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Research Article

Study of Wood Drying with Two-Stage Compression High Temperature Heat Pump

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Abstract: In order to enhance the quality of woodwork, a new drying equipment of two-stage compression high temperature heat pump was developed. This heat pump drying equipment is capable of switching between one-stage compression and two-stage compressing. Components and working principle of two-stage compression high temperature heat pump equipment were introduced in this study. Drying experiment was conducted with Pinus massoniana plates. The results show that this equipment had great energy saving performance and the average energy recycling rate could be achieved beyond 28%. Meanwhile, by means of two-stage compression and utilization of new refrigerant-R245fa, condensing temperature and heating temperature reach 120 and 110°C, respectively.

Keywords: Energy saving, high temperature, pinus massoniana, two-stage compression, wood drying

INTRODUCTION

Wood drying is a key process to ensure the quality of woodwork, which is an essential technique to fulfill the effective and efficient utilization of wood. And it is one of the most potential processes to curtail the energy consummation as well (Bailian, 2006). By 2003, the consummation of wood in China reached 228,430,000 m^3, whose moisture elimination was estimated at 22,500,000 tons with the evaluation of 225 kg water per 10,000,000 m^3 of wood (Xin, 1998). Therefore, the large quantities of wood quantity and water elimination motivate the development of wood drying heat pump system, which characterize thermal energy recycling. In contraction with normal steamy drying, research have shown that the energy saving rate of heat pump drying exceed the steamy one as 40-70% (Biguang, 2005). With the development of heat pump technology, the air supply temperature of wood drying heat pump with R142b reached as high as 70°C (Mingxi and Biguang, 1994). What's more, some institutes in China have improved the temperature to 86-90°C with the utilization of HTR01 which is a kind of high temperature working fluid, which render the wood drying technique elevated (Chen, 2006; Dabing, 2006). Further, if the drying temperature could be advanced, it would result in the accelerating of drying rate and productivity, as a consequence, the prevalent utilization of heat pump is available. In this study, a two-stage compression wood drying heat pump device is devised with a environmentally-friendly refrigerant 245fa (Lihui and Jiangang, 2003; Mingshan, 2000), which is capable of switching between one-stage and two-stage compression and reaching a higher drying temperature.

The theory and the drying medium of heat pump drying and normal drying are same. Both of them rely on the heat convection between the drying chamber air and drying materials to heat the materials and absorb moisture. The difference between the two kinds of drying technique is the approach to remove moisture of the air. The normal one discharges the moist air to the atmosphere and absorbs commensurable fresh air at the mean time, as shown in Fig. 1. The open-loop air exchange is energy consuming. By contrast, the humidity of drying chamber air declines as a result of air condition by the heat exchanges between the air and heat pump, which is a close-loop one and free of discharging, as shown in Fig. 2. More specifically, dehumidifier comprises compressor, evaporator, expansion valve and condenser. The refrigerant in

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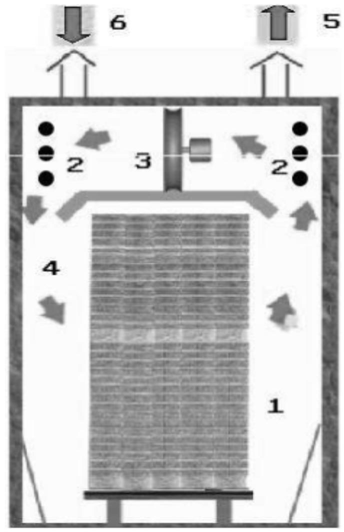

Fig. 1: Conventional hot air drying kiln
1: Woodpile; 2: Steam heater; 3: Blower; 4: Circulating air; 5: Discharged moist air; 6: Fresh air

