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Simulation on vapour compression heat pump system for rough rice drying

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Abstract. In this study, a simulation of a vapor compression heat pump system for bed drying of rough rice have been carried out for various thicknesses in the range of 20-50 cm and various drying air mass flow rates in the range of 0.06 - 0.22 kg/s-m^2. The modelling used was grouped into two parts, i.e. the determination of temperature and humidity of the air coming out of the heat pump and the drying process of the rough rice using these air conditions. Parameters related to flow rate and energy were expressed in units of cross-sectional area of the drying bed. Simulation results showed significant differences in drying time and temperature for various thicknesses and air mass flow rates but their energy consumptions were similar. Under these conditions the drying temperature and drying time obtained ranged between 34-45^{o}C and 8-15 hours, respectively while the specific energy consumption was relatively low i.e. in the range of 1.07-1.36 MJ/kg of evaporated water for all the scenarios tested. The specific drying air mass flow rate of 0.3 and 0.5 kg/s/m^{3}did not provide significant differences in specific energy consumption. For the field applications, the selection of conditions for thickness and the appropriate air mass flow rate will depend on the user preference including the ease of mixing, drying time or energy consumption.

1. Introduction

One of the advantages of a vapor compression heat pump (VCHP) system is the quantity of heat that is greater than its energy input due to the additional heat obtained from the ambient air. This makes the use of electricity for heating purpose becomes more economical. Another advantage of this system is the ability to dehumidify the air so that the absolute humidity of the air becomes lower than the absolute humidity of the ambient air, which is suitable for the drying purposes.

Drying heat pump systems that use VCHP have been studied extensively [1-7], but these systems are more aimed to dry the temperature-sensitive agricultural/food products. The application of these systems for grains are limited. Nelwan et al. [8] have designed a VCHP laboratory-scale dryer model with R-134a refrigerant for rough rice drying. Experiments carried out in the study were aimed to analyse several intermittent drying and drying air recirculation configurations. The results showed that the potential for energy savings from the VCHP drying system for grain drying was quite high. The thermal energy consumption expressed in specific moisture extraction rate was in the range of 3.68 - 7.04 kg/kWh with reasonable drying time (approximately 12 hours).

Shallow static bed drying (bed thickness less than 50 cm) is a popular drying method in Indonesia. In a static bed drying, the bed thickness together with the drying air conditions greatly affects the drying performance.

The drying air flow rate is one of the important factors in both thermal as well as mechanical energy consumption. The use of high air flow rates can contribute to the capability of moisture transport.

However, in a drying system with a relatively fixed energy supply, a large air flow rate will reduce the resulted temperature increase, so that the increase of drying air flow rate could reduce or increase drying time for the same moisture content reduction. For this reason, this study aims to simulate the drying performance of rough rice bed using a vapor compression heat pump system at various specific air mass flow rates (SMFR) used for various bed thicknesses.

2. Method

2.1. Rough rice drying system with a heat pump
The main components of the VCHP system include a compressor, condenser, expansion valve and evaporator. R-134a was used as the refrigerant. The VCHP drying system used as the basis for this simulation study is a system with ambient air dehumidification, i.e. by passing the ambient air through the evaporator. An air-to-air counter-flow heat exchanger with the ambient air was used to heat the air which had previously been passed through the evaporator and subsequently, the air would be passed through the condenser. The heated air leaving the condenser was flowed through the drying bed inside a separate drying chamber. The depth of drying bed was varied from 20 to 50 cm. Figure 1 shows the schematic of the drying system.

