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Design of modelling and online simulation for energy systems in papermaking mill

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Abstract. This paper presents a general framework of modelling and online simulation for papermaking mill's energy systems. The energy flow models of thermal power plant, DIP and paper machine for a papermaking mill was designed and implemented an online simulation. The traditional offline, closed and scattered modelling and simulation methods were changed into online, open and integrated forms. Through the analysis of energy systems of papermaking mills, the framework has implemented the followings. The unit (equipment) models were established, it can analyse the energy of energy flow material. The corresponding material flow models library was developed. The craftwork models were designed and the energy flow models library was developed of thermal power plant, DIP and paper machine. The mathematical models of unit (equipment), energy flow, exergy flow, thermal power plant, DIP and paper machine were built. The material properties database was developed. General simulation software architecture and online simulation software architecture were designed. The framework implemented online simulation, analysis, diagnosis and optimization for energy systems of whole papermaking mill. The practical application results are fine when the framework was applied in Guangzhou Paper Group Co., Ltd., and Gold East Paper (Jiangsu) Co., Ltd. The practical application results indicate that the emulation, simulation, analysis, diagnosis and optimization of material flow and energy flow for papermaking mill whole production process can be implemented by online simulation, and the purposes of maximizing the utility efficiency of material and energy resource, reducing resource, reusing and recycling can be achieved.

Key words
Papermaking mill, energy systems, modelling, simulation, online.

1. Introduction

As one of traditional energy-intensive industries, it is necessary to take effective energy saving measures to alleviate the current energy crisis in the world for paper mill, which is not only helpful to increase the economic benefits, but also enhance the competitiveness of paper enterprises.

The problem for paper industry about energy and material consumption, and water pollutant emission are still very serious in China. There are many reasons, such as prices of raw materials and products, management level, technical level and so on, among which low utilization level and optimization degree of the energy system plays roles of great importance.

Therefore, to change the traditional model of development and develop circular economy , achieving cleaner production, building eco-paper industry and entering rapidly into eco-industrial phase which aims to highest efficiency of energy and material utilization and smallest waste production, is the fundamental way to develop Chinese Paper Industry[1].

The Paper[2] points out that technological innovation and development about energy saving for Chinese paper industry should be carried out following such two aspects:

1. Research and develop critical general characters of energy saving technology and equipment of paper enterprises.

2. Research and develop diagnostics and integrated optimization technologies of energy system of paper enterprises.

The first aspect is a hard means, replacing more energy-efficient, advanced equipments to promote eco-paper industry and circular economy.

The second aspect is a soft means, researching energy systems (including material system) from angle of optimization. The general characteristics of energy saving integration optimization technology, which can not be replaced by the single energy saving technology, makes up for defects of single technology as dispersive and non-system[2]. Therefore, it is an important approach to reform traditional industries such as paper industry with advanced integrated and optimized energy system technology, not only increasing economic efficiency and environmental quality, but also reducing their unit energy consumption.

However, the main current energy-saving measures taken by paper-making mills still are using more energy-

efficient, advanced equipment, such as gas turbine, impingement drying[3]. The modelling and simulation of papermaking mills focus on the material flow in the papermaking process, such as WinGEMS[4], WinPAMS[5][6] and so on. WinPAMS, developed by Professor Huanbin Liu and his team as early as 20 years ago, is a modelling and simulation software which models and analysis the material flow in the papermaking process. The analysis of energy flow in the papermaking process focuses on some parts, such as the energy analysis of heat recovery system with the pinch point method[4][7][8].There are few energy analyses of the whole papermaking mill[9]-[12].The Optimization of the papermaking process focuses on paper-cutting system[13] and the operation of combined heat and power[14]. As for the simulations, mostly are off-line simulation, lacking for on-line simulation, analysis, diagnosis and optimization[15]-[17].