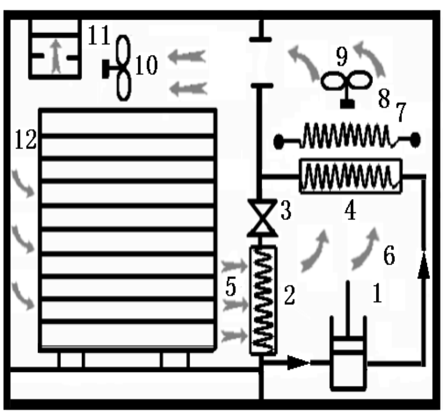

Fig. 2: Schematic diagram of single heat dehumidifier
1: Compressor; 2: Evaporator; 3: Expansion valve; 4: Condenser; 5: Moist air of evaporator outlet; 6: Dry air; 7: Accessional heater; 8: Moisture eliminating air pump; 9: Heated dry air; 10: Drying chamber blower; 11: Accessional blower; 12: Woodpile

evaporator which operates as the indoor machine of air conditioners (or freezing chamber of fridge) absorbs the heat from moist air to remove the moisture, which decreases the relative humidity and temperature. Then, after the working fluid changes into gas, it will be compressed by the compressor and sent to the condenser (heat exchanger). In the heat exchanger, the moisture removal air was heated and sent to drying the materials. The expansion valve decreases the pressure so that the working fluid can work at a low pressure with a relative low temperature.

As an energy saving drying device, the drying heat pump recycles the waste heat of moist air discharge from the drying chamber (Paul *et al*., 2002; Chua *et al*., 2002).

In order to enhance the quality of woodwork, the study provided a new drying equipment of two-stage compression high temperature heat pump.

MATERIALS AND METHODS

Pinus massoniana plates produced in Guangxi, China are used as the materials. The thickness of the plate with a primary moisture ratio of 160% is 38 mm and the length is 400 mm. Before experiment, the edges of the plates were enveloped by epoxy resin.

Methods: The experimental system of wood drying heat pump is described in Fig. 3. It comprises heat pump system, air cycling system and drying chamber. More exactly, the drying chamber's size is 6100×520×360 mm. And the heat pump system is consist of two compressors of input powers 172 W and 116 W, respectively two electric expansion valves, two capillaries, two plate heat exchangers, four electric valves, four condensers and four evaporators. In addition, a 400 W accessorial heater is attached to the system to raise the temperature of drying chamber at the beginning of experiment. What's more, the ventilation pipe is made of galvanized steel plain sheet and foam insulation materials and both air outlet and air bypass outlet are installed with regulating valves. And the input power of blower engine and cycling engine are respectively 56 and 68 W. Finally, the working conditions of system can be controlled by different combination of different electric cut-off valves and electric expansion valves.

As shown in Fig. 3, when operating as a one-stage compression heat pump system, electric valves No. 17 and 20 are opened while No. 22 and No. 22 are closed and electric expansion valve No. 3 is opened while No. 11 is closed. As a result, refrigerant flows through electric valve No. 20, condenser, electric expansion valve No. 17, plate heat exchanger, capillary No. 3 and evaporator, which leads to a one-stage heat pump cycle.

When operating as a two-stage compression heat pump system, electric valve No. 17, 22 and 23 are opened while No. 20 is closed and two electric cut-off valves are opened and adjusted to a certain degree. In contrast, the cycle of second stage which comprises condenser, electric valve No. 17, plate heat exchanger, capillary No. 6, electric expansion valve No. 3 and evaporator fulfills the two-stage compression. Another cycle which is consist of condenser, electric cut-off

