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Energy System Diagnosis and Analysis with "Three-Links" Models in Pulp and Paper Mill

Li Jigeng[1], Liu Huanbin[1], Yin Yongjin[1], Tao Jinsong[1], Kong Lingbo[1], Li Yugang[1], Jia Jingjiang[2]

[1]South China University of Technology, State Key Laboratory of Pulp and Paper Engineering

Wushan Road, Guangzhou, China, 510640

Email: Jigengli@scut.edu.cn

[2]Gold East Paper (Jiangsu)Co.,Ltd.

8Xing Gang Dong RD., Dagang, ZhenJiang, JiangSu, China, 212132

Email: j.j.jia@goldeastpaper.com.cn

Abstract: The methodology of Three-Links is introduced in this paper, and Three-Links model in pulp and paper mill is established based on the research on the energy system of mills. The method is applied to a coating pulp and paper mill. The energy consumption of the system of the mill is reduced and both the energy efficiency and the exergy efficiency are improved after optimization and retrofitting. Three-links model help the mill implement the optimization and retrofitting from the system point of view and realize the global optimization of energy system finally.

Key words: Energy System Analysis, Three-Links Model, Energy Flow Optimization, Energy-saving, Pulp and Paper Process

1. Introduction

Chinese Paper and paperboard production capacity is the No. 1 in the world in 2009. At the same time the pulp and paper industry consumed about 100 million metric tons of standard coal equivalently (tce). It is categorized by Chinese Government as the one of nine key typical energy intensive industries not only due to the energy consumption is too huge but also due to energy efficiency is lower. Chinese energy consumption per unit paper and paperboard is the three times compared with average energy consumption per unit paper and paperboard in developed countries in 2005. The reasons for lower energy efficiency are as following:

- The optimization level of energy system of pulp and paper mills is lower.
- The integration level of process techniques, equipments and control systems is lower.

The energy system of pulp and paper mills is very complex and many Process Integration (PI) and optimization techniques for analyzing them have been implemented during recent decades. The most energy efficiency studies today concern retrofitting. Several approaches have been suggested and applied during the 1990s. They are based on pinch analysis [1]–[4], mathematical programming [5],[6] or a combination of those two techniques [7],[8].Those methods focus on local unit processes or equipments, But is not good at analyzing the global energy system in a whole pulp and paper mill, especially combine Heat and Power (CHP) inside. To solve global integration and optimization problems of energy system in Chinese typical pulp and paper mills and improve the overall energy efficiency, the Pulp and Paper Process Three-links Method (PPPTM) based on Process integration and optimization is developed by our research team. The PPPTM can figure out the bottle-necks of the global energy system, and guide to design an optimal proposal for energy system retrofitting.

2. The methodology

Three-links is a method or strategy based on the Second Law of thermodynamics, considered the global optimization of energy system as its objective in process industry [9-11]. It uses exergy and exergy economics as its analysis tools, realizes the global optimization depended on the further understand and description of process energy system.

The energy consumed and decayed gradually in the three links with different functions in pulp and paper mills. Three links connect closely and restrict each other. The methodology illustrates the quantitative relationship of energy flow, emphasizes the mechanism of interaction and restrictive relationship among the subsystems, and constructs a complete method of the coordination and optimization from process unit, subsystem to global system [12].

2.1 Three-links model

PPPTM divides the whole energy system of pulp and paper process into three links as a Conversion and transmission link (C-Link), a U-Link (U-Link) and a R-Link (R-Link) according to the different functions. The structure of the three-links model is shown in Fig.1.