Therefore, in order to improve effectively the economic benefit and energy saving level of paper industry, it is needed to model the whole energy system, and simulate, analyze, diagnose and optimize on-line. This paper presents a general framework of modelling and online simulation for the whole paper-making mill's energy system and gives the corresponding application case to illustrate the software means of online simulation, which gives full play to existing equipment performance and promotes eco-paper industry and circular economy with information means. The modelling and online simulation should include modelling, data collection, analysis, storage, statistics, diagnostics, optimization, display and other functions in general, the model library of material and energy flow, the other basic model library of the corresponding functions, and the corresponding property database should be established at the same time.

To establish a general framework of modelling and online simulation, we must first analyse and abstract paper-making process, energy systems, and then model the energy system, including the abstract unit (equipment) model and the process model of different production line / section in Paper companies, and then establish the corresponding mathematical model. With the material flow model library, energy and material flow model library database, you can emulate the system online and form simulation model library of material flow and energy flow. Through the emulation, you can realize on-line monitoring, analysis, diagnostics and optimization of the papermaking process and energy system.

In this paper, we designed the corresponding model of all the energy systems associated with the papermaking of Guangzhou Paper Group Co., Ltd. and Gold East Paper (Jiangsu) Co., Ltd. (China) and have made an online simulation of the system.

2. Papermaking Process Energy Analysis

The energy consumption of paper-making process focused on power plants, the dryer section and so on, therefore, we mainly analyze the energy systems of these energy section in which most energy is consumed, involving the major equipments like boiler, steam turbine, steam-driven pumps, condenser, pipes, broken pulp, heat dispersion, Sec bleach, dryer, separator, heat exchanger, condensate recovery, steam enclosures, ventilation systems and so on. The energy flow is mainly manifested in the coal, diesel, natural gas (NG), liquefied petroleum gas (LPG), water, condensed water, dry air, moist air, steam, paint, pulp, wet and dry paper pages and other substances.

To model and simulate the energy systems of the papermaking process, we must first model the major equipments in paper-making process and abstract them to relatively independent units, the point of which is the building of its corresponding mathematical model, such as boiler model, back pressure steam turbine model, extraction condensing steam turbine models, dryer model. Considering the paper-specific enterprise, we first create the appropriate process model, and then combine the established model elements, as to achieve the static simulation of energy system in the paper-making process. To realize the dynamic simulation, we need to carry out the established static simulation concretely, including the software architecture model, the acquisition and storage of data, the analysis and statistics of data, the results display. The online simulation is reflected in that the real-time access to data is collected from the database (or historical database), which is then analyzed online through the model database and material property database (such as water and steam, dry air, moist air, flue gas, furnace heat, ash, etc.) and that the results is then stored in a relation database to facilitate the following statistics, the further analysis and diagnosis and the display of corresponding results, etc..

Finally, we need to optimize the energy system of the entire papermaking process through various optimization models and optimization methods, in order to achieve the goals of energy-saving.

3. Energy System Modelling

Energy system modelling includes unit (device) modelling, craftwork modelling, and mathematical modelling.

A. Unit (device) modelling

There are three categories of unit (deivce) models which is most basic abstract model in the Paper-making enterprise energy system: material flow unit model, energy flow unit model and exergy flow element model. The abstract unit (device) model of material flow is shown in Figure 1.

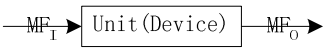

Fig.1. The abstract unit (device) model of material flow

M means materials, F means flow rate, I means the input, O means the output , the same below.

The abstract unit (device) model of energy flow is shown in Figure 2.

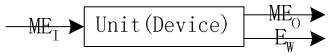

Fig.2. The abstract unit (device) model of energy flow

E means the energy, W means the other Waste, such as heat losses, mechanical losses, the same below.

The abstract unit (device) model of exergy flow is shown in Figure 3.

