Simulation and optimization of steam generation in a pulp and paper mill

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Abstract: A mathematical process integration model for the steam generation part (recovery boiler, bark boiler, and turbine) was developed based on a pulp and paper mill in the Northern Sweden. The material and energy balances were calculated theoretically and then the operation data from a pulp and paper mill in the Northern Sweden were used to validate the simulation results. By implementing it into the whole plant, the effect of the operation conditions on the whole plant performance were investigated. The introductory studies were carried out with an objective function to minimize the energy cost. The influence of different parameters was rigorously studied. The correlation between economic and energy optima was discussed.

Keywords: *Pulp and Paper Mill, Steam Generation, Simulation, Optimization*

1. Introduction

The pulp and paper industry is a very energy-intensive industrial sector where it is crucial to improve the material and energy efficiency to the greatest possible extent. Process integration methods represent useful tools for evaluating possible process alternatives. Many process integration studies in the pulp and paper industry have previously been carried out mainly by using Pinch analysis[1,2] and mathematical programming[3,4]. However, the scope of modeling and simulation of the energy and material balances is not as complete as it is in other modern process industries. More detailed work is required especially as large efforts are currently put on turning pulp mills into bio-refineries.

Based on the mixed integer linear programming (MILP) combined with ReMIND[5] and CPLEX[6], mathematical process integration models of steelmaking industries have been developed in our research groups. The developed model has been successfully applied, for example to give suggestions on choosing a new blast furnace, to reduce the CO_2 emission by using alternative production routines, etc[7,8]. Recently, the research work has been extended to mining industries also[9,10].

To extend researches to pulp and paper mill, a complete plant model was developed based on a pulp and paper mill in the Northern Sweden and described briefly in our previous work[11]. In this work, a mathematical process integration model for the steam generation part (recovery boiler, bark boiler, and turbine) was developed in which the material and energy balances were performed theoretically and the operation data (measurements) from the mill were used to validate the model results, which was presented in detail. By implementing it into the complete plant model, the effects of the operation conditions in the steam generation part on the whole plant performance were investigated. Furthermore, introductory studies were carried out with the main objective to minimize the energy cost, and the correlation and differences between economic and energy were also discussed.

2. Process description and model construction

The pulp and paper mill in the Northern Sweden is illustrated in Fig. 1. The lignin is removed to produce the brightness pulp by passing through the digester, O_2 delignification, and bleaching plant. Paper is produced from pulp in paper making section. The by-product extracted from pulping chips in the digester, i.e. the black liquor, is concentrated in a multi-effect evaporation plant and burned in a recovery boiler (RB) where the combustion of organics provides energy and recovers chemicals which are used to generate the solution of NaOH and Na_2S by passing through the causticizing plant. Bark boiler (BB) provides additional high pressure steam to satisfy the steam demand for the whole plant. The high pressure steam produced in the RB and BB is expanded in a steam turbine producing process steam of 10 and 4 bar. Steam of 30 bar is extracted from the turbine for soot-blowing in the RB and steam 10 bar is used for soot-blowing in the BB. Biomass in form of bark or forest residues and fuel oil are used in the BB. Fuel oil is also used to start up the RB.