Firstly, the C-Link converts the primary energy (exergy) or the secondary energy (exergy) into the special type energy (exergy) by heating furnaces, boilers, gas turbines and steam turbines, and so on, which should meet the requirement of process system. As for pulp and paper industry, besides the energy emitting into the surrounding (E_W), the others divide into three parts when the primary energy (E_p) is converted into the energy that it is useful for to drive pulp and paper process, such as coal, sludge: 1)

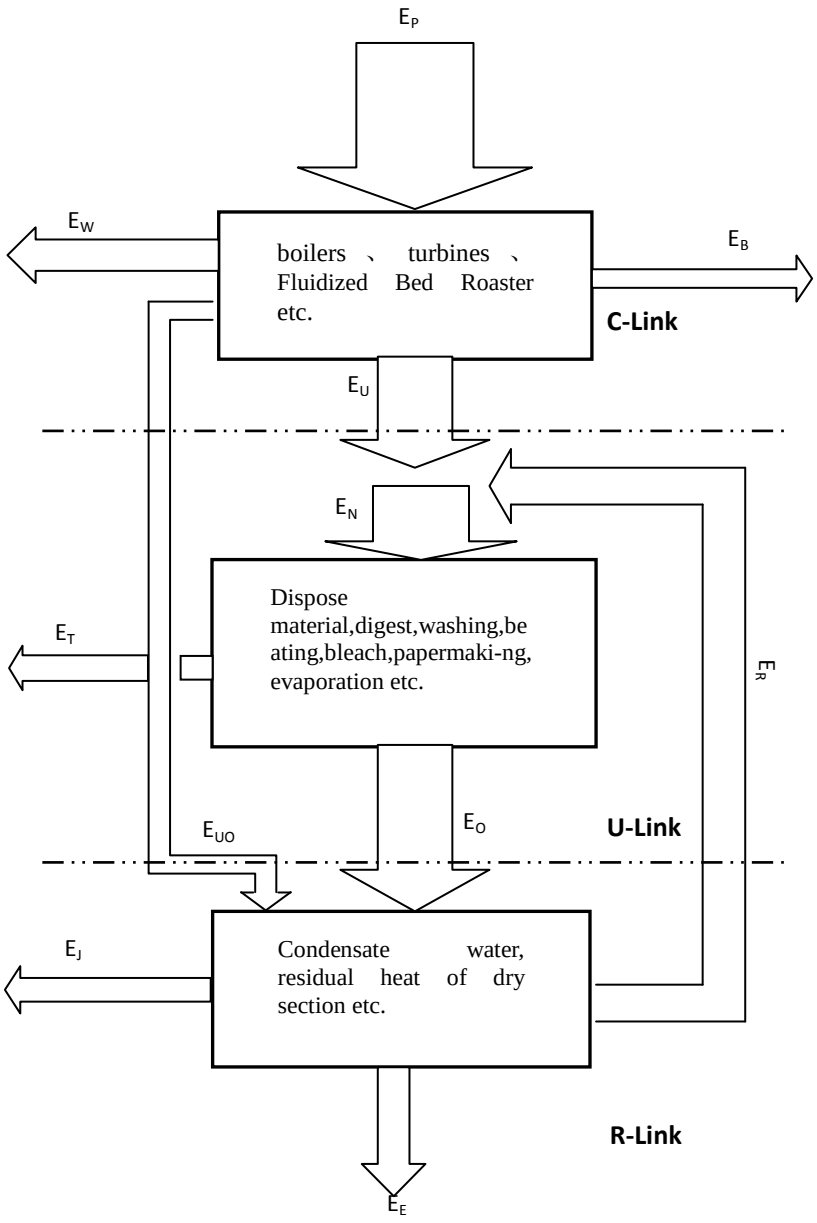

Fig.1 three-links model structure of pulp and paper industry

The effective energy (E_u) supplies to the U-Link. 2) The energy to drive energy supply to the R-Link (E_{UO}). 3) The output energy (E_B) export to the external. We evaluate the process with the conversion efficiency of energy and exergy.

Secondly, the U-Link is the core of process energy (exergy) analysis and optimization. In this link, the energy drives the pulp and paper manufacture process and makes the material into the product. The level of energy utilization can be reflected by the utilization efficiency of energy and exergy. The energy (exergy) used properly or not is main factors of impacting the whole process energy consumption. The energy which input into the U-Link includes the effective energy (E_U) from the former link and the recovery energy (E_R) from the R-Link as the total energy consumption of the process (E_N). E_N is used in operation units and section of the process system, which makes the process operated properly.