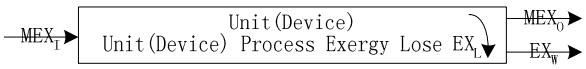

Fig.3. The abstract unit (device) model of exergy flow

EX means the amount of Exergy, L means Losses, the same below.

B. craftwork Modelling

By abstracting the physical energy system into the corresponding craftwork model, craftwork model is composed by the corresponding unit (equipment) model. Guangzhou Paper Group Co., Ltd. (China) 1# paper machine, for example, the physical energy system is mainly distributed in the thermal power plants, deinking line and paper machine production line.

1) thermal power plant craftwork model

Thermal power plant belonging to energy conversion and transport links. The segments are mainly related to two parts: the boiler and steam turbine, mainly construction section 1#, 2#, 3# boiler, high pressure the mother tube, 1# front-end (extraction condensing steam turbine), 2# front-end (extraction condensing steam turbine), condenser, medium pressure heating network, 3# post-machine (back pressure steam turbine), 4# Post-plane (full condensing steam turbine), 5# Post-plane (back pressure steam turbine), steam-driven pumps, low-pressure heating network and power grid construction section and so on. Material mainly related to coal, air, water and steam and so on, the energy flow mainly related to coal, steam and electricity. Which reduced temperature valves, and other transmission devices due to little effect, in order to reduce the complexity of the model, it has not been considered.

2) Deinking-line craftwork model

Deinking line belongs to the energy use of links. Mainly related to the pulper, high concentrated slag, the former screening, heavy slag, the former flotation after screening, the former multi-disk condensed, spiral pressing, heat dispersion, a period of drift, after flotation, after the multi-disk condensed, spiral dilution, Sec drift, plate mill and other construction section. Since the material are raw materials, pulp, water and steam, etc., but in the entire DIP production lines, the steam is used mainly in broken pulp, heat dispersion, Sec bleach steps, so de-inking line energy system on an abstract process model is only contains broken pulp, heat dispersion, Sec bleach three construction section.

3) paper machine craftwork model

Paper machine belonging to energy utilization and recycling sectors. Mainly related to the slag, paper machine screen, headbox, wire part, press section, dryer section, pressure light, coiling and other construction section. Since the materials are pulp, air, water and steam, etc., but in the whole paper machine production line, the steam used mainly in the dryer section and other sections, Therefore, the energy system, the abstract machine process model that contains only the dryer section on the steps, it contains gas dryer hood systems, air preheat and heat recovery subsystem, condensate water recovery subsystem three subsystems. One dryer hood system belongs to the energy use and air links, energy recovery aspects are mainly related to the air preheat and heat recovery subsystem, condensate water recovery subsystem and other subsystems, materials, the main consideration of air, water and steam and so on.

C. Mathematical Modelling

Mathematical model is based on the process of system data source which artificially created mathematical description. This mathematical description can produces the behavioural data similar with the process. Mathematical description commonly used algebraic equations, differential equations law or equation of state law, and so on. The mechanism of mathematical model mainly contains analysis method, process identification method and mechanism - three types of experiment[5][6]. Mathematical modelling includes the unit (device) model of mathematical modelling, energy flow and exergy flow of mathematical modelling, as well as the corresponding craftwork model for mathematical modelling. The mathematical modelling include the model of unit (equipment) model, energy and exergy model and the corresponding industrial art model.

1) unit (device) mathematical model

The abstract material flow balance model is shown as equation (1).

$$\sum MF_I = \sum MF_O \tag{1}$$

The abstracted balance of energy flow models is shown as equation (2).

$$\sum ME_I = \sum ME_O + \sum E_W \tag{2}$$

The abstracted balance model of exergy is shown as equation(3).

$$\sum MEX_I = \sum MEX_O + \sum EX_W + EX_D \tag{3}$$

2) the mathematical model of the energy and exergy

In the papermaking process, the basic material is the pulp (raw material, fibre), water, steam, and air (absolutely dry). For the air (absolutely dry), fibres and raw materials, the mathematical model is expressed as the following formulation (4).