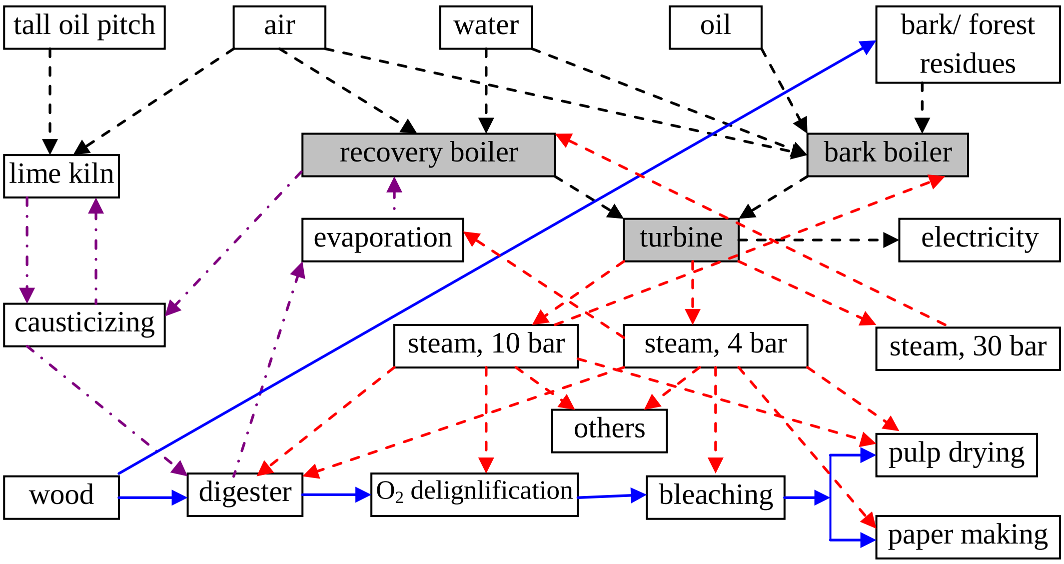

Fig. 1. Schematic representation of the pulp and paper mill.

To perform the process integration, each process unit was modeled as separate modules and thereafter linked. The construction of modules was based on a mathematical programming, i.e. mixed integer linear programming (MILP), and the equation editor used was a Java based programming — ReMIND[5]. In ReMIND, the model structure is represented as a network of nodes and branches, which represent process units and energy/material flows, respectively. The different nodes are connected depending on the input and output to/from each process unit. Each node contains linear equations to express the energy and mass balances required in the process unit. There are two options to express the energy and mass balances for each node, i.e. representing theoretically (option one), or obtaining an equation from the operation measurement under a set of conditions (option two). We chose the option one. The steam generation part including RB, BB, and back pressure turbine is the heart of energy utilization in the plant, and it was studied in the present work.

For RB and BB (boilers), the energy and mass balances were estimated from the chemical compositions of the fuels, the effective heat value of the fuels (H_{eff}) and the corresponding thermodynamic properties of all the related flows. This has been described in detail in literature[12] under operation conditions, such as the temperature of water, air, and flue gas, and the temperature and pressure of steam generated. From the chemical composition of the fuel and the amount of the excess air, the air demand and the amount of flue gas were calculated based on the mass balances. The fuel demand (ton fuel/ ton steam) was calculated from the air demand, the amount of the flue gas, the heat value of fuels together with conditions for the air, flue gas, water and steam. The principle was briefly summarized in Fig. 2, and the brief description was given in the following text. The properties of the fuels and the related heat capacities were taken from public references and listed in Tables 1 and 2, respectively.

Table 1. Properties of fuels.

	C	H	O	S	Na	K	Slagg	N	H_2O	$H_{eff,dry}$, kJ/kg
black liquor	36.4	3.7	34	5.2	19.9	0.8	0	0	0	12400
fuel oil 5	85.9	11.4	0.9	1	0	0	0.03	0.3	0.5	40700
forest residues	51.9	6.15	40.5	0.02	0.05	0.3	0.86	0.22	0	19300

Table 2.Heat capacity.

substance	heat capacity (kJ/(kgK))		heat capacity (kJ/(Nm^{3}K))
black liquor	3.74	air	1.29
Na_2CO_3	1.09	flue gas	1.40
Oil	1.92		
bark	2.97		

