Effect Of Compressor Speeds On Performance Of Industrial Waste Water Treatment System Driven By Heat Pump Based On Humidification-Dehumidification Principle

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Abstract

This paper designs and builds a set of industrial wastewater treatment system driven by heat pump based on principle of humidification and dehumidification. The influence of compressor speed on performance of whole humidification and dehumidification system is studied. The results show that: with raise of compressor speed within 1800 to 4800 r/min, suction pressure and temperature of compressor are almost unaffected, while exhaust pressure and temperature of compressor all increase. Inlet and outlet temperature of humidifier keeps rising, while relative humidity of inlet and outlet is basically unchanged. Power, refrigeration capacity and heating capacity of system are increasing, while COP (coefficient of performance) of system is decreasing. Moisture extraction rate (MER) rises with the raise of compressor speed, while specific moisture extraction rate (SMER) is almost constant. In actual industrial wastewater treatment process, compressor speed should be adjusted according to specific demand to balance relationship between COP and MER. When COP of the system is mainly concerned, compressor speed should be reduced as much as possible. When MER of the system is mainly considered, compressor speed should be increased as far as possible under condition of ensuring safety of heat pump system and compressor.

1 Background

Cutting fluid plays an important role in cooling and lubricating props and workpiece in process of industrial metal cutting and grinding. With process of cutting, a large amount of waste cutting fluid will be generated. The composition of waste liquid is complex and COD (chemical oxygen demand) is high. Therefore, with continuous improvement of environmental protection requirements, it is necessary to carry out chemical treatment of cutting waste liquid. The actual sewage treatment enterprises generally do not consider the composition of waste liquid, but directly according to amount of waste liquid to be treated. Therefore, reducing amount of waste liquid to be treated by other methods before chemical treatment will play an important role in saving enterprise investment in environmental protection and improving enterprise enthusiasm for environmental protection.

The common method to reduce amount of waste liquid treated is evaporation, which separates original industrial waste water into high-concentration waste water and recyclable water purification through evaporation. Then enterprises only need to invest capital to treat high-concentration industrial waste water. Solution treatment system based on humidification-dehumidification (HDH) is a new solution evaporation treatment system. Humidification-dehumidification is a low-temperature distillation technology that uses air as carrier to absorb water from solution in the humidifier, and then condenses water absorbed in the air in the dehumidifier, which is different from traditional boiling evaporation method and membrane separation method. In order to improve efficiency of solution treatment, the circulating medium (air or solution) of humidification-dehumidification system needs to be heated initially, but heating temperature is far below the boiling point. Common heat sources include electric heating, solar energy, industrial waste heat, etc. Common cold sources in dehumidifiers include normal temperature water or cooling water provided by refrigeration units.

Humidification-dehumidification systems have been widely studied in the field of seawater desalination [1-5]. Li (2019) also use humidification-dehumidification system to make clean water for life [6]. The research of humidification-dehumidification system in the field of industrial wastewater treatment is still in its infancy. For example, R. Santosh et al. (2020) [7] studied HDH system for separating and recovering fresh water from domestic wastewater. Liu Jun et al. (2020, 2013) [8, 9] studied a closed-cycle HDH system for treatment of wastewater containing high concentration of inorganic salts and organic matter. Wang Panpan et al. (2014) [10] studied an HDH system for concentration of low-concentration biogas slurry. Peng Gaohui et al. (2013) [11] introduced HDH technology in separation and treatment of coal wastewater.

In addition, under the promotion of carbon neutrality and emission peak, reducing system energy consumption and carbon emissions has become a necessary consideration for industrial equipment. Therefore, this paper designed a set of industrial cutting waste liquid treatment system driven by heat pump based on humidification-dehumidification principle. Condenser of heat pump system provides heat for HDH system, and evaporator provides cooling capacity for HDH system, thus improving system energy efficiency. The main objective of this paper is to study influence of speed of variable frequency compressor on performance of whole HDH waste liquid treatment system.

