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Research on Utilization of Waste Heat and Waste Resource in a Soy Protein Powder Plant

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Abstract

Soy bean is one of the main cereal crops in the world, the protein content of which accounts for nearly 40%. As nourishing food, soy protein has been widely applied in food industry. Alkali extraction and acid precipitation is the main manufacturing technique of soy protein. The energy consumption of this manufacture process is considerable. In the traditional manufacture process, exhaust air from the cyclone and the soy whey water are discharged to the environment directly. However, the temperature and the humidity of the exhaust air is much higher than those of the environment, thus, there is great potential to recover heat from the exhaust air. The soy whey water is the wastewater from the manufacturing process. More than 60 tons of wastewater will be discharged to the environment to produce 1 ton of soy protein according to the survey data. It contains nearly 2% of protein and other substances in the wastewater, and it will not only pollute the environment but also causes resource waste by discharging directly. Condensing the wastewater could solve the problem, as the condensing product could be used as feed for animals, which could recover resource and prevent pollution at the same time.

A water loop with a heat pump is established as the waste heat recovery system from the exhaust air. The whole year operating performance is analyzed according to the meteorological parameters. Compared with the traditional manufacture process, the total energy saving amount could reach 3100 tce per year, and the energy saving rate is 21%.

A mechanical vapor recompression system is established as the waste resource recovery system from the soy whey water. Operating performance under different evaporating temperature is analyzed of the system. When the evaporating temperature is 60 °C, the energy consumption of the compressor is 31 kWh to evaporate per ton of water. Both of the evaporation rate and the energy consumption increase as the increase of the evaporating temperature. And there is a trade-off between the evaporation rate and the energy consumption.

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Keywords: soy protein; waste heat recovery; waste resource recovery; operating performance

Nomenclature

α	mass transfer coefficient (kg/(s • m^2))	*comp*	compressor
c	concentration of solution	*cw*	condensed water
c_p	specific heat capacity (kJ/(kg • K))	*dis*	discharge
d	humidity ratio (kg/kg)	*e*	evaporating
d_{wb}	humidity ratio of the saturated air on the surface of the spray water film (kg/kg)	*ele*	electricity
E	energy consumption (kW)	*hrhx*	heat recovery heat exchanger
F	heat transfer area (m^2)	*hx*	heat exchanger
h	specific enthalpy (kJ/kg)	*i*	inlet
K	heat transfer coefficient (kW/m^2/K)	*np*	normal pressure
m	mass flow rate (kg/s)	*o*	outlet
n	polytropic index	*oli*	oligosaccharide
Q	heat exchange capacity (kW)	*op*	other pressure

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Q_n	heating load (kW)	*p*	exhaust air
R_g	gas constant	*pol*	polytropic
r_w	latent heat of vaporization of water(kJ/kg)	*pro*	protein powder
t	temperature (°C)	*r*	heat recovery
Δ	boiling point elevation	*s*	protein solution
η	efficiency	*suc*	suction
Subscript		*ste*	steam
1	the first step of air heating	*sw*	spray water
2	the second step of air heating	*v*	vapor
3	the third step of air heating	*w*	water
a	air	**Abbreviation**	
b	boiling point	*COP*	coefficient of performance (W/W)
c	condensing		

1. Introduction

Soy bean is one of the main cereal crops in China, and the average annual output has reached 14.6 million tons in the last two decades [1]. The protein content of soy bean is quite high, which accounts for nearly 40%. Especially, the protein content could reach over 90% of soy protein isolate. Therefore, as nourishing food, soy protein has been widely utilized as raw materials in food industry.

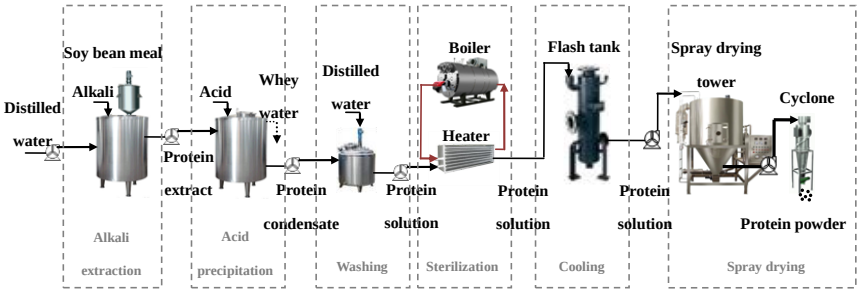


Fig. 1. Manufacture process of alkali extraction and acid precipitation of soy protein powder

