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ORIGINAL ARTICLE

Performance evaluation of heat pump dryer

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Abstract A batch type heat pump assisted dehumidified air dryer was developed successfully with a medium range of temperatures (30–41°C) for safe drying of heat sensitive crops. Dehumidification system of the developed heat pump dryer (HPD) maintained the relative humidity (RH) of air entering the drying chamber below 40%. The inlet drying air temperature decreased during early hours of drying followed by rapid rise between the 2nd and 10th h, after which the temperature was almost stable. The RH of inlet and exhaust drying air increased initially and decreased subsequently with drying time as product became drier. The HPD was found to have a specific moisture extraction rate between 0.55 and 1.10 kg/kWh. Energy consumption for HPD for 24 h of operation was found less (4.48–5.05 kWh) than the hot air dryer (5.65–9.6 kWh) while operating under different drying conditions. Better quality dried sweet pepper (*Capsicum annuum* L.) was obtained in HPD owing to lower drying air temperature.

Keywords Heat pump dryer · Dehumidification system · Hot air dryer · Specific moisture extraction rate · Sweet pepper

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Introduction

Thermal drying is often conducted at high temperatures. However many agricultural and food materials are sensitive to high temperatures. Dehydrated products usually suffer distinct losses in quality during processing. It is reported that the pigment and vitamin degradation rate increases as the drying temperature increases (Malchev et al. 1982). Further conventionally air dried products do not rehydrate satisfactorily because of structural changes in the product due to excessive thermal damage (Holdsworth 1986). Owing to these quality differences compared to other preservation techniques, the demand for dried fruits and vegetables has been almost static. During last few years, emphasis has been laid on improving the rehydration characteristics and quality attributes of hot air dehydrated commodities by changing process variables using pre-drying treatments and low temperature processes (Pal and Khan 2007). Thus drying at low temperature to enhance the quality of food products has been a growing interest in recent years. High value products, which are extremely heat sensitive, are often freeze dried. However, this is an expensive drying process (Baker 1997). Vacuum drying system is normally used for sensitive materials that can be damaged or decomposed at high temperatures but it is an energy intensive process for maintaining vacuum inside the drying chamber. The dryer has special parts, pumps and hermetical closed circuit and requires frequent inspection. The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput. A drying system that is both energy efficient and preserves product quality is desired (Adapa et al. 2002). This creates challenges for researchers, food industry and dryer manufacturers to develop new technologies to process difficult-sensitive materials and to supply final products with high quality and improved properties. Recently, there has been a significant growth in the potential market for heat pump dryers. Heat pumps have been known to be energy efficient when used in conjunction with drying operations. The evaporator and the condenser recover heat and reduce the energy consumption of the drying process (Strommen and Kramer 1994, Prasertsan and Saen-Saby 1998, Chua et al. 2002).

Materials and methods

Development of heat pump dryer: Because of the possibility of providing hermetically closed drying environments while drying with high energy efficiency, a suitably designed heat pump dehumidifier would be the best option to provide the required low temperature and low humidity condition. A laboratory model heat pump dryer with special features of variable drying air temperature and mode of operation (open and close) was fabricated. The line diagram of the dryer are shown in Fig. 1. The developed dryer consisted of dehumidifier unit and the drying chamber. The dryer is a closed insulated chamber consisting of a dehumidifier unit with evaporator and condenser at its lower portion and a drying chamber at its upper portion. The reciprocating compressor (power 470 W and swept volume 7.8 cc) and external condenser are located at the bottom of the chamber. The evaporator and condenser were finned tube designs consisting of copper pipes of 9.5 mm external diameter and face dimension of 28 cm × 25 cm. Control devices in the refrigerant circuit enabled distribution of the refrigerant (on the high pressure side) between 2 condensers for heating the process air. The temperature of the drying air was controlled by a thermostat, which operated the solenoid valve connected to internal condenser line and allowed the refrigerant to flow.

Hot air dryer (HAD): The HAD consisted of insulated drying chamber with trays, fan, electrical heater and digital temperature indicator cum controller to maintain the desired drying air temperature. The drying air temperature, relative humidity and energy consumption were also measured during the experiment.