2 Experimental system and conditions

The HDH system used in this experiment consists of three parts: humidification and dehumidification subsystem, heat pump circulation subsystem and data acquisition subsystem. Schematic diagram of the experimental system is shown in Figure 1.

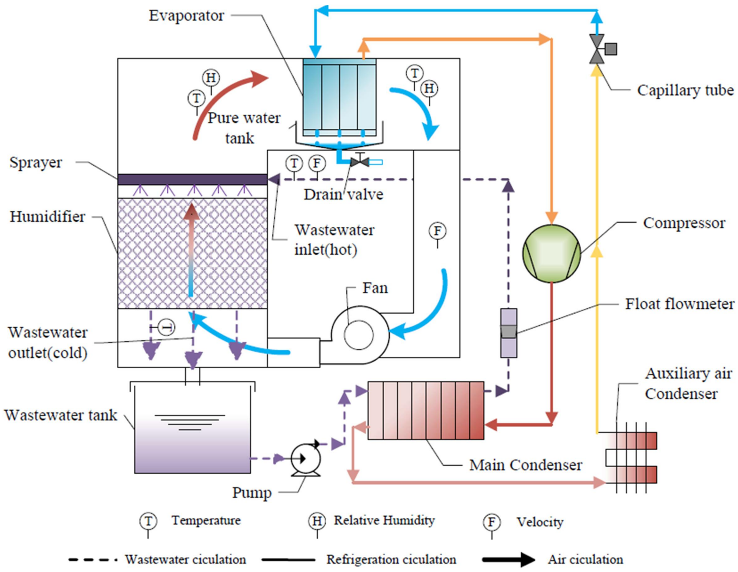

Figure 1: System schematic diagram of humidification and dehumidification system driven by heat pump

1) Humidification and dehumidification subsystem (HDH): the system consists of a humidifier (its interior is filled with stainless steel corrugated plate packing), a dehumidifier (evaporator), a variable frequency fan, a solution storage tank, a solution circulation pump, a main condenser, water recovery device, an auxiliary condenser, etc. Working flow of the system is divided into solution circulation flow and air circulation flow. The solution circulation process is as follows: The solution in solution storage tank is pushed by solution circulation pump and heated by main condenser. Then solution is sprayed from distributor onto the surface of filler in the humidifier. In the humidifier, high-temperature solution is in direct contact with low-temperature and dry air, and air absorbs water in solution and separates water from the pollutant solute. The separated concentrated solution is then returned to solution storage tank to realize low temperature distillation of solution. The air circulation process is as follows: fan drives low-temperature dry air into the humidifier, which conducts heat and mass transfer with high-temperature solution to form high-temperature and high-humidity air. Then wet air enters evaporator to condense and precipitate water carried in air (precipitated water enters water purification recycler), forming low temperature air for the system to circulate. This cycle is repeated until the solution can no longer be concentrated.
2) Heat pump circulation subsystem: the system consists of variable frequency refrigeration compressor (rotary compressor with a theoretical displacement of 54.8 ml/rev), evaporator (dehumidifier), main condenser, auxiliary air cooling condenser, thermal expansion valve and so on. The cooling capacity provided by heat pump system is used by evaporator to recover water and restore hygroscopic capacity of circulating air. Condensation heat of heat pump is used to heat solution in main condenser to achieve heat recovery. Since air and solution circulation in the HDH system are closed systems, heat pump system generates more heat than cold. In order to ensure stable operation of system, an auxiliary air condenser is connected behind the main condenser to discharge excess heat of heat pump system. The refrigerant cycle is shown as follows: Refrigerant is

compressed by compressor into high temperature and high pressure steam. In primary condenser, refrigerant transfers heat to waste liquid and then to auxiliary condenser to release excess heat. After being throttled by throttle valve, refrigerant enters evaporator to cool and dehumidify humid air. Finally, refrigerant returns to compressor to continue the cycle.