$$E = F*Cp*t/3600$$
$$Ex = F*(Cp*(T - T_0) - T_0*Cp*LN(T/T_0))/3600$$

Where:

E ––*Energy(kW)*

Ex ––*Exergy(kW)*

F ––*Flow(kg/h)*

Cp ––*Specific isobaric heat capacity(kJ/(kg K))*

t ––*Temperature(°C)*

T ––*Absolute temperature(K)*

T_0 ––*Environment Absolute temperature(K)* (4)

For water and steam, the mathematical model of their energy and exergy is expressed as the following formulation (5).

$$E = F*h/3600$$
$$Ex = F*((h - h_0) - T_0*(S - S_0))/3600$$

Where:

E ––*Energy(kW)*

Ex ––*Exergy(kW)*

F ––*Flow(kg/h)*

h ––*Specific enthalpy(kJ/kg)*

h_0 ––*Environment Specific enthalpy(kJ/kg)*

T_0 ––*Environment Absolute temperature(K)*

S ––*Specific entropy(kJ/(kg K))*

S_0 ––*Environmnet Specific entropy(kJ/(kg K))* (5)

3) craftwork mathematical modelling

After the craftwork models of each link have been established, it is necessary to build the mathematic models of the equipments which are used to calculate the energy and dosage of the construction section or the equipments. The overall energy efficiency (%) is defined as the percentage of the all the output energy expect the loss to the all input energy and the product energy efficiency (%) is the percentage of the energy of the output product except losing to the all the input energy. If all the output is the product available used, the overall energy efficiency (%) is equal to the product energy efficiency. According to the PM1 of the factory, the mathematical models of the thermal power plant、the deinking line and paper machine are to be established.

4. Energy system emulation and online simulation

The material and energy used in the papermaking mill can be converted to the variable versus to time, such as temperature, pressure, flux, level gauge, humidity, concentration, specific heat and caloric content, while simulation and emulation[5][6].

In order to realize the simulation of the energy system of papermaking mills, it is to simulate the material flow first, of which we have achieved initial simulation using WinPAMS. The cells available simulated include mixing, separating, dehydrating, transmitter, hydraclone, PID, delaying, stuff tank, pump, rotor screen, headbox, white water pool, dryer, steam-water separator, ventilation system, heat withdrawer, water heat exchanger and gas mixer[5,6]. Obviously, beyond the cell modules mentioned above, it is also needed to simulate and analyze the material flow and energy flow of the boiler ,steam turbine, pipeline, condenser, mid-pressure heating network, steam pump, low-pressure heating network and power grid in the thermal power plant, the pulping, flotation, thickener, screw press, heat dispersion, bleach and refiner in the DIP mill, especially pulping, heat dispersion, wire section, press, drying, calendering, and reeling.

The simulation and analysis of the material flow and energy flow cell modules mentioned above will not be described. It is to describe the software architecture of the energy system simulation and emulation online in details in the following section.

A. Simulation software architecture

By DDR(Display-Definition-Realization) software architecture[18], realized the modelling and simulation of the papermaking corporation through energy system "three-link" method[19][20]. The DDR software architecture of is shown as Figure.4.

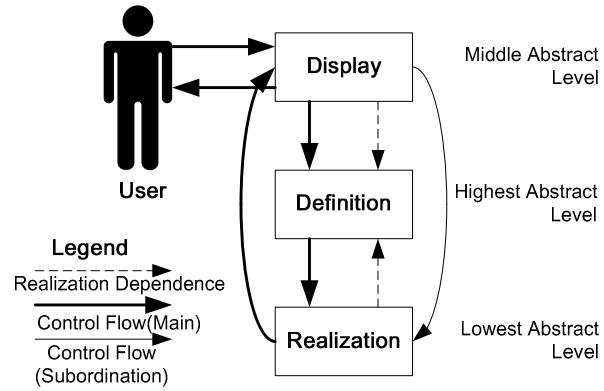

Fig.4. DDR Software Architectur

There are three layers in the DDR, where the abstract layer in bottom is the realizing layer, and the middle displaying layer, the top definition layer. Most of function has three layers except the functions which are difficulty to abstract their definition, and they can only have the realization layer and displaying layer because they only interaction with the displaying layer for most users.