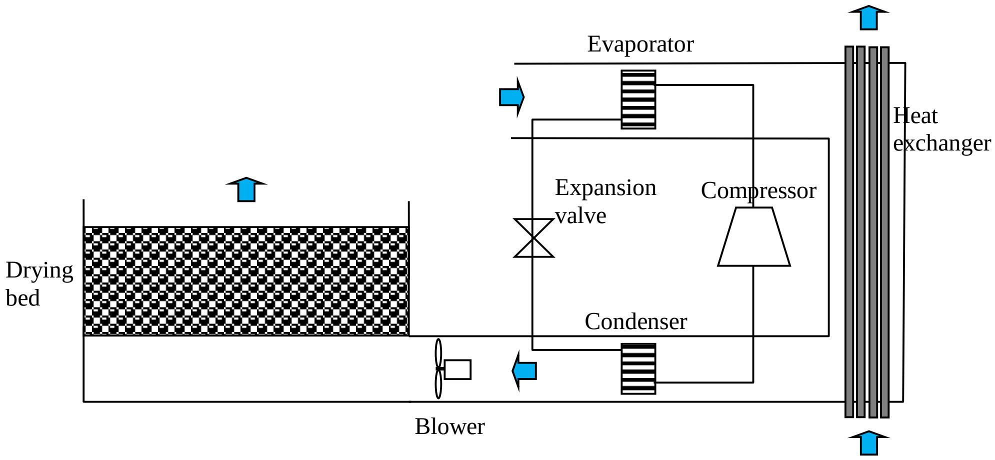

Figure 1. The drying system (blue arrow shows the air flow)

2.2. Modeling and simulation
The heat pump performance simulation was based on the previously developed model [8-9] involving the characteristic equations of the heat absorbed by evaporator (Q_e), compressor power (P), heat released in condenser (Q_c) and refrigerant mass flow rate (m in kg/s) in form of polynomial functions of the evaporator temperature (T_e) and condenser temperature (T_c) as well as the convective heat transfer equations on the evaporator, heat exchanger and condenser. Temperatures were expressed in ^{o}C, while the heat (Q_e and Q_c) and power (P) were expressed in W. The corresponding energies were calculated by multiplying the power with time (s) required.

Air temperature after passing through the evaporator and condenser was calculated from the energy balance and heat transfer in the evaporator. The energy balance for the evaporator and condenser are respectively expressed as:

$$Q_e(T_e,T_c) = \dot{m}_{ud}\left(h_{e,out} - h_{e,in}\right) \tag{1}$$

$$Q_c(T_e,T_c) = \dot{m}_{ud}\left(h_{c,out} - h_{c,in}\right) \tag{2}$$

where $h_{e,in}$ and $h_{e,out}$ are enthalpy of air(kJ/kg dry air) entering and leaving the evaporator, respectively while $h_{c,in}$and $h_{c,out}$are enthalpy of air entering and leaving the condenser, respectively. $Q_e(T_e,T_c)$ and $Q_c(T_e,T_c)$ denote the characteristic equations for evaporator and condenser respectively which can be found in reference [8] and [9].

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Changes in absolute humidity are assumed to occur only in the evaporator where condensation of part of the moisture from the air passing through the evaporator, which is expressed as:

$$\frac{\left(h_{e,out}-h_{coil}\right)}{\left(h_{e,in}-h_{coil}\right)}=\frac{\left(H_{e,out}-H_{coil}\right)}{\left(H_{e,in}-H_{coil}\right)} \quad (3)$$

where h_{coil} are enthalpy of air (kJ/kg dry air) at the evaporator surface condition, $H_{e,in}$ and $H_{e,out}$ are the absolute humidity (kg/kg dry air) of the entering and leaving the evaporator, while H_{coil} the absolute humidity of the air at the evaporator surface condition. A counterflow shell and tube heat exchanger was installed between the evaporator and the condenser which is intended to heat the air leaving from the evaporator. The product of overall heat transfer coefficient and heat exchanger area (UA) used was 0.15 kW/m^{2o}C.

Air enthalpy was determined using psychrometry functions of air temperature and humidity. Because the equations involving non-linear forms, Newton Raphson method was used to obtain the necessary variables, namely the temperature and humidity of the air leaving the evaporator and condenser. Furthermore, the resulting air conditions were used as input variables in rough rice drying using model from Nelwan et al. [10] developed from the Bala [11].

