RESEARCH ARTICLE

Modeling of Ventilation's Influence on Energy Consumption in Multi-cylinder Dryer Section Part 2: Simulations and Applications

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Abstract

Ventilation system affects the water evaporation rate, energy consumption and the paper quality, which is considered as the largest optimization potential part of multi-cylinder dryer section. In this paper, energy consumption models of multi-cylinder dryer section are constructed by combining energy modules of moisture evaporation, heat recovery system, air heaters, supply air and exhaust air. Taking a corrugated paper machine as an example, ventilation system influence on the energy consumption of drying system is analyzed systematically. It is concluded that reducing the temperature of supply air and increasing exhaust humidity as much as possible to save energy consumption on the premise of meeting the safety production. The increase of supply air humidity will lead to the increase of steam consumption for heating supply air, power consumption of fans, and the total steam consumption in the drying process, so the intake point of supply air should be chosen at the point with low absolute humidity. The models can predict the energy consumption of ventilation system adjustment and optimization, and provide a method for energy-saving evaluation of ventilation system technical transformation in drying process.

Keywords Paper drying · Ventilation system · Energy saving · Energy consumption model · Simulation and optimization

Abbreviations

DCS	Distributed control system
QCS	Quality control system

Variable

A	Area, m^2
B	Paper width, m
c	Specific heat, kJ/(kg*°C)
D_{wa}	Diffusion coefficient of vapor in air, m^2/s
d	Paper dryness, %
$d.a$	Absolute dry air, –
$d.f$	Dry fiber, –
E	Electrical energy, kWh
F	Mass flow, kg/h
G	Basic weight, kg/m^2
h	Heat transfer coefficient, $W/(m^2 *°C)$
H_a	Absolute humidity of air, kg H_2O/kg d.a.
I	Enthalpy value, kJ/kg
I_0	Latent heat of vaporization at 0 °C, kJ/kg
k	Mass transfer coefficient, m/s
l	Length, m
m	Flow rate, kg/h
M	Molar mass, g/mol
N	Amount, –
Nu	Nusselt number, –
p	Electricity consumption, kWh
P	Pressure, Pa
P_0	Atmospheric pressure, Pa
Pr	Prandtl number, –
Q	Heat flow rate, kJ/s;
R	Gas constant, J/(mol*°C)
Re	Reynolds number, –
RH_a	Relative humidity of air, %
Sc	Schmidt number, –
Sh	Sherwood number, –
T	Temperature, °C
V	Volumetric flow, m^3/s
V_a	Diffusion volume of air molecule, cm^3/g mol
V_v	Diffusion volume of vapor molecule, cm^3/g mol
v_a	Air flow speed, m/s
v_m	Running speed of drying section, m/min
x_p	Paper moisture ratio, kg H_2O/kg d.s.
x_a	Relative humidity of air, %

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Δh_{v}	Latent heat of moisture vaporization, kJ/kg
Δh_{s}	Absorption heat of paper, kJ/kg
Δh_{vap}	Latent heat of water vaporization, kJ/kg

Greek alphabet

β	Air leakage ratio of hood, %
γ	Binding factor of water vapor and air, –
η_{fan}	Fan efficiency, %
η_{m}	Mechanical efficiency, %
λ_{a}	Coefficient of thermal conductivity, W/(m^2 *°C)
μ_{a}	Air viscosity, Pa*s
ρ_{a}	Air density, kg/m^3
Φ	The isotherm adsorption line equation

Subscript

a	Air
ah	Air heater
$a\text{-}p$	Between air and paper
aw	Water vapor in air
c	Dryer
$c\text{-}a$	Air and dryer room
$cond$	Condensation
$cont$	Contact drying
$conv$	Convection drying
$c\text{-}p$	Between the dryer and the sheet
d	Dew point
ex	Exhaust
f	Fiber
fa	Fresh air
fan	Fan
h	Hood
hr	Heat recovery system
i	Number of cylinder; –
j	Number of drying area, –
la	Air leakage
$loss$	Loss
p	Paper
pa	Pocket air
pw	Water vapor on paper surface
s	Steam
sa	Supply air
sao	Output of supply air
sai	Input of supply air
sat	Saturation state
ν	Vapor
w	Water

1 Introduction

According to the actual production process and control logic, combined with the module models established by Part 1, energy consumption model of drying system affected by ventilation system is constructed. Steam consumption of cylinders, power consumption of supply and exhaust fans, and steam consumption of air heaters are involved. The evaluation of the model and its applications are showed in this part of the work. The predictions of the model are compared with measurements performed on a paper machine in China.

2 Methodologies

To establish the energy consumption model in line with the operation status of the paper machine ventilation system, some preparations need to be completed, such as investigation of the application case, collection or testing of the model parameters, and determination of some model coefficients based on the measured data. Then, the simulation of energy consumption situation could be realized, and the effects of ventilation parameters on energy consumption of drying process can be analyzed systematically based on the established energy consumption model.

2.1 Investigation and Data Collection

A corrugated paper mill producing 500 ton per day in Henan province of China was studied. The paper machine is equipped with Distributed control system (DCS) and Quality control system (QCS). A closed hood is established, which is equipped with control modules of exhaust air humidity, hood zero position and supply air temperature. The drying section is divided into two parts by sizing. Three sets of heat recovery systems, supply and exhaust air systems are equipped in the pre-drying and one set in the after-drying. The supply and exhaust fans are all controlled by frequency conversion, the steam condensate system can be simplified by analyzing the process flow and on-site investigating, as shown in Fig. 1. The dryer section consists of 61 steam-heated cylinders. The pre-dryer consists of 45 cylinders with a diameter of 1.83 m, and the after-dryer has 16 cylinders with a diameter of 1.83 m. The machine speed is 450 m/min, the basis weight is 200 g/m^2, both dryers are arranged in the form of double row cylinders.

By consulting the design data of paper machine and devices, investigating the operation status of paper machine, testing and collecting the operation data of DCS and QCS, the basic information and main operation parameters of paper machine during the test are shown in Table 1.