The definition layer includes the accessing interface of the abstract data and general data processing centre. And the realization layer also has two parts. One is the design of the database table and another is the realization of the mathematical modelling and calculating formulas. The calculation formulas such as equation(4) and (5) and others are realized with class CeTMSCalculator. In the

database design, we have designed about 60 tables to express the modelling and emulating online of the energy system in the papermaking using the method of “three link”.

B. online simulation

To diagnose the energy system, modelling and simulation should be finished before emulating it online. Then we can diagnose the bottleneck of the energy system. For example, we can find which line, section, device even the unit whose production efficiency is low. Besides the production efficiency, the energy efficiency should be taken into count.

The next is to how to improve the system. We can use the optimizing and integrated technology. The key problem is to simulate and optimize it online, which is so called online emulation.

If the data used for modelling and analyzing can be collected for the database in real-time, online simulation will be realized. The software architecture of the online simulation is shown as Figure.5.

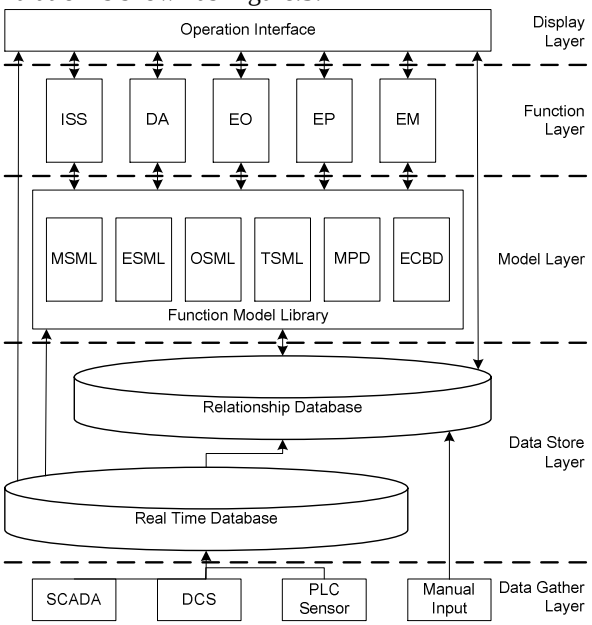

Fig.5. Online simulation software architecture

Where the abbreviations mean:
ISS: Information Supervise and Schedule
DA: Data Analyse
EO: Energy Optimize
EP: Energy Plan
EM: Event Manage
MSML: Material flow Simulation Model Library
ESML: Energy flow Simulation Model Library
OSML: runtime Optimization Simulation Model Library
TSML: "Three-link" energy system Simulation Model Library
MPD: Material Property Database
ECBD: Energy Consume Benchmark Database

The online simulation software architecture is composed with data acquisition layer, data storage layer, modelling layer, function layer and displaying layer. The data acquisition layer is to acquire the data from SCADA DCS, PLC sensors connected to all kinds of equipments, and then the acquired data is stored into the real-time database iHistorian. To facilitate the functional model library call, we can collect part of the data in the real-time database to put into the relation database, so does the data that need to be entered manually or to be configured. The analysis result of the modelling layer is transmitted to the functional layer in time. At the same, it will be stored into the relation database. To improve the efficiency of the analyzing, inspecting and displaying, the modelling layer and the displaying layer can access the data in the real-time database directly. What’s more, the displaying layer can also access directly the data in the relation database. The modelling layer also called functional model library, includes material flow simulation model library, energy flow simulation library, optimizing simulation library, three step energy system model library, property database and the energy consumption standard database.