Thirdly, recovery means recycling the heat during making the product and the byproduct, Refers specifically to heat transfer process in pulp and paper mills. The level of energy recovery can be defined as the recovery efficiency of energy and exergy. The energy which input into the R-Link includes the energy release from the former link (E_o) and the drive energy from the first link (E_{UO}). the R-Link includes the recovery waste heat from hoods and the recovery condensate water from pulp and paper process. The recovery energy can be used as one part of the energy

consumption of the process (E_N) and as the part of the feed water for boilers. However, the energy that it can't be recovered or difficult to be recovered (E_J) will be discharged. The rationality of using the energy (exergy) on different materials with special temperature determines the recovery efficiency of energy. Increasing recovery energy (exergy) means decreasing exhaust energy. As a result, improving the R-Link efficiency has positive effect on energy-saving of the processes and the equipments.

2.2 Energy efficiency index

The mathematical model and energy efficiency index of three-links were shown in table 1, according to the physical and structure model of energy system in pulp and paper process as known in fig.1.

Table I. The energy efficiency index of three-links model in pulp and paper industry

links		energy U-Link	energy R-Link	energy C-Link
energy	balance equations	$E_U+E_R = E_N = E_T+E_O$	$E_O+E_{UO}=E_R+E_E+E_J$	$E_P=E_U+E_B+E_W+E_{UO}$
	energy efficiency index	$\eta_T =1- E_{UD}/E_N$	$\eta_R = (E_R+E_E)/(E_O+E_{UO})$	$\eta_U = (E_U+E_B+E_{UO})/E_P$
exergy	balance equations	$EX_U+ EX_R = EX_N = D_T +D_{KP}+ EX_O$	$EX_O+EX_{UO} = EX_R+ EX_E+DK_P+D_{JR}$	$EX_P = EX_U+ EX_B+EX_{UO}+D_{KU}+D_{JU}$
	energy efficiency index	$\eta_{XT}= (EX_O+D_T)/EX_N$	$\eta_{XR}= 1-(D_{KR}+D_{JR})/(EX_O+EX_{UO})$	$\eta_{XU}= 1-(D_{KU}+D_{JU})/EX_P$

Here:η_T——the energy efficiency of U-Link; η_{XT}——the exergy efficiency of U-Link ;η_R——the energy efficiency of R-Link; η_{XR}——the exergy efficiency of R-Link; η_U——the energy efficiency of C-Link; η_{XU}——the exergy efficiency of C-Link.

2.3 Collect energy system data

We got energy system data by measurement on site and from operation record statistics respectively. The data includes C-Link, U-Link and R-Link divided at section 2.1. Take boilers and turbines as an example, which belong to the C-Link. For boilers, we got the relevant data to compute the input energy (exergy), the effective energy, the loss energy, etc, such as material flow rate, temperature, pressure, and so on. Then, the energy (exergy) efficiency and the loss can be computed. Similarly, the relevant data of turbines, such as flow rate, temperature and pressure of steam, and so on, were acquired to compute the input and the output energy (exergy). Also, we can get the energy (exergy) and the loss of turbines. The methodology of statistics and calculation is suitable to paper machine and other equipments in U-Link.

2.4 global analysis energy system three- links

Gathering the energy (exergy) flows under the order of C-Link, U-Link, R-Link based on the statistic and analysis of the energy consumption of unit processes and equipments. The total input energy (exergy), the output energy (exergy), the energy (exergy) efficiency of C-Link, U-Link, R-Link can be presented considering link as a unit.

3. Case study

Gold East Paper (Jiangsu) Co.Ltd is the biggest company of fine paper in the world. It produces more than 2 million tons per year with three pulp and paper lines. We studied the thermal energy system of Gold East Paper (Jiangsu) Co.Ltd systemically from Nov. 2008 to May. 2009. We diagnose and analyze the bottleneck of the energy system with three-links method, and finally help the mill to find out more energy-saving potential, and effectively design the plan for energy-saving retrofitting projects.

3.1 Energy System Data Collection

The data collection procedure includes primary investigation and detail investigation with 4 people during the 8 weeks. The Thermal related data was collected from design document, production statistical report, DCS, QCS, and measuring on site.

3.2 Energy System Analysis

According the PPPTM Methodology and thermal energy system data, we computed and drew the energy (exergy) flows of energy system，as shown in Fig2 and Fig3. Following, we analyze the energy system according to the figures.