2.2 Measurements

In addition to the basic information, process data and data from control systems described above, some process parameters still need to be measured. To obtain the heat and mass transfer model, it is necessary to measure the data including the surface temperature of cylinders, indoor
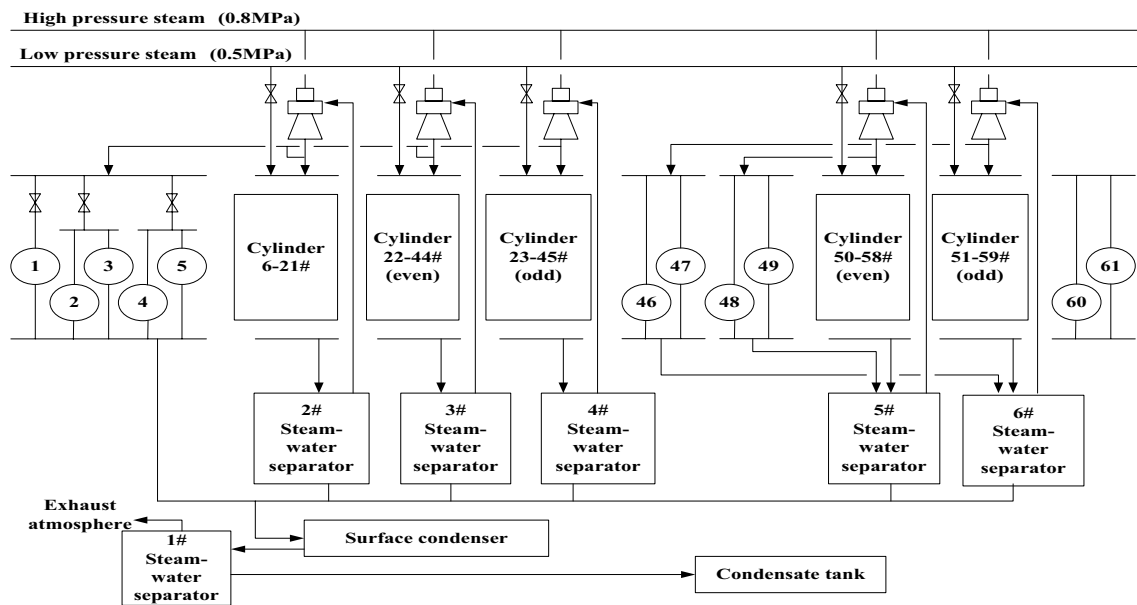
Fig. 1 Schematic diagram of the studied condensate and steam system

and outdoor air condition, paper moisture ratio, and so on. Also, paper temperature was measured to verify the simulation results, each test point is shown in Fig. 2.

(1) Cylinder temperature

A special temperature instrument (Swema Temp 20 and SWT 315, Swema, Sweden) is adopted to measure the temperature of cylinder surface. As shown in the blue box in Fig. 2, several positions were measured by extending the operating rod, and then take the average value for analysis.

(2) Paper temperature

An infrared thermal imager (Fluke Ti40, Fluke international Corporation, USA) is selected to measure the temperature profile of the sheet. To reduce the influence of the test error, the average value of paper temperature is adopted for calculation and analysis based on multiple measurement results of test position as shown in Fig. 2.

(3) Air properties

According to the heat and mass transfer equation of paper drying, the temperature and humidity of supply air are the important factors affecting the evaporation. Parameters of supply air at the intake point should be measured. A multi-functional portable measuring instrument (Testo 435, Testo AG, Germany) cooperated with the sensors was selected to measure.

(4) Paper moisture ratio

A measuring device using γ-radiation (NDC 8110-F/104, NDC infrared Engineering, USA) was used to measure the moisture ratio. The device was calibrated by using a dry cardboard sample. The device is designed to be portable, which mainly relies on the manual support of the scanning rod. Due to the limitation of human force and rod length, the test point is close to the operation side. Several measurements were performed at various positions of the cylinder.

(5) Fan power quality

A power quality analyzer (Fluke 435, Fluke international Corporation, USA) was used to measure the power consumption of fans, voltage and current are measured simultaneously. The average values of test cycle are adopted for calculation and analysis.

2.3 Simulation Program—Parameters and Conditions

Determining heat transfer coefficient between the cylinder and the paper (h_{cp}) is a complex process, because h_{cp} is affected by several factors, including the gap between the cylinder and the paper, the thickness of the paper, paper moisture ratio, the smoothness of the paper and the cylinder surface, the tension of fabric, and so on. h_{cp} was fixed based on the measured data and determined by simulation based on MATLAB programming in this study. A Runge Kutta optimizer by searching

Table 1 The main operating parameters and equipment information of paper machine

Parameter type	Parameters	Amount	Data sources
Structural parameters of paper machine	Paper width, m	4.4	Design data
	Dryer wrap angle, °	230°	Design data
	Number of front drying cylinders N_{C1}, -	45	Design data
	Number of post drying cylinders N_{C2}, -	16	Design data
	Dryer diameter, m	1.83	Design data
	Horizontal distance between drying cylinders, m	2.4	Design data
	Vertical distance between upper and lower cylinders, m	2.047	Design data
	Hood width, m	7.96	Design data
	Hood height, m	7.5	Design data
	Foundation height, m	7	Design data
	Length of front drying hood, m	49.84	Design data
	Length of rear drying hood, m	23.43	Design data
Operation parameters	Paper machine speed v_m, m/min	877	DCS
	Basic weight G_p, g/m^2	200	QCS
	Paper dryness outlet the dryer section $d_{p,o}$, %	93	QCS
	Sizing amount G_s, g/kg paper	20	DCS
	Sizing concentration, %	10	DCS
	Supply air temperature, °C	8.2	DCS
	Supply air humidity, gH_2O/kg d.a	16.69	DCS
	Set humidity of exhaust in pre-dryer, g H_2O/kg d.a	120	DCS
	Set humidity of exhaust in after-dryer, g H_2O/kg d.a	100	DCS
	Set temperature of supply air in pre-dryer, °C	85	DCS
	Set temperature of supply air in after-dryer, °C	85	DCS
	Enthalpy of main steam, kJ/kg	2767.22	Check in IAPWS-IF97[a]
	Condensate enthalpy, kJ/kg	406.79	Check in IAPWS-IF97[b]
Equipment parameters	Total pressure of blowers, Pa	2850	Equipment manual
	Rated volume flow of blowers, m^3/h	62,000	Equipment manual
	Rated power of blowers, kW	75	Equipment manual
	Total pressure of exhaust fans, Pa	1500	Equipment manual
	Rated volume flow of exhaust fans, m^3/h	82,600	Equipment manual
	Rated power of exhaust fans, kW	55	Equipment manual
	Area of gas heat exchanger in pre-dryer, m^2	730	Equipment manual
	Area of gas heat exchanger in after-dryer, m^2	280	Equipment manual
	Heat transfer coefficient of exchanger, W/(m2*°C)	30	Equipment manual