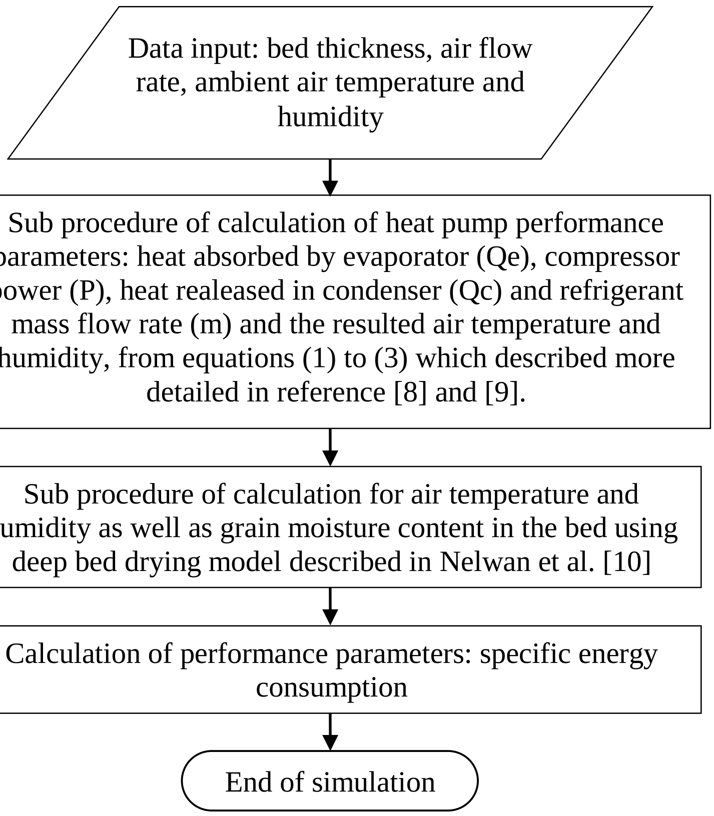

Figure 2. Flowcharts describing simulation stages

In this simulation the air mass flow rate was expressed in the cross-sectional area of the drying bed, so that P and Q_e, as well as their energy consumption were also expressed in the cross-sectional area of drying bed. Total energy consumption consists of heat pump and blower energy consumption. The power required for blower was determined from the pressure drop equation of rough rice [12], with the blower power efficiency was assumed to be 20%. Figure 2 shows the flow chart of the simulation procedure.

3. Results and Discussion

3.1. The duration of the drying process

The simulation was performed in VBA of Microsoft Excel. The simulation was performed assuming an initial moisture content of 23% b.b. and final moisture content of 14% b.b, with 28°C environment ambient air with absolute humidity 0.019 kg water / kg dry air. The bed thickness of rough rice ranges from 20 to 35 cm with a bulk density of 600 kg/m^3. With such the data, mass of evaporated water was 104.65 kg per ton of grain being dried.

The results of the simulation of drying performance at various superficial velocities (0.1 - 0.22 kg/s-m^2) and bed thicknesses (20-35 cm) are presented in table 1. In general, an increase in air flow rate tends to increase drying time for all bed thickness. Increasing the drying air flow rate will increase the ability of air to carry water vapour but reduced the temperature of the drying air (from 44.18°C to 35.24°C) because the heat rate generated by the heat pump is relatively fixed. The heat rate from the heat pump was only determined by the temperature of the condenser and evaporator which was relatively unchanged with the air flow rate. It seems that the temperature reduction was compensated by the amount of water vapour that can be carried by the air flow so that the drying time was not too different even though the air temperature decreases significantly. For all simulation conditions the drying time were sufficient for the application in the range of 8.98 - 15.38 hours. Drying that can be performed in less than 10 hours should have a bed thickness less than 20 cm.

Table 1. Drying performance at various superficial velocity (0.1 - 0.22 kg/s-m^2) and bed thickness (20-35 cm)

Bed depth (cm)	Superficial velocity (kg/s-m^2)	Time (hours)	Air temperature leaving condenser (°C)	Energy consumption (MJ/m^2 bed cross section)		Average heat pump power (W/m^2 bed cross section)	Specific air mass flow rate (kg/s/m^3)	Specific energy consumption (MJ/kg water evaporated)	
				Heat pump	Blower			Heat pump	Total
20	0.1	8.98	44.18	14.64	0.41	452.69	0.50	1.17	1.20
	0.14	9.08	40.10	14.81	0.69	452.91	0.70	1.18	1.23
	0.18	10.43	36.52	16.58	1.21	441.43	0.90	1.32	1.42
	0.22	10.74	35.24	17.12	1.79	442.72	1.10	1.36	1.51
25	0.1	10.83	44.18	17.65	0.62	452.91	0.40	1.12	1.16
	0.14	10.73	40.10	17.48	1.02	452.73	0.56	1.11	1.18
	0.18	12.10	36.52	19.14	1.74	439.49	0.72	1.22	1.33
	0.22	12.22	35.24	19.47	2.54	442.70	0.88	1.24	1.40
30	0.1	12.67	44.18	20.65	0.88	452.85	0.33	1.10	1.14
	0.14	12.37	40.10	20.17	1.41	452.85	0.47	1.07	1.15
	0.18	13.70	36.52	21.78	2.37	441.61	0.60	1.16	1.28
	0.22	13.72	35.24	21.86	3.42	442.69	0.73	1.16	1.34
35	0.1	14.51	44.18	23.65	1.17	452.80	0.29	1.08	1.13
	0.14	14.05	40.10	22.90	1.87	452.75	0.40	1.04	1.13
	0.18	15.38	36.52	24.45	3.10	441.50	0.51	1.11	1.25
	0.22	15.24	35.24	24.29	4.43	442.68	0.63	1.11	1.31