As shown in Fig.2 and Fig.3, the total energy (exergy)

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consumption in C-Link is 1162759.82 (1077493.16) kWh/h, including the energy (chemical exergy) of coal about 825034.20kWh/h, the energy (exergy) of feed water about 254882.72 (169616.06) kWh/h, the energy (chemical exergy) of natural gas 82752.86kWh/h, and the energy of diesel oil and gasoline 90.04kWh/h. The power station consumed the power about 26375.23kWh/h. It covered about 13.18% of the total power produced.

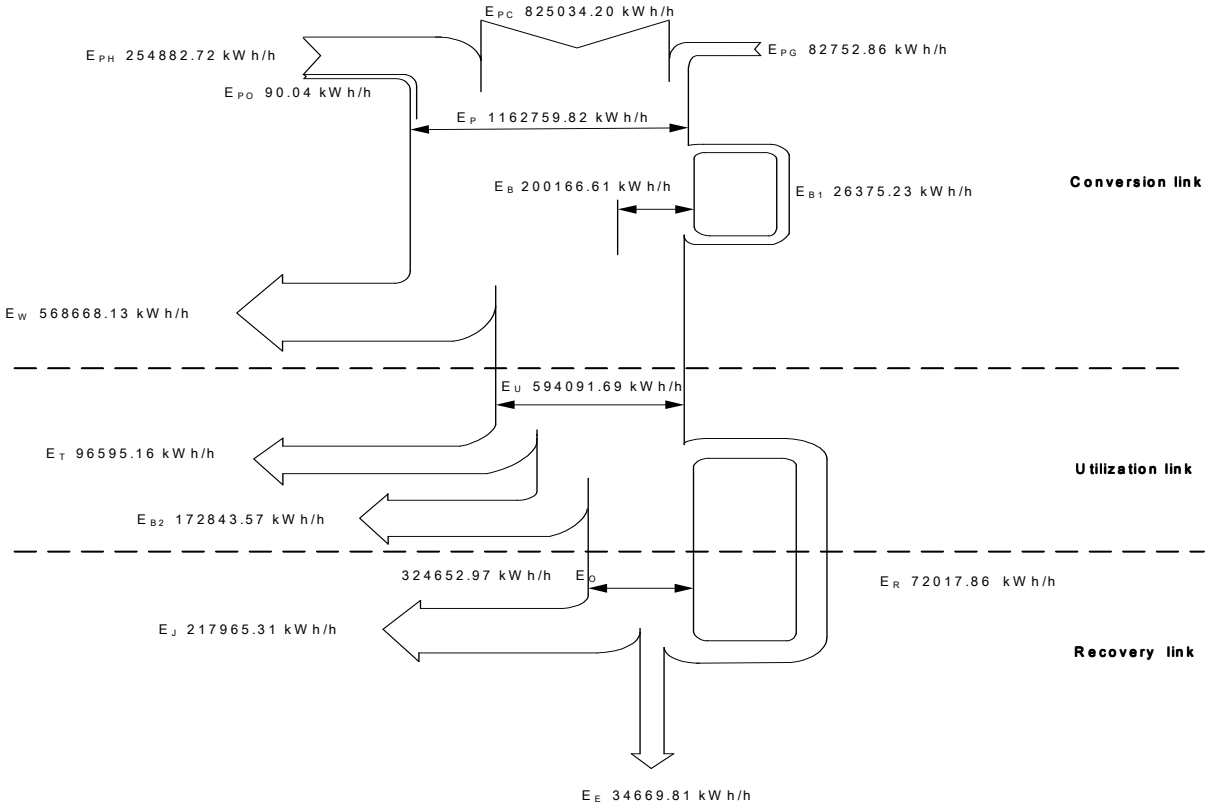

Fig.2 the energy flow of energy system in papermaking process

Here, E_{pc}: the energy of coal;E_{PE}: the energy of gas;E_{PH}: the input heat; E_{PO}:the energy of oil; E_P:the total input energy;E_B: the output energy;E_{B1}:the electricity consumption of power station;E_{B2}:the electricity consumption of process; E_W:the energy exhaust fRom conversion link; ET: the thermodynamics energy of process ; EU: the effective energy; EO:the energy waiting for recycling; EJ:the exhaust energy from recycling link;E_E:the output energy of recycling link;E_R:the recover energy.