[a]Checked in IAPWS-IF97 for inlet steam at 0.581Mpa and 160 °C

[b]Checked in IAPWS-IF97 for outlet condensate at 0.091 MPa and 97 °C

the optimal point based on the concept of computational gradient search is used to solve the paper temperature and paper moisture ratio, which has the characteristics of strong optimization ability and fast convergence speed.

3 Results and Discussion

3.1 Experimental Data

Heat flux is determined by heat transfer coefficient and temperature difference. Also, the heat flux required for evaporation can be calculated from the measured dewatering rate. By adjusting the heat transfer coefficient to fit the calculated and the measured dewatering rate, and by comparing the simulation results with the measured values of paper temperature, and moisture ratio, the estimated value of heat transfer coefficient can be obtained.

3.1.1 Surface Temperatures of Paper and Cylinders

Combined with the operation and structural parameters of the paper machine listed in Table 1, and the parameters of the sheet and the surface temperature of cylinders were
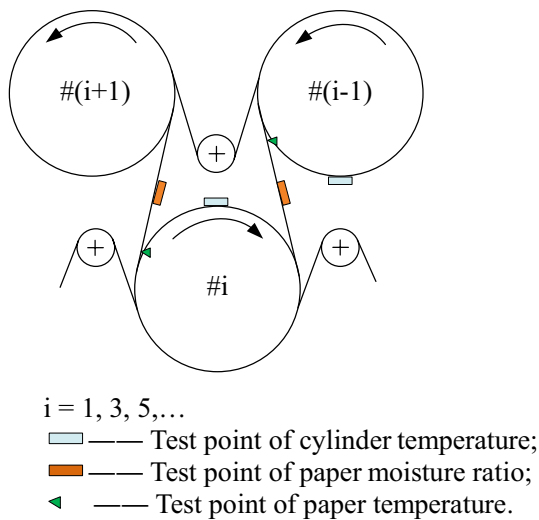
i = 1, 3, 5,…

▭ —— Test point of cylinder temperature;
▬ —— Test point of paper moisture ratio;
◄ —— Test point of paper temperature.

Fig. 2 Test points of operating parameters in multi-cylinder dryer sections

tested, the paper temperature curve can be obtained using Eqs. (1–19) in part 1 and ode 45 function of Matlab software. The calculated results based on different h_{cp} are listed in Fig. 3.

As shown by the black dotted line in Fig. 3, when $h_{cp} = 650$, the calculated T_p in the tail end of pre-dryer and after-dryer are lower than the measured value; When $h_{cp} = 850$ (green dash-dotted line) the calculated T_p in the tail end of two dryers are higher than the measured value. The calculated T_p is the best consistent with the measured value as $h_{cp} = 750$, as shown in red line. The values are also in line with $100 \sim 2200$ determined in other literatures [1–3]. Meanwhile, the temperature of cylinder surface affects paper moisture ratio by determining the heat transfer power of water evaporation. Therefore, as shown by the orange " + " in Fig. 3, the surface temperature of cylinders distribution

shows the same change law with the paper surface temperature, which indirectly proves the reliability of the simulation result when $h_{cp} = 750$. Gaps between the calculated and the measured value existed in the start stage of pre-dryer and after-dryer. Through the test of the temperature distribution on the cylinder surface, it is found that some cylinders surface in the front-end of pre-dryer and after-dryer had adhesion and paper wool, which resulting in poor heat transfer. As shown in Fig. 4, for 1 and 47# cylinder, the strip distribution of temperature means that the paper is heated unevenly at the beginning of drying.

3.1.2 Paper Moisture Ratio

The changes of paper moisture ratio under different h_{cp} are shown in Fig. 5. The dryness of paper outlet the press section ($d_{p,i}$) is 46.8%. The paper is immersed in the sizing agent to obtain the resistance of liquid diffusion and improve the paper strength. The paper moisture ratio is increased from 0.15 to 0.4 after sizing because the paper absorbs water and adheres to the sizing agent. As shown by the black dotted line in Fig. 5, when $h_{cp} = 650$, the calculated x_p (about 0.120, corresponding to 89% of paper dryness) out of the after-dryer is significantly higher than the measured value (0.07, corresponding to 93.4% of paper dryness). When $h_{cp} = 850$, the calculated x_p (0.034, corresponding to 96.7% paper dryness) outlet the after-dryer is significantly lower than the measured value, as shown by green dash-dotted line. Compared with the former two, the calculated x_p (about 0.059, corresponding to 94.4% of paper dryness) is very close to the measured value when $h_{cp} = 750$. It can be considered that the calculated paper moisture ratios are consistent with the actual situation when $h_{cp} = 750$. The calculated paper dryness is 94.4%, slightly higher than the design value (93%), and close to the value of QCS (93.4%). Considering the basis weight of paper fluctuates between 140 and 250 g/

