) and Byrd et al. (2000).

4. CONCLUSION

Optimization results from both approaches are compared and found to match closely with each other. It resulted in a reduction of energy from currently applied 250 kWh to 247 kWh. Moreover, it is found that the relative deviation in Gurley number is half of the relative deviation of SE. Hence there exists a potential for a reduction of energy consumption. Additionally, the explicit solution provides a simple and fast solution to determine the optimal specific energy for selected values of outlet consistency and Gurley number.

NOTATION

Symbol	Explanation
SE	specific energy (work per tonne applied to pulp)
SE_0	specific energy at operating point
C	consistency (solid mass fraction of pulp)
C_{SP}	desired consistency for optimization
C_{out}	consistency at outlet (solid mass fraction of pulp)
r_1	inner radius of refiner segments
r_2	outer radius of refiner segments

Symbol	Explanation
Gu	Gurley (Pulp Quality Parameter)
Gu_{SP}	desired Gurley (Pulp Quality Parameter) for optimization
Gu_0	operating point for the pulp quality model
ΔGu	difference between operating point and desired value for the pulp quality model
a, b, c, d, e	coefficients in the explicit solution
$\bar{W}_1$	weight for consistency term
$\bar{W}_2$	weight for gurley term
K_1	constant for temperature profile
K_2	constant from the pulp quality model

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