The exhaust energy of C-Link is 568668.13kWh/h
, which covers the total energy input into the system 48%, and includes the condensation loss of turbines and the loss of exhaust smoke of boilers primarily. Except the exergy loss because of the condensation and exhaust smoke, the exergy loss of conversion processes is the primary leads to low efficiency of C-Link. We can get from the exergy loss of conversion processes was 566835.49kWh/h as shown in fig.3. It covers 52.6% of the whole input exergy owing to the exergy loss of combustion process and heat transfer process primarily.

The effective energy (exergy) input into U-Link is 594091.69 (335000.05) kWh/h, including the power 172843.57kWh/h, the energy consumption due to the changeable phase of material 96595.16 (8565.15) kWh/h, the energy (exergy) recovered from R-Link (the hoods of paper machines) 72017.86 (3098.03) kWh/h, and the energy (exergy) input into the next link.

The energy is available for recovery which can be recovered in theory was 324652.97 kWh/h covers the effective energy 54%, as shown in fig.2. Maybe we considered that the great deal of energy can be recycled. But, the exergy available for recovery (EX_O) is 27366.59kWh/h which covered only 8.17% of the input effective exergy (EX_U) because most of energy is low-temperature heat. The potential of energy saving can be dug out even some of low-temperature heat difficult to recover. From the R-Link, we can get some of the energy (exergy) was recovered due to the recycle of the waste heat of hoods in dry section, it about 72017.86kWh/h. Meanwhile, the steam condensate was recovered instead of some feed water of boilers, it about 34669.81kWh/h. the rest about 21965.31kWh/h was discharged, which covered 68% of the total energy put into R-Link (EX_O).

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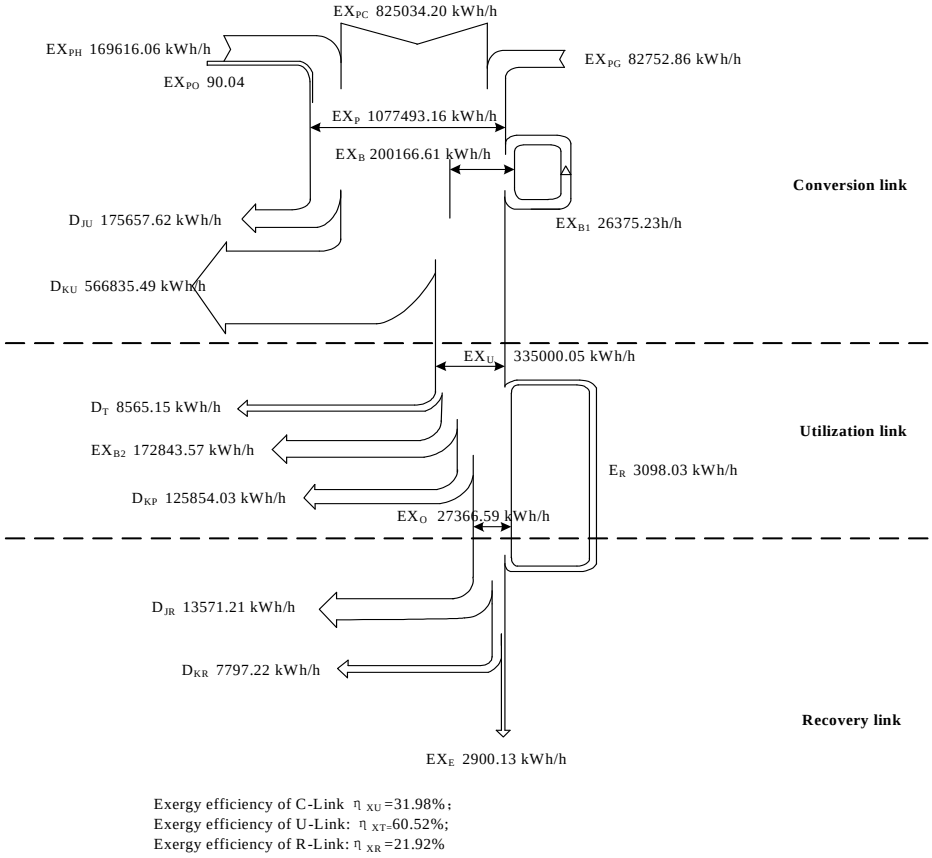