When calculating the energy and exergy of the material using the formula (4) and (5), the relative physical characteristic of the material, such as *Cp*, *h*, *s*, must be given, so the model layer includes the property database. In previous, the property data is gained by look-up table manually, so it is not only slow, but easy to make a mistake. It has established the relative database for the physical character of the dry atmosphere (*p=0.10133MPa*) , the specific heat capacity of the solid fuel ash, the physical character of the flue gas in the atmospheric pressure and furnace cooling, whose physical character is calculated by linear interpolation. The calculation of the physical character of the water and water vapour is referred to IAPWS-IF97 criterion[21][22], because of the big error calculated by the linear interpolation and the heavy workload of the construction of a database. We write the program for calculating automatically the physical character of the water and steam and embed it into the energy system modelling and online simulating[23][24].

The functional layer content can realize the function of information monitoring and scheduling, data analyzing, energy optimizing, and energy planning and event management. Besides, it can interact with the model layer and displaying layer in two-way.

As soon as the modelling library of material flux, energy flux and physical character, the simulating and emulating online of the energy system can be realized. As a result, the simulation database of the material flux and energy flux can be established. So we can diagnostic, analyze, optimize and monitor the energy system of a papermaking factory online.

5. Conclusion and discussion

There is huge potential saving in the papermaking, which is shown that it is need to improve the saving technology, including the saving technology for the equipment and system saving technology, and saving theory in the papermaking. Except for using hardware equipment with

more advanced and more saving, we can use the method of online simulation, which is to model, simulate online the energy system of the papermaking factory to realize saving, consumption decrease.

In this paper, we present a general frame of the modelling and simulating online of the energy system of the papermaking factory, which will have a conductive mean to it. For a papermaking factory, we design the flux model of the thermal power plant, deinking line and paper machine energy system， and realize the online simulation. Compare with the previous modelling and simulating which is offline, closed and fragmented, the method present in this paper is open, integrate and online.

From the analysis of the energy system in this frame, we model the boiler, steam turbine, steam pump, condenser, pipeline, repulping, thermal dissipation, bleach, dryer, steam-water separator, heat exchanger, condensed steam water recycle, hood, ventilation system. Using this framework, we can also do the energy analysis of the flux material, such as coal, diesel oil, natural gas, liquefied petroleum gas, water, condensate, dry atmosphere, wet atmosphere, steam, dope, slurry, wet and dry paper and established the mathematical model of the equipment, energy flow, exergy flow， thermal power plant， deinking line and paper machine， and the property database of the water, water vapour, dry and wet atmosphere, flue gas , boiler heat dissipation、ash, and design the general simulation software architecture which can realize the online simulation by acquire data from the real-time database. This frame can diagnostic, analyze, optimize and simulate online the energy system of the papermaking factory.

This framework we designed is used in Guangzhou Paper Group Co,Ltd and Gold East Paper (Jiangshu) Co, Ltd, the results show that the frame is practical and the flow of the material and energy can be diagnosed, analyzed, optimized, simulated and emulated during the papermaking process through the online emulation. According to the simulation of the material flow, the dosage of the product and service can be decreased, which leads to the reduction of the dosage of the material and emissions. If energy flow simulation done, the energy dosage of the product and service can also be decreased to aim to improve the energy usage efficiency and the energy saving. Similarly, the diagnosis, analysis, optimization and monitoring of the flow of the material, energy and information can be realized base on the online simulation of material flow (energy flow) that is the balance analysis of the material flux, energy flux. This also can achieve the maximum usage of the material and resource and lead to reduce reuse and recycle the resource.

But there still are many problems to be researched further more.

1. How to show and simulate the technology process more intuitionistic and visual.

2. How to combine with e!sankey to shown better energy flow and exergy flow.

3. How to combine the material flow with the energy flow to analyze.

4. How to online optimize.

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