The main manufacturing technique of soy protein isolate is alkali extraction and acid precipitation. As protein could dissolve in the alkali solution and precipitate in the acid solution, therefore the alkali extraction and acid precipitation method is utilized to extract protein from soy bean. Fig.1 is the traditional manufacture process for soy protein powder in a soy protein powder plant. Raw materials are soy bean meal. Firstly, alkali solution is added into the soy bean meal, and protein extract is obtained. Secondly, acid solution is added into the protein extract, and protein precipitates from the solution as protein condensate, and the whey water is abandoned. And the strong protein solution is obtained after washing, sterilization and cooling. Finally, the strong protein solution is leaded into the spray dryer and the cyclone for drying and separating, and the protein powder product is obtained.

Among the manufacture process of soy protein powder, spray drying is the main sector of energy consumption. As the protein solution needs to be dried to protein powder in the spray drying process, the temperature of the air, which is the heating source, must be sufficiently high, such as 190°C. Usually, the ambient air is directly heated by the hot steam from the boiler, and then it is conducted to the spray chamber to be fully contacted with the strong solution in the spray chamber, in which the micro liquid drops of the solution could be dried to powder immediately. Afterwards, the air mixed up with powder is taken into the cyclone, where the powder is then separated by centrifugal force and accumulates at the bottom of cyclone, and the exhaust air is discharged directly on the top of cyclone. The schematic diagram of the spray drying process for soy protein powder is shown in Fig. 2.

Therefore, the spray drying is an energy-intensive process [2].The UK government's Energy Efficient Best Practice Program conducted a survey of energy consumption of industrial spray dryers in 2000, and the result has indicated that the energy consumption could reach 3–20GJ to evaporate each ton of water in which the

evaporation rate is 0.1–12t/h. The average energy consumption reaches 4.87GJ for each ton of water evaporation [3]. Accordingly, it is of crucial importance to improve the manufacture process to reduce energy consumption.

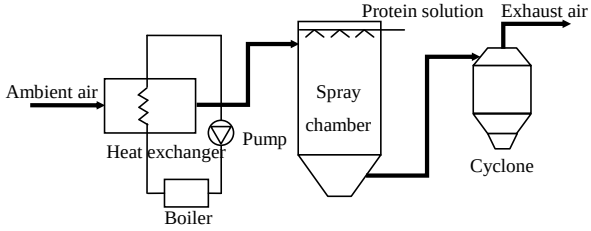


Fig. 2. Spray drying process for soy protein powder

In the traditional spray drying system, the exhaust air is discharged to the environment directly. However, the temperature and humidity of the exhaust air are still much higher than those of the ambient air, which could reach 70°C – 73°C and 50 – 63 g/kg around the whole year. Many researchers have proposed heat recovery strategies from the exhaust air to save energy. In 1980, Holland et al. [4] firstly proposed the concept of heat recovery of spray drying process. An air-to-air heat exchanger is commonly utilized to recover waste heat from the exhaust air to preheat the fresh air [5-9]. And the evaporation efficiency with the variation of the range of recirculation from the exhaust air is calculated in Velic's paper [7]. In Atkin's paper [10-11], water loops between the exhaust air and the heat sinks are established to recover heat from the exhaust air, which is more suitable for the occasion where there is long distance between the exhaust air and the fresh air. Except for heat recovery heat exchangers in the heat recovery system, Wang et al. [12] has applied a heat pump in the heat recovery system, and the selection of heat pumps is studied for heat recovery. Among the previous research, the sensible heat is recovered by applying the heat recovery heat exchanger. However, the latent heat of the exhaust air is still quite high, both of the sensible heat and the latent heat recovery are necessary. And analysis of the whole-year performance of the heat recovery system is also insufficient in the previous research.

Soy whey water is the wastewater from the alkali extraction and acid precipitation manufacture process of soy protein powder. More than 60 tons of wastewater will be discharged to the environment to produce 1 ton of soy protein according to the survey data. For the largest soy protein production base in China, the average annual output of soy protein could reach 70 thousand ton, then the soy whey water could reach 4.3 million ton per year. It contains nearly 2% of protein and other substances in the soy whey water. In the traditional manufacture process, the soy whey water is discharged directly to the environment, which not only pollutes the environment but also causes resource waste. Nowadays, as technology improves, researchers begin to focus on the treatment of soy whey water to recover resources from it, such as whey protein and oligosaccharide. However, the industrial treatment of soy whey water is complicated and quite expensive, including the ultrafiltration system to separate protein and oligosaccharide. [13-15]. Soy protein and oligosaccharide are both nutritious food, thus, if the soy whey water could be condensed with small quantity of energy consumption, then the condensate of soy protein and oligosaccharide could be raw materials added into the protein nourishment, such as soy protein drink.