Fig. 3 Comparison between the measured and calculated T_p with different h_{cp}
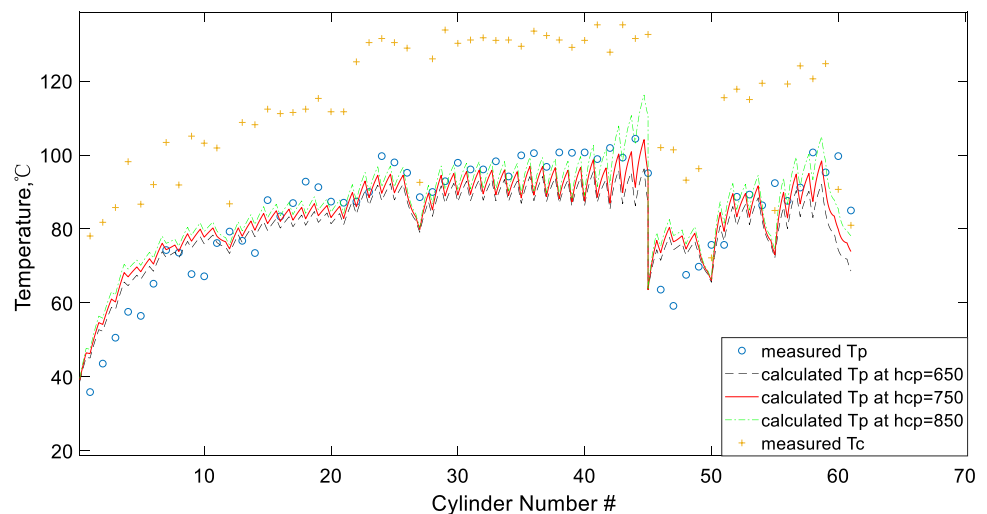
Fig. 4 IR pictures about the temperature of cylinder surface in 1 and 47# cylinder
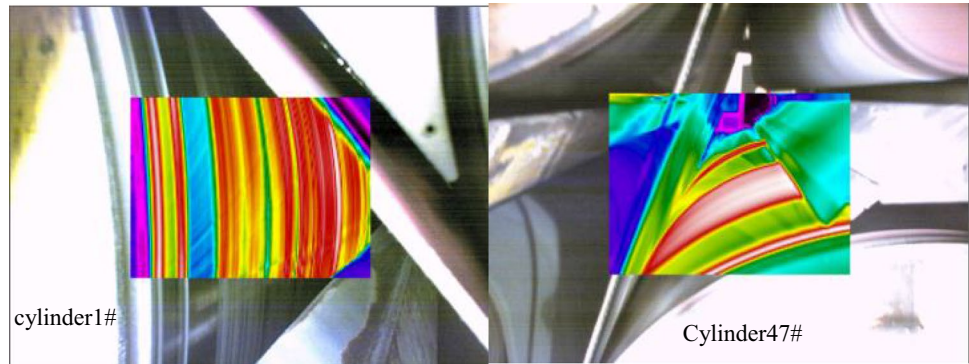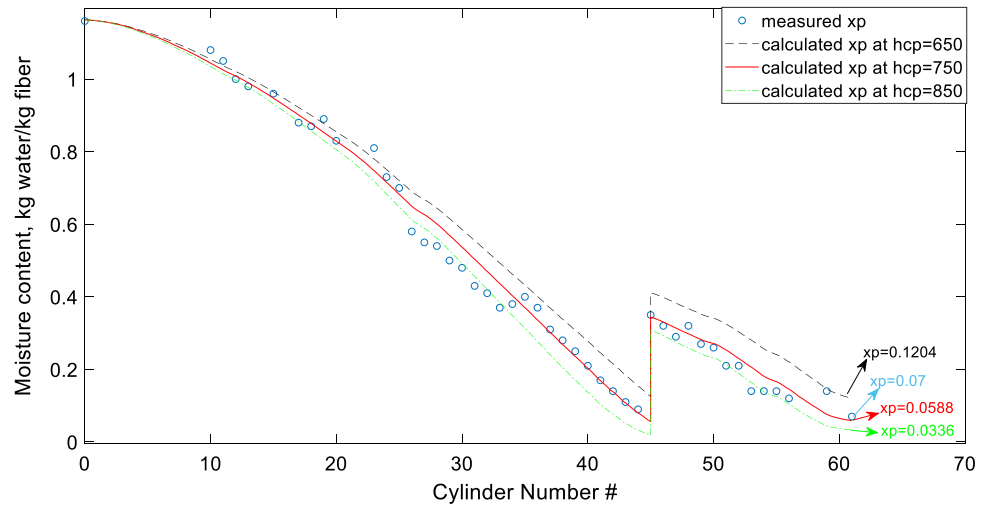

cylinder1#

Cylinder47#

Fig. 5 Comparison between the measured and calculated x_p with different h_{cp}

m^2. Generally, only the steam differential pressure will be adjusted when the basis weight changes, the number of cylinders put into use would not be changed, over drying may occur when producing low basic weight products.

3.1.3 Energy Consumption

To verify the calculated results, the statistical data of steam consumption during the test period are adopted instead of the real-time data considering the frequent fluctuations of steam flow rate. The average powers are obtained during the test period, as shown in Table 2. The running time of statistical period is 720 h, the total steam flow during the test period is 26222 ton, and the corresponding paper yield is 15714.87 ton. So, the paper yield per hour is 21.82 ton and the steam consumption for producing 1 ton paper is 1.67 ton. The tested cumulative power can be obtained by summing the average powers of all blowers and exhaust fans is 319.7 kW, the electricity consumption of ventilation system for producing 1 ton paper can be calculated as 14.7 kWh by dividing the cumulative power by the yield per hour, as shown in Fig. 6.