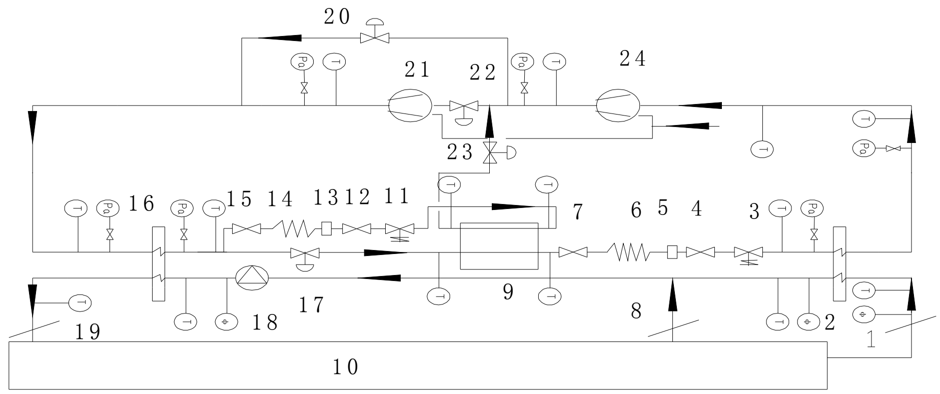

Fig. 3: Schematic diagram of 2 levels compression heat pump drier
1: Blowing volume regulating valve; 2: Evaporator; 3: Electric expansion valve; 4: Cut-off valve; 5: Drying filter; 6: Capillary; 7: Cut-off valve; 8: Blowing volume regulating valve; 9: Plate heat exchanger; 10: Drying chamber; 11: Electric expansion valve; 12: Cut-off valve; 13: Drying filter; 14: Capillary; 15: Cut-off valve; 16: Condenser; 17: Cut-off valve; 18: Air pump; 19: Accessorial heater; 20: Cut-off valve; 21: Second stage compressor; 22: Cut-off valve; 23: Cut-off valve; 24: First stage compressor

valve No. 11, plate heat exchanger and electric cut-off valve No. 23 results in the entropy improvement cycle in second stage compressor.

For the air cycling and flux control, as can be seen in Fig. 3, the air derives from drying chamber flows through blowing volume regulating valve No. 1, evaporator and the inlet. While the bypass air flows through blowing volume regulating valve No. 8 and blends with the moisture removed air, then they are heated by the condenser and accessional heater before returning to drying chamber. This is the air cycling. Blowing volume and bypass blowing volume can be adjusted by the regulating valves.

Figure 3 also shows the data acquisition system which contains 43 data acquisition points with two data acquisition systems. One of their patterns is XSL TE-XMDB and it contains 19 data acquisition points, including 3 temperature and humidity sensors whose precision is 0.2% RH and 13 temperature sensors whose precision is 0.5°C. Another one is Agilent 34970A and it comprises 20 sensors: 6 for pressure, 13 for temperature and 1 for weight. What's more, the condensate water is measured by electronic weigher. And the electric power consummation is measured by electric energy meter for each half an h. A pendant type sensor is used to measure the moisture of wood online.

Analysis methods: The parameters measured in the experiment contain the parameters of air system and heat pump system, as follows: T-average temperature of drying chamber air, Φ-average humidity of drying chamber air, MC-moisture ratio of materials, V-drying rate of materials, Tva1-average temperature of evaporator inlet air, Tva2-average temperature of evaporator outlet air, P-energy consummation, W-quantity of condensing water, R-energy recycling rate of heat pump.

Drying rate refers to the percentage of material moisture decreasing per hour. For example, provided that during 10:00-11:00, the moisture ratio of material drops as 1.1054%, it means that the drying rate is 1.1054%/h.

Because the thermal energy recycled by the evaporator is approximately equal to the discharge lost of normal drying, energy saving rate reflects the energy saving effect of heat pump to an extent. The recycled thermal heat comprises of the latent heat of water vapor Qa and sensible heat of air Qb (Biguang and Guangqing, 1995; Biguang and Xianjun, 2004). Specifically, total latent heat is yielded by condensation and equal to the product of latent heat at dew point temperature expelled water per h. While sensible heat is calculated by air quantity timing its thermal capacity and temperature difference.

Take the case for example: Within a high moisture ratio period (about 4 h), condensing water quantity is 1435.9 g and the temperature of drying chamber air and humidity is 49.3°C and 68.2%, respectively. What's more, the dew point temperature is 42.609°C. The energy consummation and air thermal capacity are, respectively 0.41 kW and 1.0 kJ/kg. In addition, the temperature of evaporater outlet and inlet are 55 and 43.62°C. According to the describing above, the energy saving rate is calculated as follows:

Table 1: Drying schedule of pinus massoniana

Moisture ratio (%)	Dry-bulb temperature (°C)	Wet-bulb temperature (°C)	Temperature difference (°C)
110	65	61	4
110~70	65	61	4
70~60	67	62	5
60~50	70	62	8
50~40	73	62	11
40~35	77	63	14
35~30	81	63	17
30~25	85	63	22
25~20	86	64	22
20~15	86	64	22
below 15	95	65	30

$$Qa = 1435.9 \text{ g} \times 2400.7600 \text{ kJ/kg} \div 1000 \text{ g/kg} \div 4 \text{ h} \div 3600 \text{ s/h} = 0.2394 \text{ kW}$$

$$Qb = 48.864 \text{ kg} \times 1 \text{ kJ/ (kg·°C)} \times (55\text{-}43.62°\text{C}) \div 4 \text{ h} \div 3600 \text{ s/h} = 0.038625 \text{ kW}$$

$$Q = Qa + Qb = 0.2394 \text{ kW} + 0.038625 \text{ kW} = 0.278025 \text{ kW}$$

As a consequence, the energy saving rate:

$$R = 0.278025 \text{ kW} \div 0.41 \text{ kW} = 67.81\%$$

The materials whose average primary moisture ratio is over 130% stem from Guangxi, China. The density of Pinus massoniana is 0.468 g/cm^3. Consult to the high temperature drying schedule in bibliography (Biguang, 2005), the parameter of materials is revised as shown in Table 1.

RESULTS AND DISCUSSION

As shown in Fig. 4, the moisture ratio of wood experiences a decline trend. However the real moisture ratio fluctuates as the compressor high temperature halt. Even so, the trend line shows the trend clearly and the moisture ratio drops to 30% within 260 h. Furthermore, the transfer rate decreases because the absorbed water transfers slowly at low moisture content in wood, during 200-260 h.

The temperature sees an increasing trend during the experiment, as shown in Fig. 5. As the temperature data in the drying chamber is controlled with the drying schedule, the temperature of different drying period can be read. The reason of fluctuation is the same with the one of humidity. In addition, the decrease of moisture removing leads to the fall of temperature rising rate.

The relative humidity fluctuates dramatically and it drop to around 5% before rising to a peak. Even so, it experiences a decreasing trend according to the drying

Table 2: Drying rate of various moisture content period

Moisture ratio periods (%)	Time of period (h)	Drying rate (%/h)
148-90	47	1.23
90-70	24	0.833333
70-40	70	0.428571
40-10	116	0.258621
Average drying rate		0.689%/h