3) Data acquisition subsystem: the system is mainly composed of temperature and humidity sensor, thermometer, flowmeter, anemometer, data acquisition instrument and computer. Parameters measured during the experiment: temperature and humidity of humidifier inlet and outlet air, circulating air volume, solution temperature of main condenser inlet and outlet, solution flow, suction and exhaust temperature and pressure of compressor, system power. All parameters are collected by data acquisition instrument and stored by computer. The parameters measured in experimental system and measurement components used are shown in Table 1.

Table 1: Measuring elements of an experimental system

Measured parameters	Instrument	Range	Accuracy	Standard uncertainty
Solution flow rate	LZB-32S float meter	0.4~4m^3/h	±4%	±2.31%
Air velocity	RA610 anemometer	0~30m/s	±3.0%	±1.73%
Air temperature and humidity	VAISALA HMD82 temperature and humidity sensor	0~100%RH	±3.0%RH	±1.73%RH
		-40~+60℃	±0.3℃	±0.17℃
Temperature	PT100 platinum resistance	-50~300℃	±0.5℃	±0.29℃
Pressure	GE Druck PTX5072 pressure sensor	0~3 MPa	±3 kPa	±1.73 kPa
Power consumption	DDS47 single-phase watt-hour meter	0~5000W	±10W	±5.77W

The experimental conditions of this paper are shown in the figure below:

Table 2: Adjustment ranges of experimental parameters

Parameter	Unit	Value
Air circulation flow rate	kg/s	0.342
Water circulation flow rate	kg/s	0.372
Ambient temperature	℃	25
Ambient relative humidity	%	55
Compressor speed	r/min	1800~4800

3 Statistical analysis

In the experiment of this paper, working state of circulating fan, solution pump and solution spray temperature have great influence on system performance. An auxiliary electric heater is used to control initial temperature of solution (40℃±0.5℃) to avoid influence of solution initial temperature on experiment results. In addition, the experiment does not involve influence of environment on system, and the experiment is carried out in an environmental chamber with constant temperature and humidity. Air flow rate and circulating solution flow rate are constant. Solution spray temperature varies only with working state of heat pump system, which is regulated by the speed of compressor. When inlet and outlet temperature fluctuation of compressor is less than 0.1 ℃, the HDH system is considered to be in stable operation state.

To evaluate the actual operating performance of whole humidification- dehumidification system, the following indicators are used to evaluate, including heating capacity, refrigeration capacity, COP, MER and SMER.

1) Heating capacity and refrigeration capacity [12]

$$Q_h = c_p \cdot q_{m,w} \cdot (t_{out} - t_{in}) \tag{1}$$

$$Q_c = q_{m,a} \cdot (h_{in} - h_{out}) \tag{2}$$

Where Q_h and Q_c are heating capacity and refrigeration capacity respectively; c_p is specific heat capacity of waste water; $q_{m,w}$ and $q_{m,a}$ are circulating waste water flow and circulating air flow respectively; t_{in} and t_{out} are inlet and outlet temperature of waste water in main condenser respectively; h_{in} and h_{out} are enthalpy of air at inlet and outlet of evaporator. Enthalpy of wet air can be determined by the following formula [13-14]:

$$h = 1010 \cdot t + (2.5 \times 10^6 + 1840 \cdot t) \cdot d \tag{3}$$

$$d = 0.622\frac{\varphi P_s}{P_a - \varphi P_s} \tag{4}$$

Where t is air temperature; d is air moisture content; φ is relative humidity; P_s is partial pressure of saturated water vapor in air; P_a is atmospheric pressure.

2) COP

COP (coefficient of performance) refers to ratio of energy generated in revenue to energy consumed during operation of system [15]. The revenue energy of system includes heat transferred to circulating solution by main condenser and heat absorbed from circulating air by evaporator (refrigeration capacity). The power consumed by system is the sum of compression power, fan power and solution pump power. The calculation of COP is shown as the following equation:

$$\text{COP} = \frac{Q_h + Q_c}{W} \tag{5}$$

Where W is the system power.