Table 2 Energy consumption test during the test period

Items	Units	Amount	Source
Running time of statistical period	h	720	Statistical report
Output in test period	Ton	15,714.87	Statistical report
Steam consumption during test period	Ton	26,222	Statistical report
Pre drying 1# forced draft fan power	kW	27.9	Tested
Pre drying 2# forced draft fan power	kW	67.0	Tested
Pre drying 3# forced draft fan power	kW	25.1	Tested
Power of rear drying blower	kW	17.4	Tested
Pre drying 1# exhaust fan power	kW	28.9	Tested
Pre drying 2# exhaust fan power	kW	85.3	Tested
Pre drying 3# exhaust fan power	kW	45.4	Tested
Power of rear drying exhaust fan	kW	22.9	Tested

Based on the models established in Part 1, the steam consumption of cylinders can be obtained according to the evaporation model as different h_{cp} adopted. The
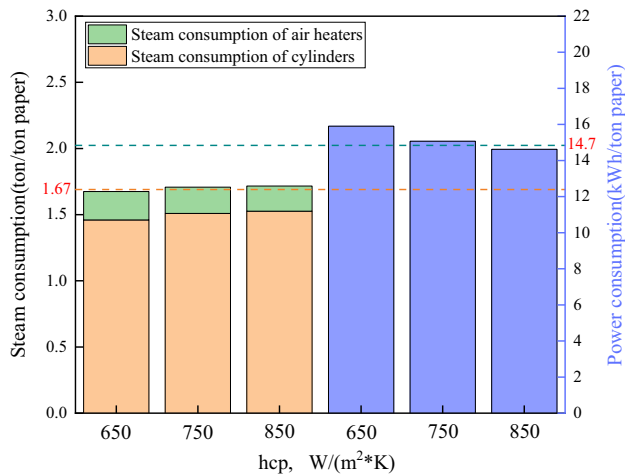
Fig. 6 Comparison of the calculated and the measured energy consumption

corresponding steam consumption of the air heater can be obtained by calculating air heater model and heat recovery model based on hood operation parameters. The corresponding power consumption of supply and exhaust fans can be obtained according to the calculated air volume and parameters of fans performance, the results are also shown in Fig. 6.

For comparison, the tested values are also presented, as shown by green and red dotted lines in Fig. 6. It can be seen from Fig. 6 that the calculated steam consumption is 1.70 ton steam/ton paper, which is very close to the actual situation (1.67 ton steam/ton paper), and the calculated electrical energy consumption is 15.0 kWh/ton paper, which is consistent with the measured value (14.7 kWh/ton paper). Therefore, it can be considered that the

simulation results are in good agreement with the actual situation as $h_{cp} = 750$.

3.2 Influence of Ventilation System on Energy Consumption in Drying Process

In the actual process, supply air temperature, dew point of exhaust air and the zero position of hood are usually selected to control the operation of ventilation system. The inlet supply air temperature and humidity are variable because of the weather change. Exhaust volume is mainly determined by the dew point control, and the flow rate of supply air needs to be adjusted accordingly to keep the zero position of hood. The dew point control of hood is mainly realized by controlling the exhaust humidity. To explain the influence of ventilation system parameters on energy consumption more intuitively, analysis is also carried out based on the cases above.

3.2.1 Influence of Air Supply Temperature on Paper Dryness and Energy Consumption

Literature points out that the appropriate temperature of supply air is among of 90~95 °C [4]. Tappi recommends that supply air temperature changes within 82~93 °C [5]. Therefore, the variation rule of energy consumption as the supply air temperature increases from 80 to 130 °C is analyzed, as shown in Fig. 7.

As shown in Fig. 7, as supply air temperature increases from 80 to 130 °C, the change of paper dryness can be ignored. This conclusion is consistent with other literature that the increase of evaporation rate can be ignored as supply air temperature increases from 80~90 °C to 120~130 °C [4]. Inferring from the mass transfer equation, the driving force of paper drying is the difference between the vapor

Fig. 7 Effect of supply air temperature on the paper moisture ratio
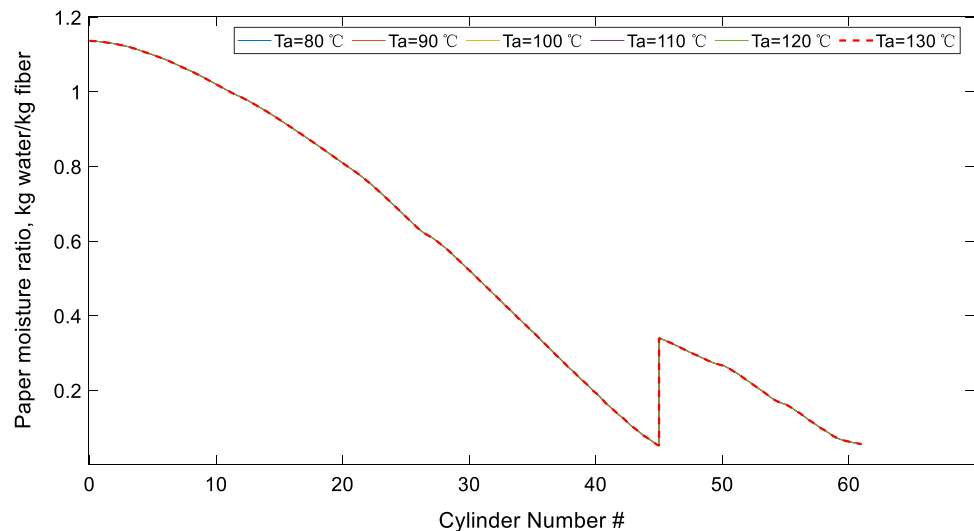
partial pressure of the paper surface and the pocket air. The low supply air temperature will decrease the evaporation rate, and increase the relative humidity of pocket area, which will lead to the easy condensation in the pocket area. Meanwhile, on the premise that other parameters are stable, if the inlet air temperature is too high, steam consumption of the air heater will be increased, as shown in Fig. 8.

As shown in Fig. 8, steam consumption of cylinders decreases from 1.52 ton/ton paper to 1.34ton/ton paper as the supply air temperature increases from 80 to 130 °C. According to the heat transfer equation, the heat transfer between air and paper will affect the evaporation rate. The higher the supply air temperature, the greater heat transfers from air to the sheet. If the evaporation load is fixed, less heat needs to absorb from the cylinder. The higher the supply air temperature, the smaller the heat dissipation of the cylinder. The increase of supply air temperature means more steam need to heat the supply air. So, the steam consumption of the air heater increases from 0.186 ton/ton paper to 0.388 ton/ton paper as the supply air temperature increases from 80 to 130 °C, as the black frame line shown in Fig. 8. As the increase of supply air temperature, the heat dissipation of cylinders will be reduced, resulting in a slight decrease in the calorific value of exhaust air, which will lead to a slight decrease in the temperature of supply air after heat recovery. The flow rate of fan also decreases, which leads to a slight decrease in the power consumption of fans, as shown in the purple asterisk line. The total energy consumption increased from 1.706 ton/ton paper to 1.728 ton/ton paper because the steam consumption of air heater increased. The similar result is obtained that the steam consumption of the drying section will increase by 2% in other literature [4]. Therefore, from the perspective of energy conservation, the supply air temperature can be reduced as much as possible to save energy consumption on the premise of meeting safety production.