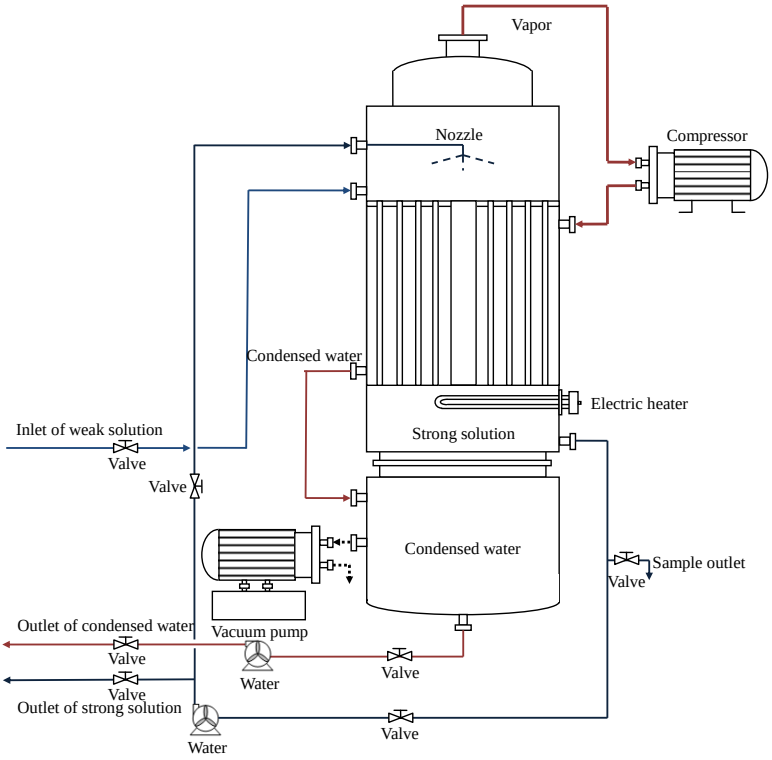


Fig. 3. Schematic diagram of mechanical vapor recompression system

Mechanical Vapor Recompression (MVR) system is an efficient system for solution concentration. The schematic diagram of the system is shown in Fig. 3. The vapor evaporated from the weak solution is conducted to the compressor, in which the vapor is heated and compressed. Afterwards, the heated and compressed vapor from the outlet of the compressor is conducted back to the evaporator, which is used as the heating source of the weak solution. Then, the weak solution is heated by the high temperature vapor, and vapor evaporates from the solution to complete the cycle. And the high temperature vapor turns to condensed water cooled by the solution. In the system, the latent heat of evaporation is recovered by the compressor. Therefore, the MVR system could concentrate solution with a small amount of energy consumption from the compressor and water pumps. Applying the MVR system to concentrate the soy whey water, not only the condensate of soy protein and oligosaccharide could be recovered, but also the condensed water could be utilized as distilled water for the manufacture process.

2. Waste heat and waste resource recovery system

In the traditional manufacture process of the soy protein powder, the exhaust air from the cyclone and the whey water are discharged to the environment directly. According to the analysis above, there is great potential of heat recovery from exhaust air and resource recovery from whey water. In this paper, two recovery systems are proposed to recover waste heat and waste resource among the soy protein manufacture process.

2.1. Waste heat recovery system

To recover the waste heat from the exhaust air of the spray drying process, a heat recovery system is proposed. Considering the distance between the exhaust air pipe and the fresh air pipe, a water loop is introduced in the system. To recover both sensible heat and latent heat from the exhaust air, the inlet water temperature of the heat recovery heat exchanger is set to be lower than the dew point of the exhaust air. A heat pump is employed in the water loop to intensify heat recovery, and the heat pump is also in charge of space heating of the plant in winter besides fresh air preheating. The schematic diagram of the heat recovery system is shown in Fig. 4.