Performance of Heat pump dryer (HPD): The dryer was operated using R22 refrigerant to study the drying air condition with closed and open mode of operation. The inlet and outlet drying air temperatures and RHs, evaporator and condenser surface temperatures, suction and delivery pressures were recorded to study the variation with drying time. In HPD system, moisture extraction rate (MER) and specific moisture extraction rate (SMER) are the dryer performance indicators. MER i.e. kilogram of moisture removed per hour indicates the dryer capacity or throughput rate. SMER i.e. kilogram of moisture removed per kilowatt-hour defines the effectiveness of the energy used in the drying process (Chua et al. 2002).

$$\mathrm{MER} = \frac{\text{Water evaporated from product}}{\text{Drying time}}$$

$$\mathrm{SMER} = \frac{\text{Water evaporated from product}}{\text{Total energy input}}$$

Drying experiment: Thin-layer drying experiments under controlled conditions were conducted for green sweet pepper (*Capsicum annuum* L.) in HPD at 30°C (RH 40%), 35°C (RH 27%) and 40°C (RH 19%). The samples were also dried in HAD at 45°C (RH 55%), 55°C (RH 35%) and 65°C (RH 20%) to compare with that of heat pump drying. Fresh samples used for the experiment were procured from the local market, sorted and washed properly. The cups, seeds and stems of sweet pepper were removed. These were then sliced into 0.5 cm thick slices using stainless steel knives and loaded in tray with 3.6 kg/m^2 density. The initial weight of the tray with sample was recorded and was weighed regularly at 30 min interval. When the weight of the sample became constant, the experiment was stopped. All the experiments were carried out at 1.5±0.2 m/sec air velocity. The total drying time and energy consumption during drying of sweet pepper at different conditions were measured. The mass of moisture evaporated and cost of drying were calculated to study the performance of the dryer. The quality parameters such as rehydration ratio, chlorophyll and ascorbic acid contents of dried sweet pepper were determined using standard experimental procedure (AOAC 1995).

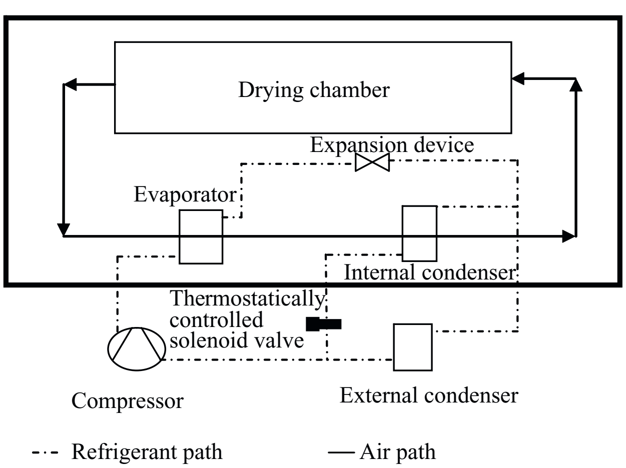

Fig. 1 Line diagram of the heat pump dryer showing refrigerant and air path

Results and discussion

No load condition: Initially, the RH of air decreased rapidly due to dehumidification of air at the evaporator surface in both the modes of operation (Fig. 2). After 20 min of operation, the RH of air in refrigeration mode increased gradually due to the lowering of drying air temperature and attained a constant value of 46%. But in the closed air circuit heat pump mode, the RH continued to decrease at a slower rate and attained a constant value of 19%. The temperature of air decreased continuously to a constant value of 22°C in refrigeration mode, whereas increased to 41°C in heat pump mode of operation. So, the drying air temperature and RH

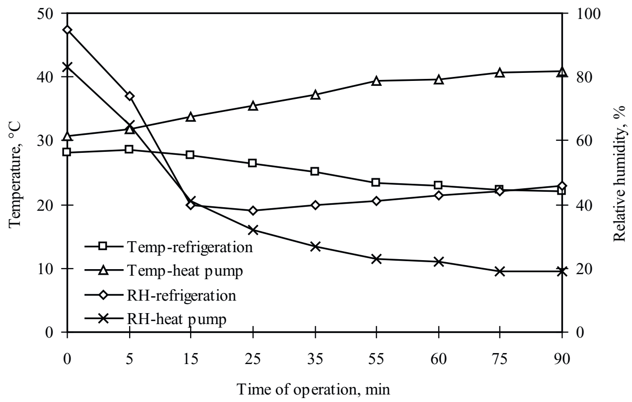

Fig. 2 Variation in drying air temperature and relative humidity with time in the heat pump dryer under no load condition at different modes of operation