3.2.2 Influence of Supply Air Humidity on Energy Consumption

Supply air humidity is mainly affected by the weather change and the selection of air intake point. This study also analyzes the variation rule of paper dryness and energy consumption as the supply air humidity increases from 0.010 kg H_2O/kg d.a to 0.050 kg H_2O/kg d.a.

As shown in Fig. 9, the final paper moisture ratio changes from 0.0552 kgH_2O/kg fiber to 0.0623, that is, the dryness decreases from 94.7 to 94.1%, as supply air humidity increases from 0.010 kg H_2O/kg d.a to 0.050 kg H_2O/kg d.a. According to the mass transfer equation, the driving force of evaporation is affected by the vapor partial pressure of pocket air. As the increase of supply air humidity, the mass transfer driving force decreases, that is, the drying rate decreases. Given the relatively small change of air humidity and the limited impact on the evaporation force, the influence of supply air humidity on the dryness of the paper can also be ignored. The heat transfer of cylinder to air increases as the increase of supply air humidity by analyzing the heat transfer equation, resulting in the increase of steam consumption. Meanwhile, the air heater will need more steam to heat supply air with higher humidity, as shown in Fig. 10 (the black frame line).

Due to the limitation of zero position and exhaust dew point or exhaust humidity, the flow rate of exhaust air increases as the increase of supply air humidity, resulting in steam consumption of air heater increases from 0.168 ton/ton paper to
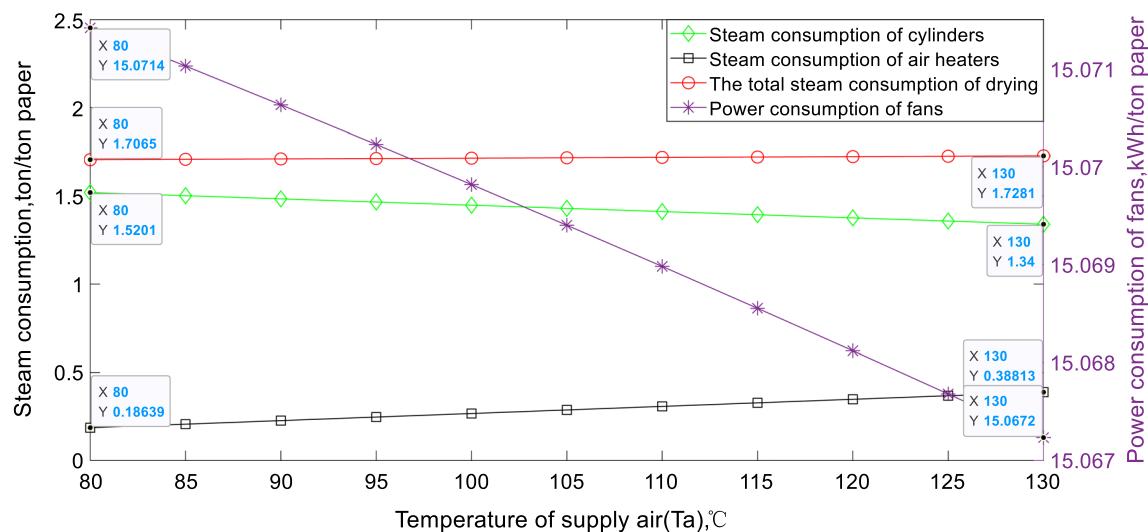

Fig. 8 Effect of air temperature on the energy consumption of drying process

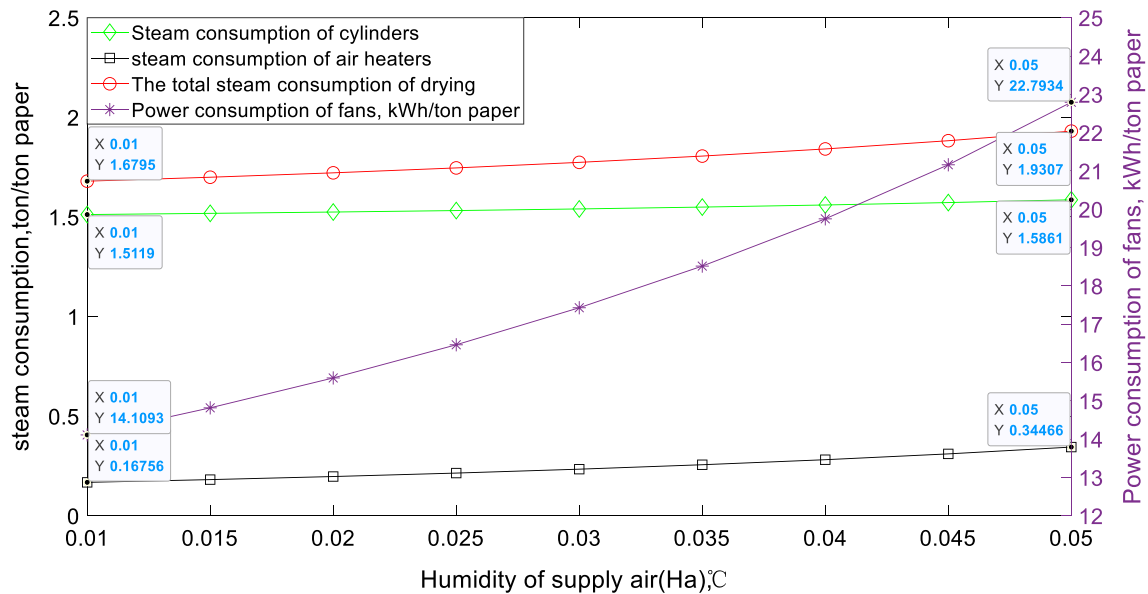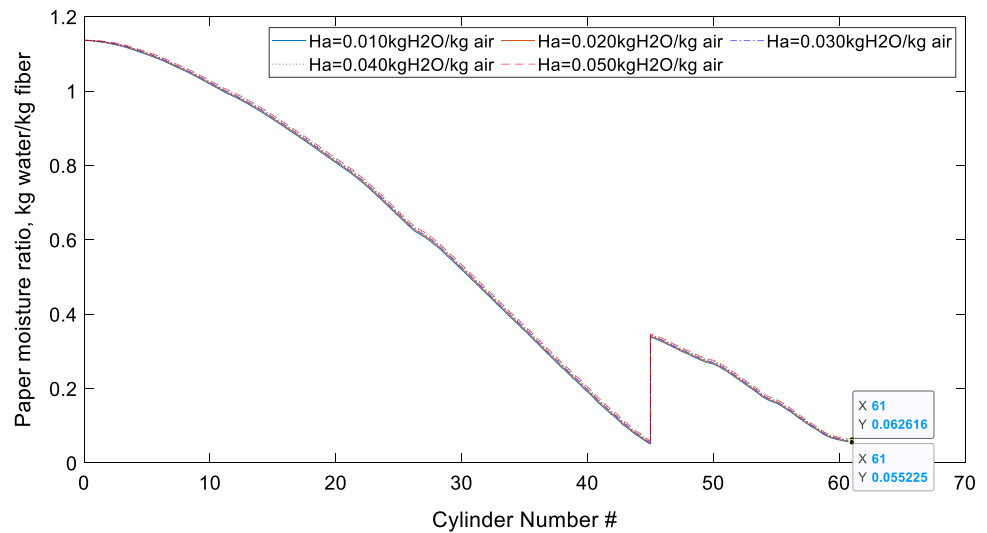**Fig. 9** Effect of supply air humidity on the paper moisture ratio