3.2. Energy consumption

Because the heat pump power was relatively similar for various conditions, the specific heat pump consumption depends more on the drying time required, especially at a thickness of 20 cm where the drying time ranges between 8.98 and 10.74 hours providing the specific heat pump energy consumption in the range 1.17 - 1.36 MJ/kg of evaporated water. The energy consumption range was narrower at a thickness of 35 cm which was 1.08 - 1.11 MJ/kg of evaporated water, because the drying time was also quite narrow, ranging between 14.51 and 15.38 hours. The specific heat pump energy consumption was lower at higher bed thicknesses.

3.3. *Effect of SMFR*

In order to obtain the effect of bed thickness on drying performance at the same specific air mass flow rate, a drying bed thickness is used between 20 - 35 cm for SMFR of 0.3 kg/s/m^3 and 20 - 50 cm for SMFR of 0.5 kg/s-m^3 as presented in table 1. At low SMFR (0.3 kg/s/m^3) for the same bed thickness, the corresponding air flow rate (represented by superficial air flow rate) would be lower. It can be seen that the superficial air flow velocity that corresponds to the bed thickness of 30 cm was 0.09 kg/s-m^2 at a specific mass air flow rate of 0.3 kg/s/m^3 and the corresponding superficial velocity of 15 kg/s-m^2 at 0.5 kg/s/m^3. The superficial velocity required will greatly affect the temperature of the air produced.

Table 2. Effect of bed thickness on drying performance at the same specific air mass flow

Specific air mass flow rate (kg/s/m^3)	Bed depth (cm)	Superficial velocity (kg/s-m^2)	Time (hours)	Air temperature leaving condenser (°C)	Energy consumption (MJ/m^2 bed cross section)		Average heat pump power (W/m^2 bed cross section)	Specific energy consumption (MJ/kg water evaporated)	
					Heat pump	Blower		Heat pump	Total
0.30	20	0.060	9.02	53.76	14.70	0.21	452.87	1.17	1.19
	30	0.090	12.76	45.77	20.80	0.76	452.86	1.10	1.14
	40	0.120	16.03	41.80	26.12	1.93	452.76	1.04	1.12
	50	0.150	20.01	37.95	31.72	4.25	440.37	1.01	1.15
0.50	20	0.100	8.98	44.18	14.64	0.41	452.69	1.17	1.20
	25	0.125	10.74	41.33	17.51	0.86	452.81	1.12	1.17
	30	0.150	13.74	37.95	21.78	1.75	440.27	1.16	1.25
	35	0.175	15.40	36.72	24.47	2.96	441.38	1.11	1.25

Table 2 shows that at the same SMFR, the specific energy consumption is almost the same for various thicknesses, but the drying time increases significantly. At SMFR of 0.3 kg/s/m^3 the drying time ranges between 9.02 and 20.01 hours in the bed thickness range between 20 and 50 cm, while at 0.5 kg/s/m^3 the drying time were between 8.98 and 15.4 hours in the bed thickness range between 20 and 35 cm. As stated earlier, the heat pump power available was almost the same for all conditions so that the specific energy consumption was also almost the same. The specific heat pump energy consumption actually tends to decrease with the increase of bed thickness but it was compensated by the increase of specific fan energy consumption.

These results also clearly show that although the SMFR affects the temperature, it did not significantly affect the drying time and specific energy consumption. In addition, the bed thickness did not greatly affect specific energy consumption. Even at SMFR 0.3 kg/s/m^3 the specific energy consumption was only slightly lower than that of 0.5 kg/s/m^3. This is mainly due to the power of the heat pump which was relatively fixed in various drying conditions. However, SMFR greatly affected the temperature and drying time. In addition, fan energy requirements also increase exponentially with bed thickness.