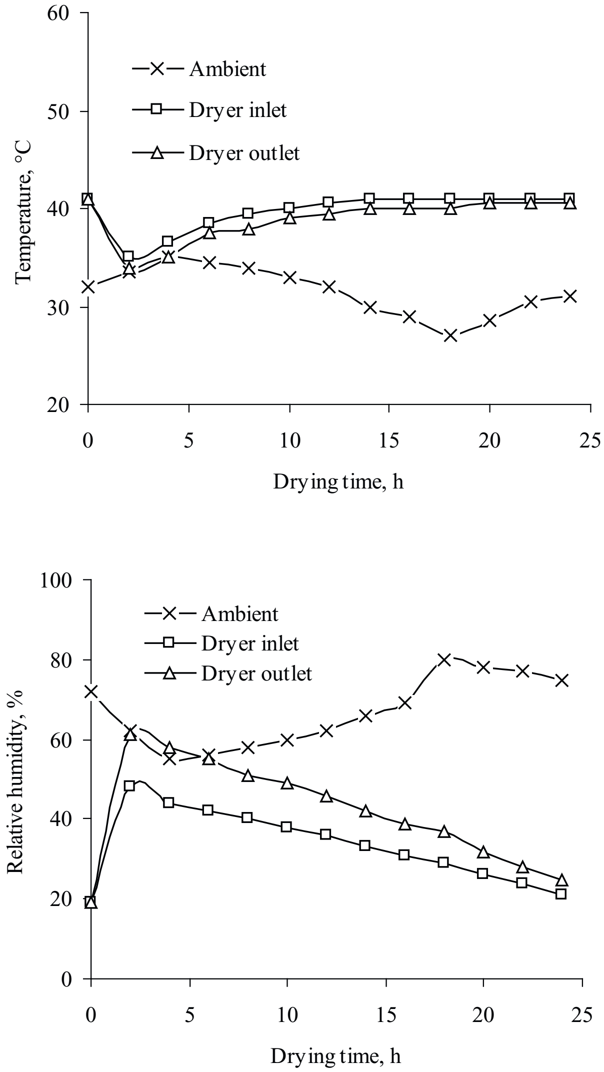

Fig. 3 Variation in ambient, dryer inlet and outlet temperature and relative humidity with drying time

in the closed air circuit heat pump mode attained a value of 41°C and 19% from an ambient value of 32°C and 72%, respectively under no load condition after 90 min of the dryer operation. Medium range of temperatures (30–41°C) for safe drying of heat sensitive crops were achieved experimentally in the HPD. Dehumidification system of the HPD maintained the RH of air entering the drying chamber below 40%. The achieved drying air temperature, RH, suction and delivery pressure in the HPD under different operating conditions and mode of operation are given in Table 1.

The suction and delivery pressure in case of heat pump mode were found to be 179 and 1999 kPa in closed air circuit (with recirculation of drying air) and 198 and 2084 kPa for open air circuit operation (ambient air entering the dehumidifier unit and leaving at dryer outlet without recirculation), respectively. The higher suction pressure in open air circuit operation as compared to closed air circuit may be due to higher cooling load of ambient air on the evaporator leading to superheating of refrigerant vapour and this increased the load on condenser. Both the suction and delivery pressure were higher when operated under heat pump mode as compared to refrigeration mode which might be due to improper condensation at the internal condenser.

Loaded condition: The initial phase is marked by a drop in temperature during the early hours followed by rapid rise between the 2nd and 10th h, after which the temperature was almost stable (Fig. 3). Initially the material was wet and cool. The decrease in inlet air temperature at the initial stage of drying might be due to the utilization of most of the heat transferred at the evaporator surface for dehumidification purpose. The air temperature at the inlet and outlet of the drying chamber decreased initially, after which increased and reached an asymptote at 41°C. The temperature varied between 35 and 40°C for the first 10 h during which period almost 40% of the drying took place. Most of the latent heat recovered during the early stages of the process was rejected at the secondary condenser. As the drying progressed, most of the heat exchanged at the evaporator is sensible heat and the temperature of the air entering the drying chamber increased gradually. The results were similar to the findings of Sosle et al. (2003). The exhaust drying air temperature was less than that of the inlet air temperature as part of the heat was utilized for raising the temperature of product and its associated water. As the product became drier with less water content at the later part of drying, the difference between inlet and exhaust drying air temperature decreased.

The RH of inlet and exhaust drying air increased initially to 48 and 61%, respectively from an initial value of 19% after 2 h of drying and decreased subsequently with drying time as product became drier (Fig. 3). The difference between exhaust and inlet air RH was more initially due to loss of water from the wet product. The RH of drying air at the exit of the drying chamber decreased almost exponentially from an initial value of 61% down to 25% by the end of drying. The initial high moisture content of the material and low temperature of drying air resulted in higher initial RH of the drying air. The air became drier due to the onset of falling drying rate period as reported by Adapa et al. (2002). The ambient RH value ranged from 55 to 80%. The air temperatures at the evaporator outlet ranged from 15 to 18.5°C. The evaporator and condenser surface temperatures were –16 to –20°C and 45 to 49°C, respectively. The variation in these temperatures might be due to variation of exhaust and ambient air conditions with drying time. The variation in evaporator and condenser surface temperature with drying time is shown in Fig. 4.

Specific moisture extraction rate: The energy consumption, MER and SMER calculated for different drying air temperatures are given in Table 2. The SMER and MER values increased with increase in drying air temperature due to more drying potential of high temperature air. Specific moisture extraction rate for HPD for drying sweet pepper at 40°C was more (1.1 kg/kWh) than hot air dryer (0.93 kg/kWh) while operating at 45°C. This might be due to lesser energy requirement and higher drying potential of low RH air in HPD. The HPD had SMER between 0.55 and 1.10 kg/kWh. The SMER generated agrees with those by Adapa et al. (2002).