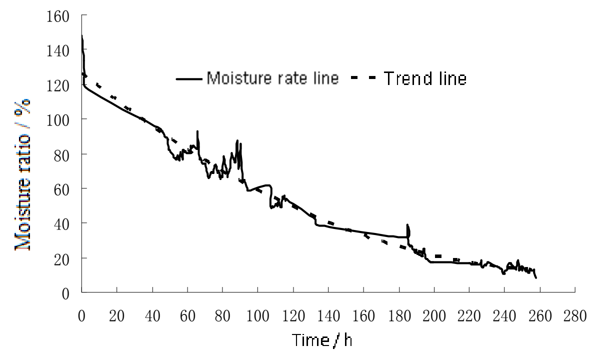

Fig. 4: Wood drying curve

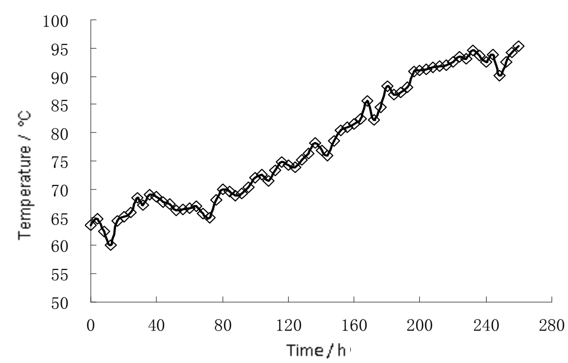

Fig. 5: Temperature curve with drying chamber

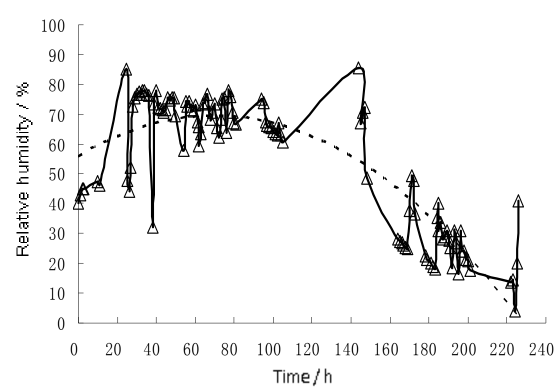

Fig. 6: Relative humidity curve with drying chamber

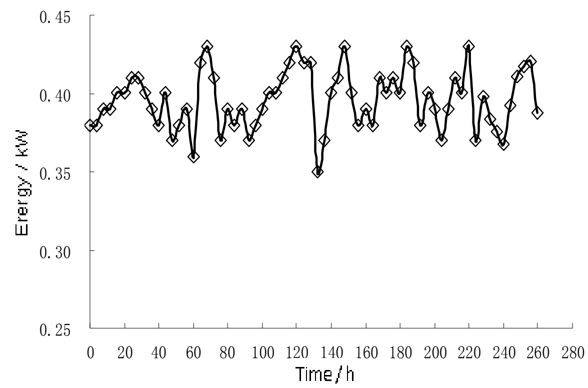

Fig. 7: Energy consumption curve

condition, as shown in Fig. 6. The energy consummation is given in Fig. 7, which is measured per hour. It is obvious that the electric energy fluctuate from 0.34 to 0.44 kW/h, whose average is 0.39 kW/h. Because of different temperature, humidity and condensing water quantity as well as different pressure in condenser and evaporator, the electricity consummation differs from each other.

Drying rates within different drying period are shown in Table 2, whereas Table 3 shows the energy recycling rate (energy saving rate).

The energy saving rate of different drying period varies with the parameters, as can be seen in Table 3. The energy saving rate is proportional to the condensing water quantity which is known as the moisture elimination. Exactly, during the high moisture drying period, the large condensing water quantity results in the large quantity of energy saving. While with the decrease of moisture ratio, the energy saving rate declines. In summary, the result of energy recycling rate of the experiment over 28%. It suggests that the utilization of two-stage compression wood drying heat pump system is energy-saving and it is a available technique to preserve the caliber of wood.

CONCLUSION

An environmentally-friendly refrigerant was used in the new designed two-stage compression wood drying heat pump system which is capable of switching between one-stage compression and two-stage compression to reach a high drying temperature. At the end of wood drying experiment, the drying temperature reaches 95°C and it is predicted to reach a higher one. As a consequence, the study promotes the prevalent utilization of two-stage compression heat pump system.

Experiment of Pinus massoniana plates was carried out. The results show that the trends of moisture ratio, temperature and humidity of heat pump drying are consistent with the normal ones. Exactly, with the augment of drying time, the moisture ratio declines and the drying rate slow down under fiber saturated point. And the temperature ascends, while humidity descends.

The heat pump drying technique makes use of the waste heat of moist air, which is known as an energy-saving technique. The research results show that, the average energy recycling rate (energy saving rate) is over 28%.

By contrast, the energy saving rate of high temperature drying heat pump is lower than the low temperature one (Biguang and Guangqing, 1995). However, the high temperature enables the drying rate to accelerate. It can be seen from the experiment that, the highest energy saving rate reaches 65.41%, when the moisture ratio ranges from 148 to 70%, while the lowest rate is 17.32% at moisture ratio 40%. Even so, the total average energy saving rate reaches as high as 28.16%.

Table 3: Energy recycling rate during various moisture content period

Moisture ratio periods (%)	Average temperature (°C)	Average humidity (%)	Expelled water quantity (g)	Evaporator inlet temperature (°C)
148-90	49.8	63.2	344.29	43.62
90-70	67.5	40	233.49	61.98
70-40	77.9	18.1	183.92	60.46
Oct-40	85	15.2	77.830	61.98
Average	-	-	-	-
Evaporate outlet temperature (°C)	**Q_a (kW)**	**Q_b (kW)**	**Energy consummation (kW)**	**Energy saving rate**
54.99	0.2296	0.039	0.410	65.41%
66.67	0.1548	0.016	0.390	43.78%
65.31	0.1221	0.017	0.385	35.53%
66.67	0.0516	0.016	0.376	17.32%
-	-	-	-	28.16%

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