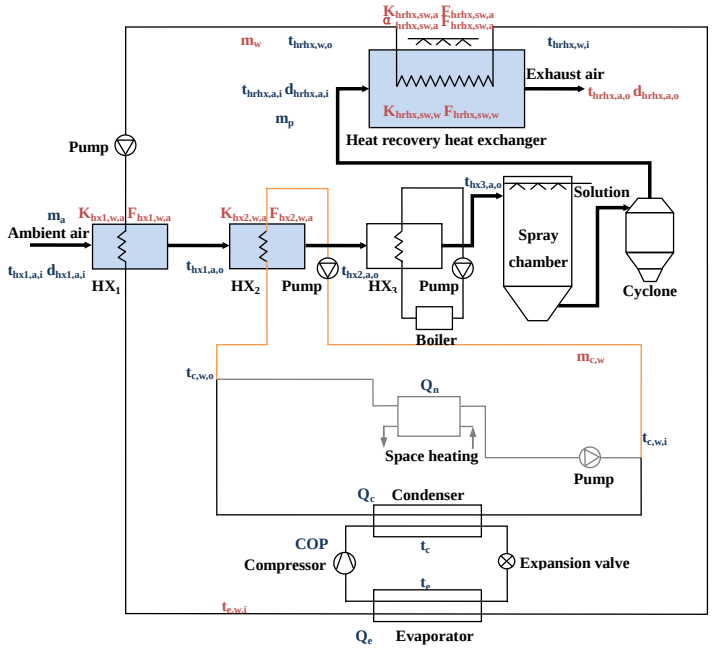


Fig. 4. Schematic diagram of the waste heat recovery system

As it is illustrated in the waste heat recovery system, the waste heat from the exhaust air is recovered by conducting the exhaust air to a tube sheet heat recovery heat exchanger to exchange heat with the water loop. The heated water out of the heat recovery heat exchanger is used to preheat the ambient air in heat exchanger 1. Afterwards, water out of heat exchanger 1 is cooled by the evaporator of the heat pump to make the temperature of it lower than the dew point of the exhaust air. The fresh air is firstly preheated in heat exchanger 1, and then it is heated by the condensing heat supplied by the heat pump in heat exchanger 2. Finally, before conducted to the spray chamber, the heated air is reheated by the hot steam from the boiler to the required temperature in heat exchanger 3.

2.2. Waste resource recovery system

To recover soy protein and oligosaccharide from the soy whey water, a mechanical vapor recompression (MVR) system is applied in the resource recovery system. The concentration of the original soy whey water is 2%, and it would be condensed to 10% by the MVR system. Afterwards, the condensed soy whey water is dried by the spray dryer to obtain the dry product of the mixture of soy protein and oligosaccharide.

The MVR system is shown in Fig. 3. Firstly, the vacuum pump is started to make the pressure inside the system to be in a vacuum condition. Then the original soy whey water is inhaled in the evaporating tank. After that, the electric heater is turned on to heat the soy whey water to the set evaporating temperature. Finally, the compressor is started to heat the vapor evaporated from the soy whey water. The heated vapor is conducted to the shell part of the evaporator to heat the soy whey water inside the tube. The soy whey water is concentrated by evaporating, and the heated steam is cooled to condensed water.

3. Methodology

3.1. Model of waste heat recovery system

A model is established of the heat recovery system, to analyze the operating performance of the system in the whole year. By inputting the whole year meteorological data in Harbin where the soy protein plant locates, the outlet parameters of the heat recovery system are calculated, along with the quantity of heat recovery and energy saving.

To simplify the system model, some assumptions are made as follows.

Heat loss of the spray chamber, cyclone and all the pipes and components is neglected in the model, as the surface of them are covered with thermal insulation materials.

All the pipes and equipment are sealed well, without leakage of air, water or solution.

The protein solution is on homogeneous flow condition.