3) MER

MER (Moisture extraction rate) is a key parameter reflecting water extraction rate and represents ratio of water removal quality to required time in the whole operation process, that is, water extraction per unit time of system. The calculation of MER is shown as the following equation:

$$\text{MER} = q_{m,a}(d_{in} - d_{out}) \tag{6}$$

Where d_{in} and d_{out} are air moisture content at inlet and outlet of evaporator.

4) SMER

SMER is another important parameter to evaluate water intake performance of system. It represents the ratio of water quality taken out and energy consumed in the whole operation process, reflecting comprehensive performance of system. The calculation of SMER is shown as the following equation:

$$\text{SMER} = \frac{\text{MER}}{W} \tag{7}$$

The standard uncertainty of directly measured parameters can be calculated by formula (8) [16]. The combined uncertainty of system performance parameters can be calculated by formula (9) and formula (10) [16]. In the formula, u is the uncertainty, a is the measurement accuracy, R is the calculated performance parameter, f is the functional relationship between the calculated performance parameter and the directly measured parameter, x_i is the i^{th} uncertainty component, and u_R is the combined uncertainty.

$$u = \frac{a}{\sqrt{3}} \tag{8}$$

$$R = f(x_1, x_2, \cdots, x_N) \tag{9}$$

$$u_R = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial R}{\partial x_i}\right)^2 u^2(x_i)} \tag{10}$$

According to the above formula, the relative uncertainty (u_R/R) of COP, MER and SMER are 2.25%, 0.31% and 0.92%, respectively.

4 Results

4.1 Effect of compressor speeds on temperatures and pressures of compressor suction and exhaust

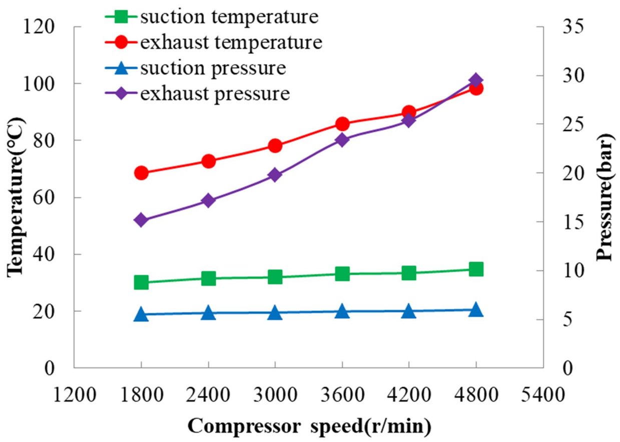

Figure 2: Effect of compressor speeds on pressures and temperatures of compressor suction and exhaust

Fig.2 shows changes of temperature and pressure at inlet and outlet of compressor with the increase of compressor speed. It can be seen that with increase of compressor speed, temperature and pressure of exhaust port gradually increase. The suction pressure and temperature change in a small range, resulting in compressor pressure ratio and power consumption continue to increase. This is because with increase of compressor speed, mass flow of refrigerant in main condenser increases, resulting in increase of heat transfer on condensing side. In this case, pressure and temperature in condenser gradually rise, resulting in a significant increase in exhaust pressure and temperature. With increase of pressure of condenser, thermal expansion valve plays a more and more obvious role and produces more and more throttling effect. Therefore, compared with main condenser, increase of pressure and temperature in evaporator is not obvious, resulting in small changes in suction pressure and temperature of compressor.

4.2 Effect of compressor speeds on inlet and outlet air temperatures of humidifier

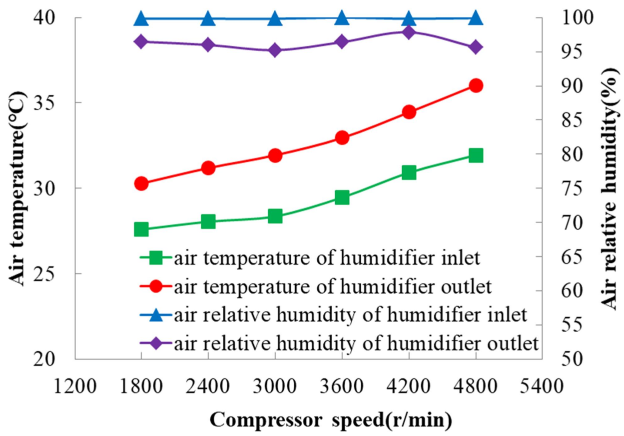

Figure 3: Effect of compressor speeds on inlet and outlet air temperatures of humidifier