Fig. 10 Effect of air humidity on the energy consumption of drying process

0.345 ton/ton paper. Power consumption of fans increases from 14.109 kWh/ton paper to 22.793kWh/ton paper as the increase of supply air and exhaust flow rate. It can also be seen from the figure that the total steam consumption in drying system increases as the increase of supply air humidity. Therefore, from the perspective of energy conservation, the air intake point should be taken at the point with low humidity, and ventilation system should be adjusted in time according to the weather change.

3.2.3 Influence of Exhaust Air Humidity on Drying and Energy Consumption

According to the mass transfer equation, the driving force of paper drying is affected by the vapor partial pressure of pocket air. The higher the exhaust humidity is, the smaller the mass transfer driving force. The variation rule of paper dryness and energy consumption are analyzed as

Fig. 11 Effect of exhaust air humidity on the paper moisture ratio
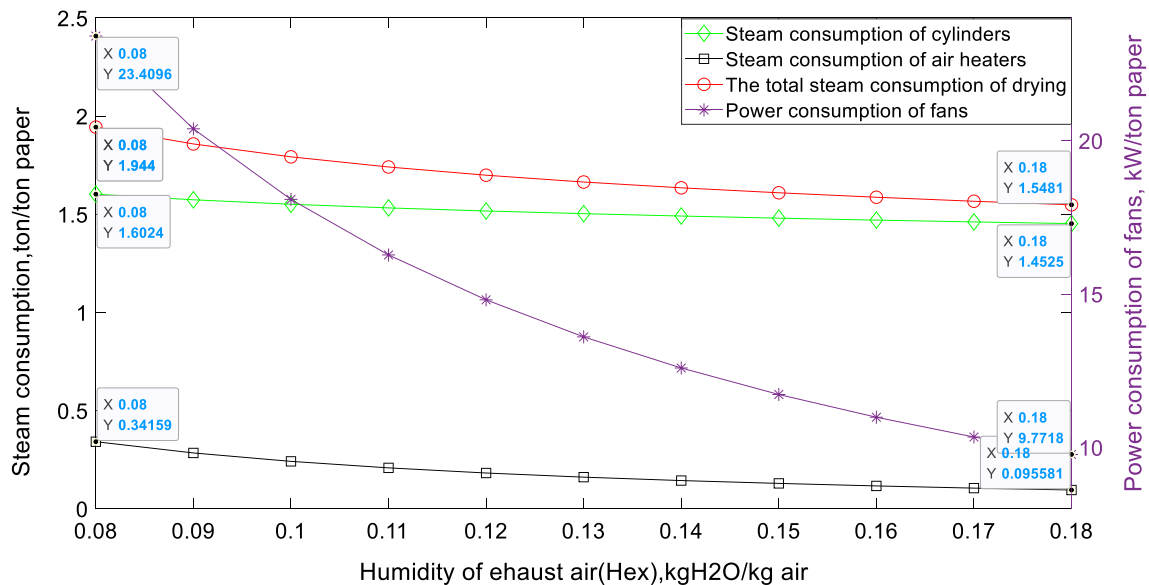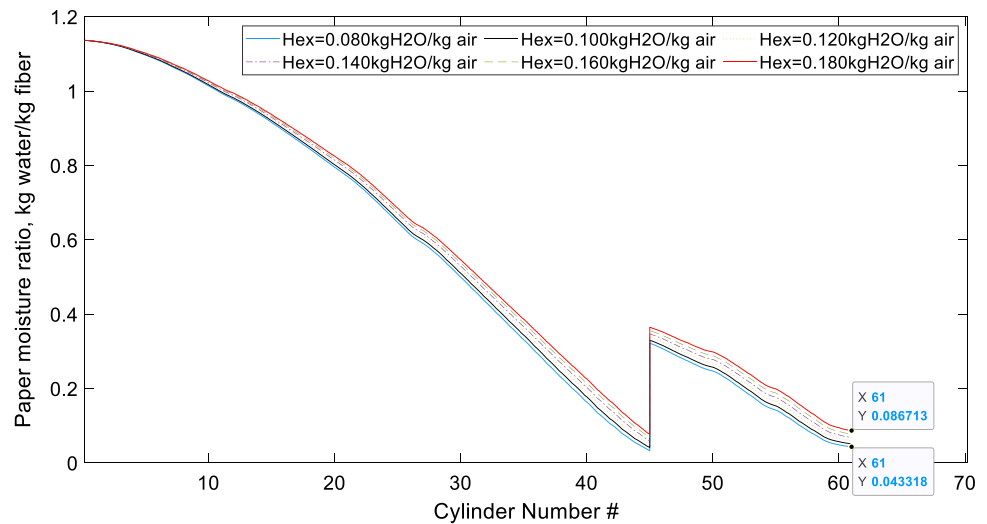
**Fig. 12** Effect of exhaust air humidity on the energy consumption of drying process

the exhaust humidity increases from 0.080 kg H_2O/kg d.a to 0.180 kg H_2O/kg d.a.