Fig.3 the exergy flow of energy system in papermaking process

Here, EX_{pc}: the exergy of coal;EX_{PE}: the exErgy of gas;EX_{PH}: the Exergy of the input heat; EX_{PO}:the exergy of oil; EX_P:the total input exergy;EX_B: the output exergy;EX_{B1}:the Exergy of electricity consumption of power station;EX_{B2}:the exergy of the electricity consumption of process; EX_W:the Exergy exhaust from conversion link; EX_T: the thermodynamics exergy of process; EX_U: the effective exergy; EX_O:the exergy waiting for recycling; $EX_J$the exhaust exergy from recycling link;EX_E:the output exergy of recycling link;EX_R:the recover

4. Results and discussion

We get the energy efficiency of C-Link is 53.73%, the energy efficiency of U-Link is 56.77%, and the energy efficiency of R-Link is 32.68%. from the fig.2 The exergy efficiency of C-Link is 31.98%, the exergy efficiency of U-Link is 60.52%, and the exergy efficiency of R-Link is 21.92% as shown in fig.3.

If the operation status is evaluated only using the energy efficiency, we'll get the result only one-side. For example, the C-Link of the energy system in Gold East paper co.ltd was in good condition according to the energy efficiency of C-Link is 53.73%, but the exergy efficiency of C-Link is too low only 31.98%. The reason can be got from the ingredients analysis of energy (exergy) loss. The condensation loss of turbines and the loss of exhaust smoke of boilers lead to the energy loss of C-Link, it difficult to do some works on them. But, the exergy loss of condensing, the exergy loss of exhaust smoke and the exergy loss of processes lead to the lower exergy efficiency of C-Link. May be some works could be done on processes to save energy, please see section 5.1.

Also, we can't evaluate the utilization process using the exergy efficiency of U-Link, ignoring of the energy efficiency. The energy efficiency of U-Link is 56.77%, lower than the exergy efficiency, The energy consumption of U-Link includes steam and electricity, we can reduce the requirement of electricity by optimal the operation of dry section of paper machine, see section 5.2. We can find out the potential of energy-saving by analyzing the ingredients of the energy (exergy) exhaust from R-Link, even both the energy efficiency and the exergy efficiency of R-Link are lower, section 5.3 display the details.

5. energy-saving potential analyzing

5.1 energy-saving potential in C-Link

There are four boilers and four turbines in power station of Gold East paper co.ltd. They supply the pulp and paper process with electricity and steam at different pressures. The high pressure steam produced by boilers, and input turbines. The steam and electricity for pulp and paper process are made by turbines which complicated conjunction. There are many strategies for load setting. The energy consumption of thermal energy system change with the variation of operation mode, absolutely, it must meet the requirement of pulp and paper process. So, there is potential to optimal the system, which can make the system consume the minimal energy.

The optimization strategy should be decided based on the structure of thermal system, the mathematic model of equipments and the optimization model of system should be established in order to obtain the optimal operation mode.

(1) **The potential of energy-saving**: the power station has different turbines and boilers. The turbine with different type has different efficiency even the efficiency of equipments may be different with the same type.

(2) **The solution proposed**: the load should be set according to the property of boilers and turbines in order to make the whole system consume the coal minimally. The data of boilers and turbines before and after optimization are shown respectively in table 3 and table 4.

Table Ⅱ the status of boilers before and after optimization.