- Heat exchanger 1 and heat exchanger 2

For heat exchanger 1 and heat exchanger 2, four equations are attained based on the principle of conservation of energy, shown below:

$$K_{hx1,w,a}F_{hx1,w,a}\cdot\frac{(T_{hrhx,w,o}-T_{hx1,a,o})-(T_{e,w,i}-T_{hx1,a,i})}{\ln\frac{T_{hrhx,w,o}-T_{hx1,a,o}}{T_{e,w,i}-T_{hx1,a,i}}}=c_{p,w}\cdot m_w\cdot(T_{hrhx,w,o}-T_{e,w,i}) \tag{1}$$

$$c_{p,w}\cdot m_w\cdot(T_{hrhx,w,o}-T_{e,w,i})=m_a\cdot(h_{hx1,a,o}-h_{hx1,a,i}) \tag{2}$$

$$K_{hx2,w,a}F_{hx2,w,a}\cdot\frac{(T_{c,w,o}-T_{hx2,a,o})-(T_{c,w,i}-T_{hx1,a,o})}{\ln\frac{T_{c,w,o}-T_{hx2,a,o}}{T_{c,w,i}-T_{hx1,a,o}}}=c_{p,w}\cdot m_{c,w}\cdot(T_{c,w,o}-T_{c,w,i}) \tag{3}$$

$$c_{p,w}\cdot m_{c,w}\cdot(T_{c,w,o}-T_{c,w,i})=m_a\cdot(h_{hx2,a,o}-h_{hx1,a,o}) \tag{4}$$

- Heat recovery heat exchanger

A tube-in-sheet heat exchanger is applied in the system as the heat recovery heat exchanger. The circulated water flows inside the sheets, and the exhaust air goes through the plates to exchange heat with the circulated water inside the sheets, and meanwhile, the spray water sprays from the bottom of the heat exchanger to the end to prevent protein sticking to the surface of the sheets. There are both heat and mass transfer between the spray water and the exhaust air, and there is heat transfer between the spray water and the circulated water. Heat and mass transfer balance equations are shown as follows:

$$K_{hrhx,sw,a}F_{hrhx,sw,a}\cdot\frac{(T_{hrhx,a,i}-T_{hrhx,sw})-(T_{hrhx,a,o}-T_{hrhx,sw})}{\ln\frac{T_{hrhx,a,i}-T_{hrhx,sw}}{T_{hrhx,a,o}-T_{hrhx,sw}}}-r_w\cdot\alpha_{hrhx,sw,a}F_{hrhx,sw,a}\cdot(d_{wb}-d_{hrhx,a,i}) \tag{5}$$
$$=m_p\cdot(h_{hrhx,a,i}-h_{hrhx,a,o})$$

$$m_p\cdot d_{hrhx,a,i}+m_{sw,i}=m_p\cdot d_{hrhx,a,o}+m_{sw,o} \tag{6}$$

$$m_p\cdot(d_{hrhx,a,o}-d_{hrhx,a,i})=\alpha_{hrhx,sw,a}F_{hrhx,sw,a}\cdot(d_{wb}-d_{hrhx,a,i}) \tag{7}$$

$$K_{hrhx,sw,w}F_{hrhx,sw,w}\cdot\frac{(T_{hrhx,sw}-T_{hrhx,w,o})-(T_{hrhx,sw}-T_{hrhx,w,i})}{\ln\frac{T_{hrhx,sw}-T_{hrhx,w,o}}{T_{hrhx,sw}-T_{hrhx,w,i}}}=c_{p,w}\cdot m_w\cdot(T_{hrhx,w,o}-T_{hrhx,w,i}) \tag{8}$$

$$m_p\cdot(h_{hrhx,a,i}-h_{hrhx,a,o})+c_{p,w}\cdot m_w\cdot(T_{hrhx,w,i}-T_{hrhx,w,o})+c_{p,w}\cdot(m_{sw,i}-m_{sw,o})\cdot T_{hrhx,sw}=0 \tag{9}$$

- Spray dryer

In the spray chamber, there is both heat and mass transfer between the heated air and the protein solution. Therefore, the outlet air temperature and humidity of the cyclone could be calculated based on the principle of conservation of mass and principle of conservation of energy, which is illustrated from Equations (10) to (11).

$$m_a\cdot h_{hx3,a,o}+m_s\cdot c_{P,s}\cdot T_s=m_p\cdot h_{hrhx,a,i}+m_{pro}\cdot c_{p,pro}\cdot T_{hrhx,a,i} \tag{10}$$

$$m_a \cdot d_{hx1,a,i} + m_s \cdot d_s = (m_p + m_{pro}) \cdot d_{hrhx,a,i} \tag{11}$$

To calculate the outlet parameters of the system, some initial parameters should be given. According to the actual requirement of the process and some experimental data, the initial parameters are given below in Table 1.