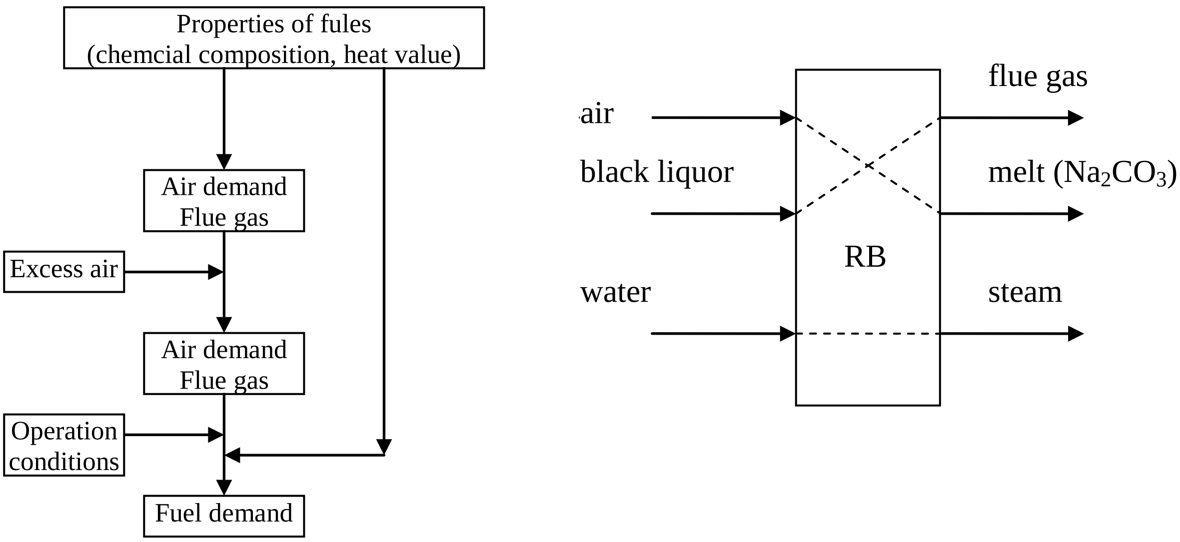

Fig. 2. Schematic representation of mass and energy balance for RB and BB.

$$f_{air,\min} = 22.7 \cdot \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_S}{32} - \frac{w_O}{32} \right) \quad (1)$$

$$f_{air} = f_{air,\min} \cdot (100 + c\%)/100 \qquad \text{m}^3\text{(n)/kg dry fuel} \quad (2)$$

$$f_{flue\ gas} = 22.7 \cdot \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_{H_2O}}{18} + \frac{w_S}{32} + \frac{w_N}{28} \right) + f_{air,\min} \cdot \left(\frac{0.791}{0.209} + c \right) \text{m}^3\text{(n)/kg dry fuel} \quad (3)$$

where *f* is the flow rate, *w* is the composition in mass fraction, and *c* is the excess air in percentage. The flow rate of the flue gas in Eq. (3) is based on the assumption that all the elements of C, H, S, N will leave the boiler as the flue gas. However, in some case, some elements may leave the boiler more than one form. For example, in the recovery boiler, the elements of C and O leaves boiler as the flue gas and melt in the form of Na_2CO_3. In this case, the following equation was used:

$$f_{flue\ gas} = 22.7 \cdot \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_{H_2O}}{18} + \frac{w_S}{32} + \frac{w_N}{28} \right) + f_{air,\min} \cdot \left(\frac{0.791}{0.209} + c \right) - f_{CO,melt} \qquad (4)$$

where $f_{CO,melt}$ is the consumption part because the element of C and O leaves in the form of Na_2CO_3 ($Na+C+O \rightarrow Na_2CO_3$). To calculate the flow rate of Na_2CO_3, the totally amount of Na is assumed to be the summation of those for Na and K. Based on the mass balance, we got Eq. (5) in which *TS*% is the dry content of black liquor, and we assumed the same flow rates for water and steam, i.e.: $f_{water} = f_{steam}$.

$$f_{Na2CO3} = 0.53 \frac{(w_{Na} + w_K)}{\left(1 + \frac{1 - TS\%/100}{TS\%/100} \right)} \qquad \text{(kg/kg wet fuel)} \qquad (5)$$