A R: after optimization, B R: before optimization

items	NO.1 boiler		NO.2 boiler		NO.3 boiler		NO.4 boiler		Sum.	
	A R	**B R**	**A R**	**B R**	**A R**	**B R**	**A R**	**B R**	**A R**	**B R**
Coal consumption(t/h)	23.093	24.99	42.021	43.56	53.882	42.72	19.74	43.45	138.74	154.72
Steam production（t/h）	150	177.06	262.04	266.34	362.67	264.21	121.16	263.73	895.87	971.34

Table Ⅲ the status of turbines before and after optimization

A R: after optimization, B R: before r optimization

items	NO.1turbine		NO.2turbine		NO.3turbine		NO.4turbine		Sum.	
	A R	**B R**	**A R**	**B R**	**A R**	**B R**	**A R**	**B R**	**A R**	**B R**
Inlet steam of turbines (t/h)	140	177.06	255.14	266.34	251.88	264.21	248.85	263.73	895.87	971.34
Mid-pressure steam extract from turbines (t/h)	5	15.35	10	27.97	29.79	33.04	65	33.43	109.79	109.79
Low-pressure steam extract from turbines (t/h)	85	69.57	140	73.29	100.65	107.20	30	104.40	354.46	354.46
Power produced (kWh)	21204	35690	58451	45597	57883	57323	62628	61556	200166	200166

We can get from the table 2 and table 3, the coal consumption of cogeneration system reduced from 154.72t/h to 138.74t/h after the optimization of operation mode with the constant secondary energy.

(3) Result: The coal consumption reduced about 10t standard coal per hour, which reduce the coal consumption of about 49,000tce/a (average operating time: 7000 hours a year), c for power station..

The result of above-mentioned noted that: ①the optimal status can be gained or closed to by adjusting the operation condition. ②the optimization method can be find out by changing the constraints, searching for operation condition to minimize the operation cost of the system, and adjusting timely according to the requirement of steam and power.

5.2 energy-saving potential in U-Link

Dry section energy flow in paper machine is a main part of U-Link. The system of steam condensate and hoods system covers 65% of the whole variables which have impact on the running performance of dry section.

Energy-saving potential: The data with reference to the feature of hoods ventilation in three paper machines were displayed respectively in table 4. We know from the table 4, all the actual humidity were lower than their design value.

After investigation, we find the motor load factor of blower and exhaust fan of the pre-drying section in PM#1and PM#2 is 100%, the motor load factor of the latter two exhaust fans of heat exchangers were 97% and 98%.

Table Ⅳ the feature of hoods ventilation in three paper machines

Items	PM#1	PM#2	PM#3

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Temperature (□)	69	68	48.4
Dew-point temperature(□)	61	56	36.2
Actual humidity (g/kg)	108	97	42
Design humidity (g/kg)	150	150	155

According to design technique documents, the humidity of hoods in PM#1 and PM#2 is lower than design value due to the air flowed too fast. All the motor load of exhaust fan in PM#3 fluctuated from 79% to 90% and the motor load of blower fluctuated from 80% to 86%.

(1) The solution proposed: The dry section is improved based on the mathematic models of hoods. In detail, the flow rate of hoods ventilation was reduced, the humidity of the air exhausted from hoods was raised, and the gap between the humidity of ventilation and dew-point temperature in order to save energy. Take PM#3 as an example, the result before and after optimization are shown in table 5.

Table Ⅴ the data before and after retrofitting for PM#3

Items	units	B R	A R
Dry fiber put into dry section	kg/h	49240.8	49240.8
The dryness of stock put into dry section	%	48%	48%
The wet paper input dry section	kg/h	102585	102585
The dryness of paper after drying	%	94%	94%
The paper output	kg/h	52383.83	52383.83
The evaporation of dry section	kg/h	50201.17	50201.17
The actual humidity of hoods	kg/kg	0.042	0.07
The requirement of fresh air	kg/h	1195266	717159.6
The exhaust air of dry section	kg/h	1245467	767360.7
Temperature of hoods	□	69	69
Dew-point temperature	□	42	55
Hoods ventilation	kg/s	332.02	199.211
The extract air of hoods	kg/s	345.96	213.1558
enthalpy of air extracted from hoods	kJ/kg	179.72	253.07
The heat of extract air	kW	59669.75	50414.41
Temperature of exhaust air	□	43	43
Humidity of exhaust air	kg/kg	0.03	0.04
Enthalpy of exhaust air	kJ/kg	120.56	148.83
The heat of exhaust air	kW	40026.54	29649.46
The heat recovered	kW	19643.21	20764.95
The motor load factor	%	100%	60.00%
The difference		1121.74	

(2) Result: After operation optimization, the heat consumption reduced about 1121.74kJ/s, it equals to 0.138t standard coal per hour. It will reduce the coal consumption of cogeneration system about 964.5tce/a (average operating time: 7000 hours a year). Also, the power input reduced because the motor load factor of fans reduced about 40%, which leads to the reduction of hoods ventilation.