Table 1. Initial parameters

Parameter	Value	Parameter	Value
COP	5	$T_{c,w,o}$	50 (ºC)
$d_{hrhx,a,i}$	0.05072 (kg/kg)	$T_{hrhx,a,i}$	70.58 (ºC)
$d_{hx1,a,i}$	0.00116 (kg/kg)	$T_{hrhx,sw}$	28 (ºC)
m_a	50.2 (kg/s)	$T_{hrhx,w,i}$	22 (ºC)
m_p	50.2 (kg/s)	$T_{hrhx,w,o}$	27 (ºC)
m_{pro}	0.278 (kg/s)	$T_{hx1,a,i}$	-10 (ºC)
m_s	2.78 (kg/s)	$T_{hx1,a,o}$	15 (ºC)
$m_{sw,i}$	50 (kg/s)	$T_{hx2,a,o}$	35 (ºC)
Q_n	3940 (kW)	$T_{hx3,a,o}$	190 (ºC)
$T_{c,w,i}$	40 (ºC)	T_s	65 (ºC)

3.2. Model of waste resource recovery system

A mechanical vapor recompression system is applied to recover the waste resource from the soy whey water. The physical property model of soy whey water and the system model are established as follows.

- Physical properties of soy whey water

The specific heat capacity of solution could be calculated as linear addition of the components [16]. Therefore, the specific heat capacity of the soy whey water could be calculated as below:

$$c_{P,s} = c_{P,w} \cdot x_w + c_{P,pro} \cdot x_{pro} + c_{P,oli} \cdot x_{oli} \tag{12}$$

The boiling point of solution is different from that of pure water. In order to obtain the boiling point of soy whey water, experiment has been conducted in the laboratory. According to the testing result, the boiling point of soy whey water at normal pressure could be calculated as below:

$$T_b = 16.67c + 100 \tag{13}$$

To calculate the boiling point of solution under other pressure, the formula below could be used [17].

$$\Delta_{op} = 0.0162 \cdot \frac{T_{b,w,np}^2}{r_{w,np}} \cdot \Delta_{np} \tag{14}$$

- Compressor

Polytropic efficiency model is applied for the compressor of MVR system. The polytropic efficiency of the compressor has been tested in the experiment which is set as constant. From the equation (15), the polytropic index could be calculated.

$$\eta_{pol} = \frac{\frac{n}{n-1}}{\frac{k}{k-1}} \tag{15}$$

And the energy consumption in polytropic efficiency model is calculated in equation (16).

$$E_{comp} = \frac{n}{n-1} \cdot R_g \cdot T_{v,in} \cdot \left(\left(\frac{P_{v,o}}{P_{v,i}} \right)^{\frac{n-1}{n}} - 1 \right) / \eta_{mechanical} / \eta_{motor} \tag{16}$$

• Evaporator

The soy whey water evaporates by heating of the high temperature vapor in the evaporator, and the high temperature vapor in cooled to condensed water. And the equations based on the laws of mass and energy conservation have been illustrated below.

$$c_{P,s,i} \cdot m_{s,i} \cdot T_{s,i} + Q = m_v \cdot h_{v,suc} + (m_{s,i} - m_v) \cdot c_{P,s,o} \cdot T_{s,o} \tag{17}$$

$$Q = \rho_{suc} \cdot V_{suc} \cdot (h_{v,dis} - h_{cw}) \tag{18}$$

$$KF \cdot \Delta T = Q \tag{19}$$

$$m_{s,i} \cdot x_{s,i} = (m_{s,i} - m_v) \cdot x_{s,o} \tag{20}$$

3.3. Model validation

For the model of heat recovery system, the component models are based on the fundamental laws of mass and energy conservation. And the solving process is conducted by Engineering Equation Solver (EES), a widely used and validated solver, so the reliability of the model can be ensured. For the model of MVR system, it has been validated by the experiment results.

4. Results and discussion

4.1. Waste heat recovery system

• Temperature parameters

According to the meteorological parameters in Harbin, the outlet temperature of heat exchangers is obtained by inputting the ambient air temperature and humidity ratio parameters, shown in Fig. 5. As the heating capacity during the non-heating season is much lower than that in the heating season, the quantity of heat taken in from the water loop is much lower in the non-heating season, and the inlet temperature of the heat recovery heat exchanger will be much higher, which causes the outlet temperature of exhaust air during the non-heating season to be much higher.