The SMFR of 0.3 kg/s/m^3 the bed height of 50 cm provided a sufficiently high temperature for safe rough rice drying, i.e. at 53.76 ° C, due to the low (superficial) air flow rate of 0.06 kg/s/m^3. Absolute air flow rate affects the amount of heat pump power because the temperature of the condenser and evaporator was affected by that rate. For SMFR of 0.3 kg/s/m^3, the temperature of the drying air was below 45oC for all thicknesses of the bed.

3.4. *Overview of small-scale applications*

For applications on a small scale processing unit, drying time, drying temperature, energy consumption, area requirements for drying as well as ease of handling are important parameters in assessing drying performance. Therefore a dryer with a relatively fixed energy source heat pump, the thickness of the bed and the SMFR become the important determining factors.

The results in table 2 show that the SMFR up to 0.5 kg/s/m^3 did not significantly affect the specific energy consumption. If the desired working time and drying temperature are less than 13 hours and

46°C respectively, then there are three drying circumstances (bed thicknesses and superficial velocity) satisfy the target, i.e. 20 cm and 0.06 kg/s-m^2, 25 cm and 0.125 kg/s-m^2 as well as 30 cm and 0.09 kg/s-m^2. The calculation results of the bed cross section area, flow rate and heat pump power which were intended to handle 23% w.b. moisture content of 2 tons (or 3.3 m^3) of rough rice for the three circumstances are presented in table 3.

Table 3. Drying system application for 2 Ton capacity of rough rice

Parameter	Bed depth, superficial velocity		
	20 cm, 0.06 kg/s-m2	25 cm, 0.125 kg/s-m2	30 cm, 0.09 kg/s-m2
Cross section bed area (m^2)	16.7	13.3	11.1
Drying time (jam)	9.0	10.7	12.8
Drying air temperature (oC)	44.2	41.3	45.8
Flow rate (m^3/s)	1.67	1.67	1.00
Heat pump power(W)	7544.8	6037.4	5031.8
Blower power (W)	211.3	296.5	183.9
Total energy (kWh)	69.7	68.0	66.5

It can be seen that although the total energy consumption for all drying circumstances are similar (66.5 - 69.7 kWh), the use of a bed thickness of 30 cm with a speed of 0.09 kg/s-m^2 can reduce the need for drying bed area, heat pump power and a blower which means reducing the need for fixed (investment) costs. However, if the priority given is drying time and ease of stirring, the selected condition is the thickness of the pile 20 cm with a speed of 0.06 kg/s-m^2, but the need for bed cross section area and power wass approximately 150% of the circumstance 30 cm bed thickness with a superficial velocity of 0.09 kg/s-m^2. Furthermore, if the priority is the safe drying temperature, then bed of 25 cm and 0.125 kg/s-m^2 can be considered.

4. Conclusion

VCHP system simulation for the rough rice bed drying has been carried out for bed thicknesses of 20-35 cm, with an air flow rates of 0.1-0.22 kg/s-m^2. Under these circumstances the drying temperature and drying time obtained ranged from 34 to 45°C and 8 to 15 hours while the specific energy consumption was relatively low, i.e. ranged from 1.07 to 1.36 MJ/kg of moisture evaporated while for all scenarios tested.

In general, an increase in the air flow rate tends to provide increased drying time. Increased air flow will increase the potential to remove moisture but reduced the temperature of the drying air because the heat rate generated by the heat pump was relatively unchanged.

SMFR levels of 0.3 and 0.5 kg/s/m^3 did not provide significant differences in specific energy consumption but SMFR of 0.3 kg/s/m^3 provided a significantly higher drying temperature than 0.5 kg/s/m^3.

For small scale applications of 2 tons with drying time and thickness limited to 13 hours and 30 cm, respectively there were three circumstances (bed thicknesses and superficial velocity) that meet the target, i.e. 20 cm and 0.06 kg/s-m^2, 25 cm and 0.125 kg/s-m^2 as well as 30 cm and 0.09 kg/s-m^2. All three have quite low energy consumption, namely 66.5 - 69.7 kWh. The selection of suitable conditions will depend on priority of the user, i.e. bed cross section area, flow rate and heat pump power.

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