Figure 3 shows change of humidifier inlet and outlet circulating air temperature and relative humidity with increase of compressor speed. It is worth noting that the air at inlet of humidifier is the air at outlet of evaporator, and the air at outlet of humidifier is the air at inlet of evaporator.

As shown in the figure, air temperature at inlet and outlet of humidifier increases significantly with the increase of compressor speed. The relative humidity of air at the inlet and outlet of the humidifier is almost unchanged. This is because mass flow rate and flow rate of refrigerant increase with increase of compressor speed, and condensation pressure and temperature rise accordingly, thus improving heat transfer temperature difference and heat transfer coefficient between refrigerant and circulating solution on the condensing side. Therefore, solution temperature increases with increase of compressor speed. The circulating solution and circulating air fully carry out heat and mass transfer in the filler of humidifier, so the higher the solution temperature is, the higher the circulating air temperature will be. In addition, the temperature difference between inlet and outlet air of humidifier is almost unchanged, which is mainly due to heat and mass transfer of air and water on the packing surface is limited by size and structure of the packing itself.

Relative humidity of air at the outlet of humidifier is kept at about 95%, because air and solution are fully heat and mass transferred on the surface of filler, so water vapor in air at the outlet of humidifier is close to saturation, so it is less affected by heat pump system. Relative humidity of air at humidifier inlet is close to 100%, because air at the humidifier inlet is air at the evaporator outlet. The wet air undergoes cooling and condensation on the surface of evaporator and water vapor in air is completely saturated. The evaporator in this paper has sufficient heat exchange performance, so wet air is fully condensed, so its relative humidity is completely not affected by heat pump system.

4.3 Effect of compressor speeds on COP, heating/refrigeration capacity and power consumption

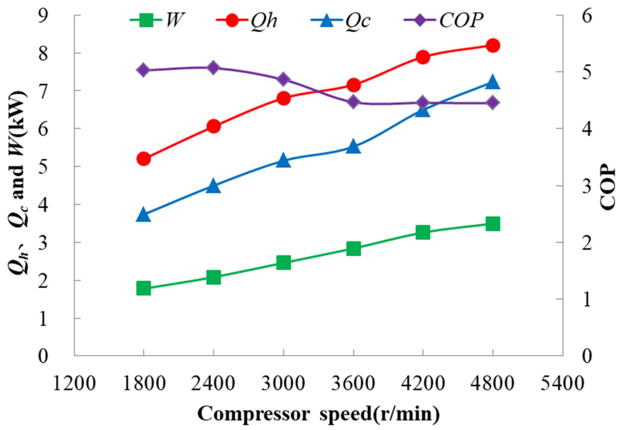

Figure 4: Effect of compressor speeds on heating/refrigeration capacity, power consumption and COP

Figure 4 shows changes of COP, heat capacity of the main condenser, refrigeration capacity and system power consumption at different compressor speeds. It can be seen that with the increase of compressor speed, refrigeration capacity of evaporator and heat capacity of the main condenser both increase, which is consistent with the analysis. As the speed of compressor increases, exhaust pressure of compressor increases, while suction pressure basically stays the same. As a result, pressure ratio of compressor increases, resulting in increasing power consumption of compressor. In addition, the increase of mass flow of heat pump system further leads to improvement of system power consumption. According to above analysis, refrigeration capacity of evaporator and heat capacity of main condenser increase with increase of compressor speed, but the increment of their sum is less than increment of total power consumption. Therefore, COP of humidification-dehumidification system driven by heat pump decreases with increase of compressor speed.