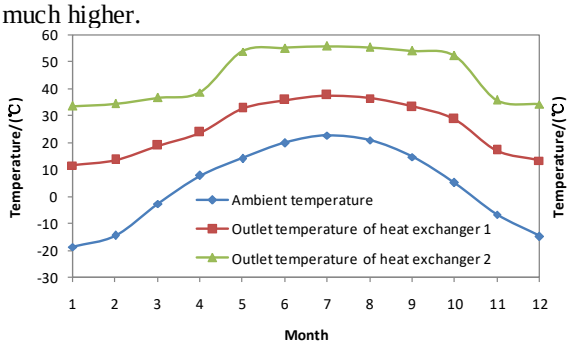


Fig. 5. (a) Outlet temperature of heat exchanger

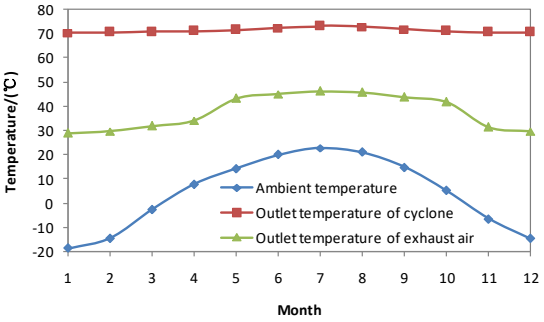


Fig. 5. (b) Outlet temperature of cyclone and exhaust air

• Quantity of heat recovery and energy consumption

According to the calculation results of the system parameters, the accumulated quantity of heat recovery and electricity consumption each month for the heat recovery system is calculated in Fig. 6.

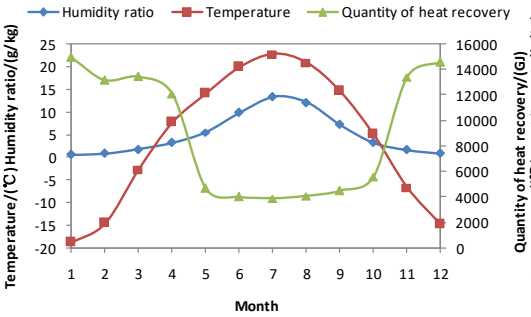


Fig. 6. (a) Quantity of heat recovery

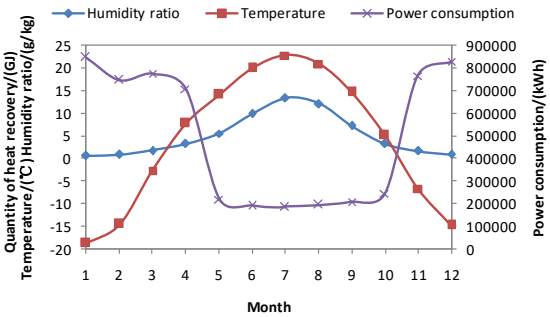


Fig. 6. (b) Power consumption

The heating capacity of the heat pump is much higher in the heating season than that in the non-heating season. Therefore, during the heating season, the quantity of heat recovery and the power consumption is much higher than that in the non-heating season.

- Economic analysis

In the traditional spray drying process, the fresh air is heated by the boiler directly. Steam consumption and the primary fuel consumption of the heat recovery system and the traditional system are calculated, shown in Fig. 7.

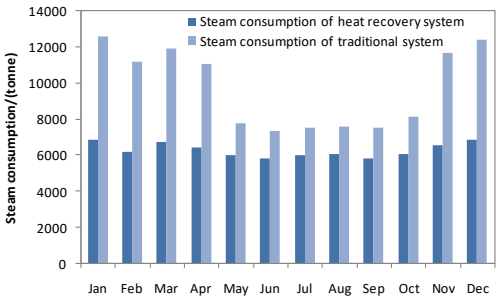


Fig. 7. (a) Steam consumption of heat recovery system and traditional system

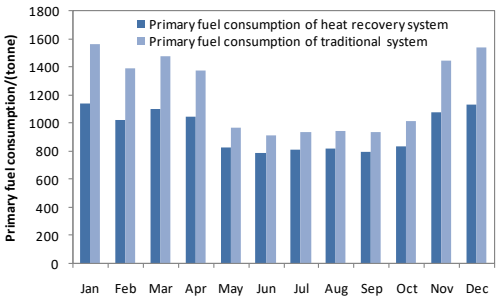
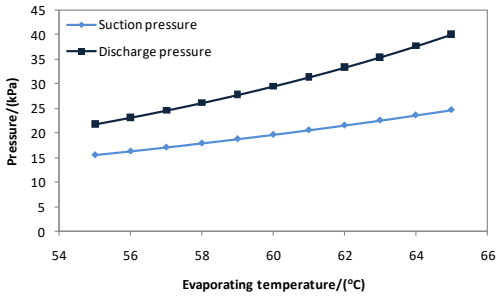