To represent the energy balance, the reference temperature was chose as 20 °C, and the enthalpy for the components except water and steam at a certain temperature was calculated with the Eq. (6) where f is the flow rate, C_p is the heat capacity, and t is the temperature in °C:

$$h = fC_p(t - 20) \qquad (6)$$

In ReMIND, the equation representing mass and energy balances should be linear, while the enthalpy of water or steam depends on both temperature and pressure. Therefore, the enthalpies of water/ steam at different temperatures and pressures were calculated firstly from the NIST online database[13] and then the calculated enthalpies were fitted to an equation that is a function of temperature and pressure by assuming the pressure effect is a linear. The fitted equation was input in the equation editor in ReMIND. For water, we obtained:

$$h = (4.2354t + 0.892) + (0.1008 - 2.51 \times 10^{-4} t)(P - 75) \qquad \text{(kJ/kg)} \qquad (7)$$

where P is the pressure in bar. For high pressure steam (60 bar), we obtained:

$$h = (2216.2 + 2.4309t) + (7.76 \times 10^{-3} t - 4.94)(P - 55) \qquad \text{(kJ/kg)} \qquad (8)$$

The total energy balance for the RB was:

$$h_{air} + h_{blackliquor} + f_{water} h_{water} + f_{blackliquor} \cdot h_{heatvalue} + h_{heatloss} = h_{fluegas} + h_{melt} + f_{water} h_{steam} \quad (9)$$

For the BB, we neglected the energy in ash, and the flow rate of the flue gas was calculated with Eq. (3), and total energy balance was:

$$h_{air} + h_{fuel} + f_{water} h_{water} + f_{fuel} \cdot h_{heatvalue} + h_{heatloss} = h_{fluegas} + f_{water} h_{steam} \qquad (10)$$

The mass and energy balances for the turbine are much easier to generate compared to those for the boilers. The enthalpies of steams were obtained with the same method as those in the boilers, and results for medium pressure steam (30bar), low pressure steam at 10 bar, and low pressure steam at 4 bar were shown as Eqs. (11), (12), and (13), respectively.

$$h = (2313.5 + 2.3058t) + (1.395 \times 10^{-2} t - 7.15)(P - 28) \quad \text{(kJ/kg)} \quad (11)$$

$$h = (2400.1 + 2.1856t) + (2.910 \times 10^{-2} t - 11.00)(P - 9) \quad \text{(kJ/kg)} \quad (12)$$

$$h = (2443.9 + 2.1157t) + (8.06 \times 10^{-2} t - 20.5)(P - 3) \quad \text{(kJ/kg)} \quad (13)$$

The material and energy balances for the turbine were:

$$f_{60bar} = f_{30bar} + f_{10bar} + f_{4bar} \quad (14)$$

$$f_{60bar} h_{60bar} \eta = f_{30bar} h_{30bar} + f_{10bar} h_{10bar} + f_{4bar} h_{4bar} + EL + h_{loss} \quad (15)$$

where the flow rate of the 30 bar steam was obtained from the plant, and η is the mechanical efficiency, and h_{loss} is the heat loss, and *EL* is the electricity generation in MW.

3. Model validation and process integration

The developed model for the steam generation part was implemented into the complete plant model in our previous work[11]. By running the process integration model for the complete plant, the model results were compared with the operation measurements for the model validation. To run the process integration model, an objective function has to be set. In the present work, the objective function was the minimization of the energy cost for the studied pulp and paper mill, and the prices of fuels and electricity used were the same as those we set in our previous work[11].

3.1. Model validation

For the RB, by assuming the heat loss 3.5% and 5% excess air with a certain flow rate of black liquor, the process integration was carried out. The steam generation calculated from model is 220.9 ton/h which is 3.8% higher than the measurement from the mill. For the BB, by assuming the heat loss 3.5%, 5% excess air and 45% dry content of bark, the ratio of the steam generation to bark consumption (dry) calculated from the model is 5.15 ton steam/ ton dry bark, and the corresponding measurements from the mill is 6.07 (ton steam/ ton dry bark). The discrepancy for the BB may be from assumption of the dry content of bark. Generally, the dry content of the bark is from 40 to 50%, and the bark consumption increases with increasing water content of bark. For the turbine, by assuming the mechanical loss 5%, the model calculation agrees well with measurements.

3.2. Process integration

The running of the BB is to satisfy the process steam demand for the whole plant. The operation conditions in the RB will affect the energy consumption for the RB itself, and then affect the performance of the BB. While the operation conditions in the BB will only affect the performance of the BB.