4.4 Effect of compressor speeds on MER and SMER

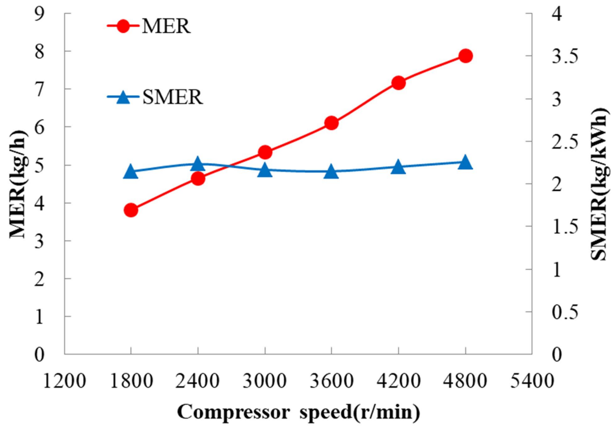

Figure 5: Effect of compressor speeds on MER and SMER

The changes in MER and SMER of the HDH system as compressor speed increases are shown in Figure 5. As can be seen from the figure, MER of the system increases gradually with increase of compressor speed. When compressor speed is 1800 r/min, the MER is 3.81 kg/h, which is the minimum. When compressor speed is 4800 r/min, the MER reaches the maximum of 7.89 kg/h. SMER hardly changes with compressor speed and remains at about 2.2 kg/kWh. The variation of MER with compressor speed can be explained by the following figure.

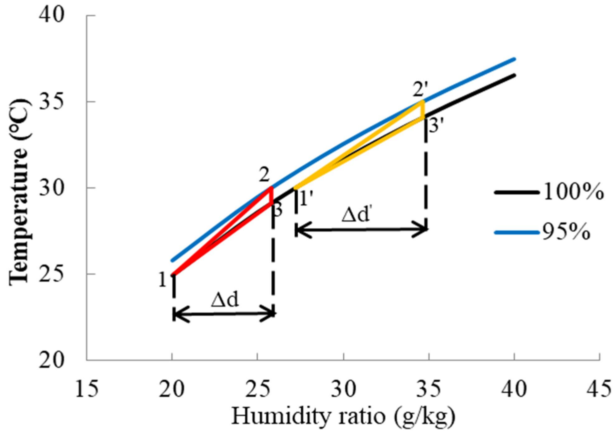

Figure 6: Changes of actual enthalpy and humidity state of wet air in the HDH system

Figure 6 shows the changes of actual enthalpy and humidity state of wet air in the HDH system. As shown in the figure, point 1 is humidifier inlet air state (evaporator outlet). Point 2 is air state at humidifier outlet (evaporator inlet). Point 3 is the transition state of wet air cooling and condensing on surface of evaporator. 1-2 is the heat and mass transfer process of air and solution in humidifier packing. 2-3 refers to the cooling process of wet air on surface of evaporator. 3-1 is the condensation process of wet air on the surface of evaporator. MER is equal to the difference between moisture ratio at point 1 and point 3 multiplied by the circulating air volume. When compressor speed increases, temperature of 1 point increases and 1 point changes into 1’ point. As can be seen from Figure 3, due to the limitation of structure and size of packing, temperature rise of air inside the humidifier and relative humidity at the outlet are almost unchanged, thus the state of point 2’ can be determined. It can be seen from the figure 6 that the moisture ratio difference between point 3’ and point 1’ is greater than that between point 3 and point 1.

5 Conclusions

In order to reduce amount of industrial wastewater and save investment of environmental protection, this paper designs and builds a set of industrial wastewater treatment system driven by heat pump based on principle of humidification and dehumidification. The effects of compressor speeds on compressor inlet and exhaust pressure and temperature, circulating air temperature and relative humidity, MER, COP and SMER were investigated experimentally. The following conclusions are drawn:

1) With rise of compressor speed within 1800 to 4800 r/min, suction pressure and temperature of compressor are almost unaffected, while exhaust pressure and temperature of compressor all increase.
2) Inlet and outlet temperature of humidifier keeps rising, while relative humidity of inlet and outlet is basically unchanged with rise of compressor speed.
3) Power, refrigeration capacity and heating capacity of system are increasing, while COP (coefficient of performance) of system is decreasing with rise of compressor speed.
4) Moisture extraction rate (MER) rises with the raise of compressor speed, while specific moisture extraction rate (SMER) is almost constant.
5) When COP of the system is mainly concerned, compressor speed should be reduced as much as possible. When MER of the system is mainly considered, compressor speed should be increased as far as possible under condition of ensuring safety of heat pump system and compressor.