Fig. 7. (b) Primary fuel consumption of heat recovery system and traditional system

Compared to the traditional system, the energy saving amount for the heat recovery system is much higher during the heating season, which indicates that the heat recovery system is much more efficient during the heating season. The annual primary fuel consumption of the traditional system is 14500 tons coal, and for the heat recovery system it is 11400 tons coal; thus, the energy saving rate could reach 21%.

4.2. Waste resource recovery system

Evaporating temperature of the MVR system is one of the most important influence factors of the system operating performance. Therefore, the operating performance is analyzed by changing the evaporating temperature.



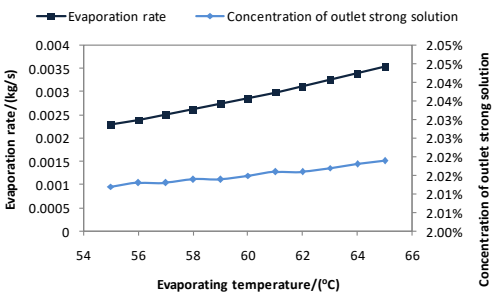


Fig. 8. Suction pressure and discharge pressure

Fig. 9. Evaporation rate and the concentration of outlet strong solution

From Fig. 8, it is concluded that both of the suction pressure and the discharge pressure increase as the evaporating temperature increases. And the pressure ratio increases with the increasing of the evaporating temperature.

To study the influence of the evaporating temperature on the evaporation rate, mass flow rate of vapor and concentration of outlet strong solution is shown in Fig. 9. As the increase of evaporating temperature, the density of the suction vapor increases, which leads to the increase of the suction mass flow rate of vapor. The concentration of outlet strong solution increases as well.

Based on the parameters of the system, quantity of heat transfer and energy consumption of compressor is calculated. To justify the operating performance, two performance indicators are introduced in the system. SMER is specific moisture extraction rate, which indicates the energy consumption for evaporation of per mass unit of water. COP is coefficient of performance, which indicates the quantity of heat output per unit of energy consumption.

As the evaporating rate increases, quantity of heat transfer increases. Power consumption of compressor increases as the increases of the pressure ratio. Energy consumption to evaporate per mass unit water increases as the evaporating temperature increases. When the evaporating temperature is 60 °C, the energy consumption of the compressor is 31 kWh to evaporate per ton of water. And COP decreases with the increase of evaporating temperature. Therefore, there is a trade-off between the evaporation rate and the energy consumption.

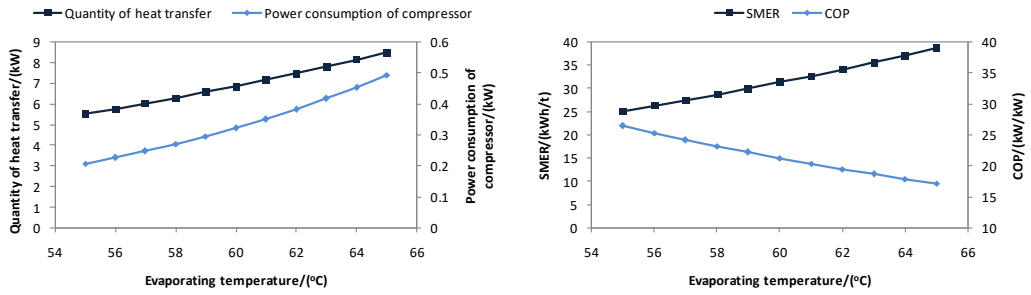


Fig. 10. Operating performance indicators

5. Conclusions

Energy consumption of the traditional process of producing soy protein is quite high. To make full use of the waste heat and the waste resource of the manufacture process, a heat recovery system and a resource recovery system are established in the paper.

From the operating parameters, it is concluded that both of the two recovery systems could work efficiently under given working conditions.

For the heat recovery system, compared to the traditional spray drying process, the total energy saving amount is around 3100 tce per year.

For the mechanical vapor recompression system, both of the evaporation rate and the energy consumption increase as the increase of the evaporating temperature. And there is a trade-off between the evaporation rate and the energy consumption.

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