As shown in Fig. 11, the final paper moisture ratio changes from 0.0433 to 0.0867 kg H_2O/kg fiber (that is, the dryness decreases from 95.8 to 92%), as the increase of exhaust humidity from 0.080 to 0.180 kg H_2O/kg d.a. Supply air and exhaust air flow rate decrease under the influence of zero control if exhaust humidity increases. The decrease of supply air flow rate leads the increase of vapor partial pressure in the pocket area, and reduces the drying rate. So, the dryness of the paper is declined.

The influence of exhaust humidity on energy consumption is shown in Fig. 12. As the increase of exhaust humidity, the steam consumption of cylinders and air heaters decreases

from 1.602 and 0.342 to 1.453 ton/ton paper and 0.096 ton/ton paper, respectively. Supply air and exhaust flow rate will be reduced as the increase of exhaust humidity considering dew point control and zero position control. The steam required to heat the supply air and the heat dissipation of cylinder are reduced, and the power consumption of fans will decrease from 23.410 to 9.772 kWh/ton paper because the flow rates of supply air and exhaust decrease. Therefore, the steam consumption and fan power consumption decrease as the increase of exhaust humidity. The overall energy consumption also decreases, which is consistent with other research results [6]. From the perspective of energy conservation, the exhaust humidity should be increased as much as possible.

Fig. 13 Paper moisture ratio as three cylinders are added at Hex = 0.180 kg H2O/kg d.a
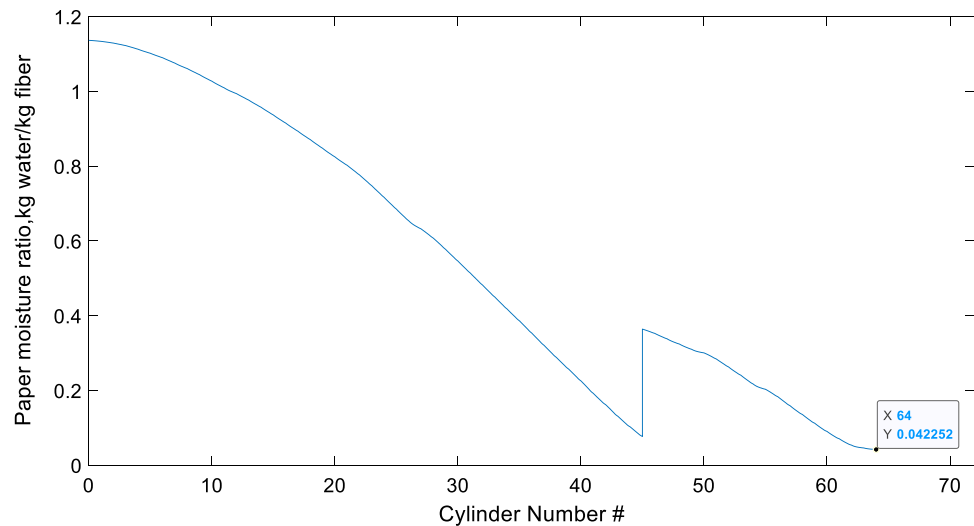
As shown in Fig. 11, the total energy consumption of drying system decreases as the increase of exhaust humidity, but it reduces the final dryness of paper. To achieve the paper dryness at 0.080 kg H_2O/kg air, three cylinders need to be added as exhaust humidity is 0.180 kg H_2O/kg air, as shown in Fig. 13. The calculation result shows the steam consumption of cylinders and air heaters will be increased to 1.487 ton/ton paper and 0.107 ton/ton paper, respectively. The total steam consumption is 1.594 ton/ton paper, and power consumption of fans is 9.803 kWh/ton paper, which is still significantly less than the energy consumption as exhaust humidity at 0.080 kg H_2O/kg air.

4 Conclusion

Simulation of ventilation systems in multi-cylinder dryer section can be realized through the combination of the functional modules established in Part 1. Taking a corrugated paper machine as an example, the energy consumption model is established using the measurement data, operation data and basic information of the paper machine. The influence of the key variables of the ventilation system on the energy consumption is analyzed systematically.

It is proposed that the increase of supply air humidity will increase the steam consumption of air heater, the power consumption of fans, and the total steam consumption in the drying process. The air intake point should be selected the point with low absolute humidity, and the ventilation system should be adjusted in time according to the weather changes. It can be concluded the supply air temperature and exhaust humidity should be reduced as much as possible to save energy consumption. Considering the adjustment variables are consistent with the site, this study can predict the energy consumption of ventilation system adjustment, and provide theoretical foundation and analytical tool to analyze the variation rule of energy consumption affected by the operational parameters of ventilation system. It also has important reference value for guiding the optimization of ventilation system and the reduction in energy consumption.

This study perfects the mechanism of ventilation system assisted drying. The change of ventilation parameters will affect the heat transfer process of paper drying. In this study, the steam condensate system is simplified as the heat source. The steam condensate system should be integrated to realize the simulation of the whole drying system in the follow-up study. The research of the models is the key to the integration the control of ventilation system and steam condensate system, and it is also the premise to realize the intelligent control of paper drying process, intelligent fault diagnosis with uncertainties and intelligent real-time industrial process monitoring and control. Meanwhile, modeling the influence of ventilation system on drying energy consumption is the basis of realizing the operation optimization of the whole drying process. The researches about operation optimization of the whole drying system and model's algorithm will be carried out in the future to realize the intelligent manufacturing of complex system.

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Data Availability The data are given in the paper.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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