For the RB, the temperature of the flue gas, the temperature of the liquid into the RB, the temperature of the water into the RB, the amount of the access air, the temperature of the air, the water content of the liquor, and the heat loss of the RB will affect the steam generation from the RB. Since the RB is insulated well, the heat loss may be in the range of 1 to 5%. Meanwhile, the amount of the excess air may be from 5% to 15%. The model calculation results show that the variations of these two operation conditions do not affect the performance of the RB a lot, and the discussions were not shown. In addition, the influence the water content of the liquor to the RB has been discussed in our previous work[11].

Fig. 3 illustrates the influence of the temperature of the flue gas on the performance of the RB and the BB. The utilization of the waste heat from the flue gas is very promising. If the temperature of the flue gas decreases from 250 to 125 °C by using heat exchanger to exchange the heat with flows to the RB, the steam generation will increase from 215 to 232 ton/h, and the corresponding bark consumption (wet basis) will decrease from 22.6 to 15.6 to/h. How to utilize the waste heat is a big challenge, and the following text will give the discussion.

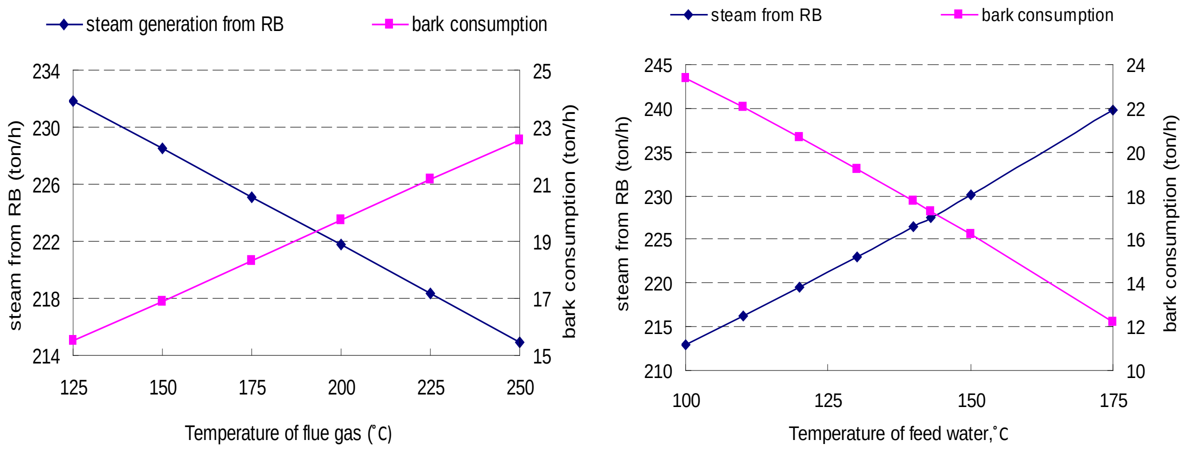

Fig.3. The effects of temperature of flue gas and feed water on the performance of the RB and the BB.

The influence of the temperature of the water on the performance of the RB is also shown in Fig. 3. If the temperature of water increases from 100 to 175 °C, the steam generation from the RB will increase from 213 to 240 ton/h, and the corresponding bark consumption will decrease from 23 to 12 ton/h. This is one possibility to utilize the waste heat in the flue gas. Sometimes, the waste heat from flue gas may not be enough to preheat water, which means that how to reasonably use the waste heat for the whole plant to preheat water is a vital issue to save the energy. On the other hand, the improvement of process performance by adding new heat exchangers and/or changing the existing routines always requires additional investment. It is worth or not? The model results can provide the possibility for the process improvement, and then make the cost estimation to help people to make a decision, which is just the goal of our work.

The temperature of the liquor to the RB will affect the performance of the RB and BB. When the liquor leaves from the evaporation plant, the temperature of the liquor is around 125 °C. From the energy point of view, if the temperature of the liquor can be further increased, the steam generation from the RB will be increased obviously as shown in Fig. 4. However, from the practice point of view, the temperature of the liquor should be lower than the boiling temperature of the liquor which is around 130 °C. Because of this reason, the insulation of the pipe for the black liquor distribution from the evaporation plant to the RB is very important. For example, if the black liquor is cooled to 100 °C to enter the RB, the steam generation will decrease to 3.5 ton/h and the bark consumption will increase 1.5 ton/h compared to 130°C.