5.3 energy-saving potential in R-Link

The energy (exergy) efficiency of R-Link is 32.86% (21.92%) based on the analysis of energy system above, it is inferior. Some of the reasons were the smoke exhausted from natural gas combustion with 120 □ was discharged into the atmosphere directly in coating dry section.

(1) **Energy-saving potential:** the waste heat of the exhaust smoke of natural gas combustion can be recycled by installing some pipelines or equipments.

(2) **The solution proposed:** the air of hoods ventilation in raw paper dry section was heated by the heat of exhaust smoke, it can reduce the consumption of the fresh steam.

Table Ⅵ the waste heat exhaust from NG/LPG combustion in PM#1

Items	Consumption	Units	Energy (kJ)	Equivalent value

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					(tce)
The exhaust air	NG	12940969	m^3	-	16243.12
	NG-Air	123327432	m^3		
Add up		136268401	m^3	5.55E+11	18934.84

Taking PM#1 as an example, the waste heat exhausted from PM#1 equals to 18934.84t standard coal, as shown in table 6. The energy of low-pressure steam used to heating the fresh air of hoods equals to 5997.18t standard coal, it covers 31.6% of the waste heat. So, the low-pressure steam can be displaced by the exhaust air only the efficiency of heat exchanger arrive at 32-35%.

(3) **Result:** The fresh steam can be saved equals to 17219.42t standard coal per year if the waste heat of exhaust air of gas was recovered by installing the heat exchangers in all lines.

6. Optimization and retrofitting energy system

The U-Link of energy system is the key link which decides the size of energy consumption of the pulp and paper mills. It impacts the quantity of primary energy and secondary energy should be put into the C-Link. Also, the R-Link is very important. The more energy was recovered, and then the less energy would be input. Three-links model help the managers implement the optimization and retrofit from the system point of view and realize the global optimization of energy system finally. For Gold East paper co.ltd, the operation optimization of dry section should be carried out firstly. Then, the waste heat of the exhaust smoke of natural gas combustion will be recovered to heat the fresh air of hoods. The optimization of cogeneration system should be started after the formers were completed.

Table 7 the energy (exergy) consumption of system before and after retrofitting

Items	B R	A R
The total input energy/exergy (E_p/EX_P) (kWh/h)	1162759.8/1077493.16	867439.3512/836424.58
The energy/exergy efficiency of C-Link (%)	53.73/31.98	57.78/37.66
The effective energy/exergy (E_U) (kWh/h)	594091.69/335000.05	521490.01/314970.39
The energy/exergy efficiency of U-Link (kWh/h)	57.48/60.52	59.27/62.04
the total energy put into R-Link (EX_O) (kWh/h)	324652.97/27366.59	275157.17/25730.34
the energy (exergy) recovered from R-Link(E_R/EX_R) (kWh/h)	72017.86/3098.03	143497.8/6172.92
The energy/exergy efficiency of R-Link (kWh/h)	32.86/21.92	62.52/35.26

As shown in Table 7, the energy (exergy) consumption of system after optimization and retrofitting was decreased, but both the energy efficiency and the exergy of efficiency are improved all the three links.

7. Conclusions

(1) The energy system of pulp and paper process is analyzed scientifically by Three-links model and described quantitatively.

(2) The problems and bottle-necks of energy system in pulp and paper process can be analyzed and diagnosed systematically and comprehensively by three-links mode. The energy-saving potential can be found out in pulp and paper mills.

(3) Three- links model can help the managers and the operators comprehend the whole process of energy consumption by themselves, it helpful to do more optimization and retrofitting on energy-saving.

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