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References

[1] Mohamed A.S.A., Shahdy Abanob G., Salem Ahmed M. (2021). Investigation on solar humidification dehumidification water desalination system using a closed-air cycle. Applied Thermal Engineering, 188, 116621.
[2] A.S.A. Mohamed, M. Salem Ahmed, Abanob.G. Shahdy. (2020). Theoretical and experimental study of a seawater desalination system based on humidification-dehumidification technique. Renewable Energy, 152, 823-834.
[3] Emad Ayati, Zohreh Rahimi-Ahar, Mohammad Sadegh Hatamipour, et al. (2020). Performance evaluation of a heat pump-driven vacuum humidification-dehumidification desalination system. Applied Thermal Engineering, 180, 115872.
[4] Alnaimat Fadi, Ziauddin Mohammed, Mathew Bobby. (2021). A review of recent advances in humidification and dehumidification desalination technologies using solar energy. Desalination, 499, 114860.
[5] Zohreh Rahimi-Ahar, Mohammad Sadegh Hatamipour, Leile Rahimi Ahar. (2020). Air humidification-dehumidification process for desalination: A review. Progress in Energy and Combustion Science, 80, 100850.
[6] Kun Li, Weidong Wu, Kun Hu, et al. (2019). Performance analysis of a novel household water purification system based on humidification-dehumidification principle. Desalination, 469, 114099.
[7] Andras Jozsef Toth. (2020). Modelling and Optimisation of Multi-Stage Flash Distillation and Reverse Osmosis for Desalination of Saline Process Wastewater Sources. Membranes. 10(10), 265.
[8] Ruijing Liu, Tiezhu Zhang, Hongxin Zhang, et al. (2020). Thermodynamic Analysis of Multistage Flash Seawater Desalination System. Journal of Coastal Research, 105, 237-241.
[9] M. Khamis Mansour, Hassan E.S. Fath. (2013). Comparative study for different demister locations in multistage flash (MSF) flash chamber (FC). Desalination and Water Treatment, 51(40-42), 7379-7393.
[10] Mostafa H. Sharqawy, Mohamed A. Antar, Syed M. Zubair, etc. (2014). Optimum thermal design of humidifification dehumidifification desalination systems. Desalination, 349, 10-21.
[11] G. Prakash Narayan, Karim M. Chehayeb, Ronan K. McGovern, etc. (2013).Thermodynamic balancing of the humidifification dehumidifification desalination system by mass extraction and injection. International Journal of Heat and Mass Transfer, 57, 756-770.
[12] S. Liu, X. Li., M. Song, H. Li, Z. Sun. (2018). Experimental investigation on drying performance of an existed enclosed fixed frequency air source heat pump drying system, Appl. Therm. Eng., 130, 735-744.
[13] S.S. Shenvi, A.M. Isloor, A.F. Ismail. (2015). A review on RO membrane technology: developments and challenges. Desalination, 368, 10–26.
[14] A.E. Kabeel, M. Abdelgaied. (2018). Experimental evaluation of a two-stage indirect solar dryer with reheating coupled with HDH desalination system for remote areas. Desalination, 425, 22–29.
[15] A. Francis. (2016). The use of enhanced heat transfer phase change materials (PCM) to improve the coefficient of performance (COP) of solar powered LiBr/H2O absorption cooling systems. Renew. Energ, 87, 229-239.
[16] N. Rahbar, J.A. Esfahani. (2012). Experimental study of a novel portable solar still by utilizing the heat pipe and thermoelectric module. Desalination, 284, 55–61.