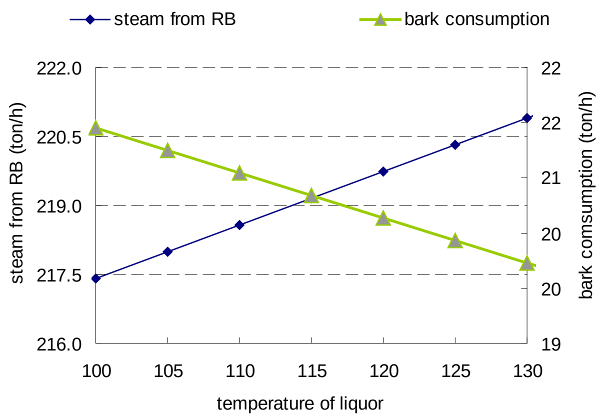

Fig.4. The effect of the temperature of the liquor on the performance of RB and BB.

For the BB, the influences of the temperature of the flue gas, the temperature of the water into the boiler, the amount of the excess air, the temperature of the air, and the heat loss of the boiler on the performance of the BB is the same as those for RB. The effects of the temperature and the water content of the bark are illustrated in Fig. 5, respectively. The increases of temperature of the bark will decrease the bark consumption. Although the energy saving is not so obviously, but it should be very easy to increase the temperature of the bark from 20 to 80 °C. On the contrary, the effect of water content on the bark consumption is considerable, and this explains the possible reason for the discrepancies of the model results from the measurement in model validation part.

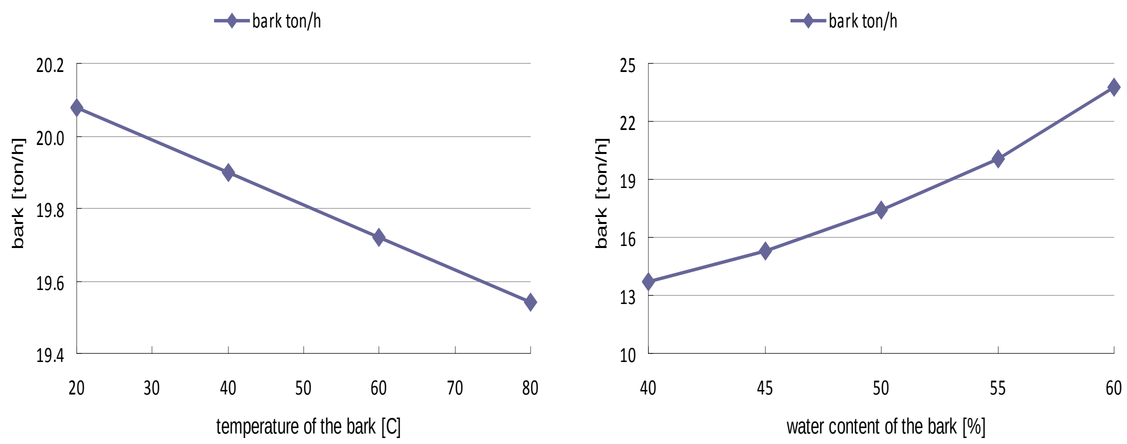

Fig.5. The effect of the temperature and water content of the bark on the performance of BB.

4. Conclusions

A mathematical process integration model for the steam generation part was developed. The material and energy balances were obtained theoretically. The model of the steam generation part was implemented into the previous developed whole plant model, and the model results of the steam generation part were validated with the operation data by running the process integration model with the low energy cost as the objective function. The effects of the operation conditions in the steam generation part on the whole plant performance were investigated. It shows that the utilization of the waste heat from the flue gas to increase the temperature of the feed water into the boiler is an option to decrease the bark consumption, and the insulation of the pipes for the black liquor distribution from the evaporation plant to the RB is very important. For the BB, the water content of the bark affects the bark consumption considerably.

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