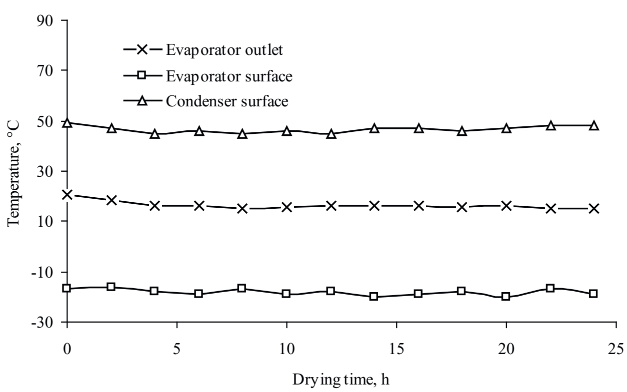

Fig. 4 Variation in evaporator outlet, evaporator and condenser surface temperature with drying time

Energy consumption for HPD for 24 h of operation was found less (4.48-5.05 kWh) than the HAD (5.65-9.6 kWh) while operating under different drying conditions. It was also observed that the variation of energy requirement (for 24 h of operation) in HPD at different drying air temperatures was not much (at low drying air temperatures) as the compressor was to operate for same duration leading to almost equal energy consumption and the excess heat was rejected at the external condenser. The higher energy requirement at 65°C in HAD might be due to more time of operation of the heater controlled by thermostat to maintain the high drying air temperature in the drying chamber.

Cost of drying: Cost of drying was found to be more in HAD at 45 and 55°C as compared to 40°C in HPD with Rs 3.35/kg of sweet pepper (Table 2). This might be due to higher energy consumption and longer drying time in case of hot air drying. The cost of drying was more when dried at 30°C in HPD due to longer drying time at lower temperature.

Quality of dried product: The rehydration ratios ranged from 6.5 to 7.2 for sweet pepper with the lower value for hot air dried product at 65°C (Table 3). Total chlorophyll content of sweet pepper reduced from the initial value of 103 to

Table 1 Drying air temperature, relative humidity, suction and delivery pressure obtained in heat pump dryer under different operating conditions with R22 refrigerant

Operating condition		Drying air condition		Suction pressure, kPa	Delivery pressure, kPa
		Temp,°C	RH, %		
Refrigeration	Closed air	22	46	138	1545
Refrigeration	Open air	25	42	151	1720
Heat pump	Closed air	41	19	179	1999
Heat pump	Open air	35	43	198	2084

Table 2 Comparison of energy consumption, MER and SMER at different temperatures in hot air dryer(HAD) and heat pump dryer(HPD)

Drying air temp,°C	Energy, kWh	Drying time, h	Drying cost, Rs/kg	MER, kg/h	SMER, kg/kWh
HPD					
30	4.48	36	6.70	0.103	0.55
35	4.84	25	5.05	0.148	0.74
40	5.05	16	3.35	0.232	1.10
HAD					
45	5.65	17	4.00	0.218	0.93
55	8.4	10	3.50	0.370	1.06
65	9.6	6	2.40	0.618	1.55

MER: Moisture extraction rate, SMER: Specific moisture extraction rate Energy is for consumption for 24 h operation

Table 3 Quality of heat pump and hot air dried sweet pepper at different temperatures

Quality parameters	Initial value	Heat pump drying			Hot air drying		
		30°C	35°C	40°C	45°C	55°C	65°C
Rehydration ratio	-	7.2	7.0	6.9	6.8	6.6	6.5
Chlorophyll, mg/100 g (db)	103	96	93	89	86	78	66
Ascorbic acid, mg/100 g (db)	1060	312	337	294	238	216	174

66 mg/100 g (db) in HAD at 65°C and to 96 mg/100 g (db) in HPD at 30°C. The ascorbic acid content of sweet pepper decreased from an initial value of 1060 to 312 mg/100 g (db) when dried at 30°C in HPD and to 174 mg/100 g (db) in HAD at 65°C. So better quality dried product was obtained in HPD owing to lower drying air temperature.

Conclusion

A batch type heat pump assisted dehumidified air dryer was developed and a medium range of temperatures (30–41°C) for safe drying of heat sensitive crops were achieved. Dehumidification system of the developed HPD maintained RH of air entering the drying chamber below 40%. Better quality dried sweet pepper was obtained in HPD owing to lower drying air temperature. The dehumidified air dryer using heat pump system can be tried for drying fruits, vegetables, spices, condiments, medicinal, aromatic and other high value commodities at near ambient temperature for producing better quality dehydrated product.

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