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Performance comparison of Closed Loop Heat Pump Dryer with Bed, Tray and Bed-Tray Dryer for Curry Leaves

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Abstract - Heat pump assisted drying provides a regulated drying environment by controlling the temperature and humidity of air through which the product quality can be improved with less energy consumption. It has incredible potential for the future, as well as the opportunity for a revolution in drying techniques. An expansion valve, evaporator, condenser, and compressor make up the heat pump system, in connection with the copper tube of each component. In this project, the heat pump dryer was designed and fabricated where R134a is used as the working fluid to dry the Indian spice Murraya koenigii (curry leaves). Murraya koenigii has many bioactive principles as a result of which it is a medicinally valuable herb. The curry leaves are dried in a closed-loop heat pump dryer under three different methods namely, Bed drying, tray drying, and compound drying which is a combination of both bed and tray drying at three different velocities 1.5 m/s, 2 m/s and 2.5 m/s. The drying characteristics of the closed loop heat pump dryer is analysed with different combination of drying methods and velocities for curry leaves.

Keywords – Drying; Heat pump dryer; Moisture Removal Rate; Bed dryer; Bed-Tray Dryer; Curry leaves.

INTRODUCTION

Heat pump drying method is one in which the drying can be achieved without relying on atmospheric conditions and with minimal energy use. The growth of fungus, yeasts, bacteria and other microorganisms' are prevented in the dried food and medicinal products when it is stored for long duration. The heat pump recovers the latent and sensible heat of evaporated moisture of the drying product and that heat is returned to the dryer by reheating the dehumidified air, resulting in a significant gain in energy efficiency due to heat recovery that would otherwise be lost to the atmosphere in traditional dryers [1]. Three Heat Pump Dryer (HPD) system designs with no air recirculation, two with partial air recirculation, and one with full air recirculation were investigated, As the air recirculation rate is increased, the efficiency of HPD systems with partial air recirculation falls and partial air recirculation systems are more efficient than no air and full air recirculation systems [2]. Heat pump assisted dryer prototype with mechanical opener drying system is fabricated and test was conducted to investigate the performance of heat pump dryer which has done by calculating SMER (Specific Moisture Extraction Rate) and COP (Coefficient of Performance). The homogenous drying is attained in this system with four times higher drying rate compared to natural drying [3]. A proportional–integral–derivative controller (PID) temperature controlled bed heat pump dryer is designed and constructed and thermodynamic analysis was done. The experimental tests were conducted for three different products mint, parsley and basil at 40°C operating temperature with uncertainty of ±0.36°C for the drying air velocity of minimum of 1.01 m/s to 7.4 m/s, the COP of heat pump dryer is obtained as 1.91[4]. The heat pump dryer operating at low temperature is constructed and experiments were conducted for 5 hour duration in sludge with different temperature and mass flow rate conditions. The rise in condensing temperature increases the drying rate whereas the drying rate drops while the evaporation temperature increases and the increase in air mass flow rate will causes for first increase and then decrease in drying rate [5]. The mathematical model was developed by which the drying rate can be calculated for change in parameters during the process to the product of corn in a bed dryer. The model's advantage is that it just uses thermal and physical characteristics, which eliminates the need for preparatory studies to determine kinetic parameters. [6]. To evaluate long-term performance characteristics for the drying

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system, mathematical modelling of wheat drying system operating with a ground coupled heat pump and an underground Thermal Energy Storage (TES) tank charged by solar energy was developed. The efficiency of the drying system is greatly influenced by the thermophysical parameters of the geological structure surrounding the subterranean TES tank. [7]. The hybrid drying system, water/air heat pump powered by a concentrated photovoltaic thermal system is designed and developed to dry the softwood and it is reducing the electrical energy consumption 39% and 89% in January and July, respectively than the conventional drying system [8]. The drawback and benefits of different drying technologies, solar dryer, Biomass, Biogas and geothermal which are operating based on the sustainable energy of single heat source and solar hybrid heat sources were discussed quantitatively and qualitatively [9]. The close loop heat pump dryer operating with lower than atmospheric pressure is designed and fabricated and the experiments were conducted for combinations of 0.9 & 0.8 bar pressure and 1.1 & 1.4 m/s velocity operating conditions and the result shows that the drying rate is increased 58.33% by inducing the vacuum pressure and increasing velocity in the close loop heat pump dryer compared to conventional heat pump dryer [10]. The drying behaviour of the grape pomace is investigated in closed loop heat pump dryer at 45 and 50°C temperatures and the better quality of drying is achieved at 45°C [11]. The hot air dryer equipped with heat pump and air recirculated system is constructed to dry Kiwifruit slices and the test was conducted for various ratio of recirculation air and the results conclude at 45°C, 0% recirculation condition consumes maximum specific energy of 21.7 kWh/kg and the minimum specific energy consumption of 7.5 kWh/kg is obtained at 65°C, 100 % air recirculation condition [12]. The drying kinetic of mint leaves is observed in solar assisted bed dryer with different sources of heat energy like electric heater or microwave energy, solar air heater and parabolic trough collector [13]. Exergy analysis of heat pump drying system for drying food products has been completed and the result shows that the exergy efficiency is increased from 65.94 to 91.95% when increasing the operation temperature from 45°C to 55°C [14]. The multifunctional air source heat pump dryer was designed and fabricated for investigating the drying characters of food product and the experiments were conducted for drying garlic chips and results of three different types open, semi-open and closed type of Heat pump dryers performance were compared and the closed type heat pump dryer is less affected by ambient conditions [15]. The drying rate and quality of mature ginger is compared in the types of drying methods, tray drying, heat pump–Dehumidified drying at the temperatures of 40, 50 and 60°C and mixed–mode solar drying at 62.82°C with a radiation intensity of 62.82°C. The better quality is achieved in heat pump–Dehumidified dryer at 40°C and the best drying rate is achieved in the mixed mode of solar dryer [16]. The proposed work compares the performance of closed loop heat pump dryer at three different types of dryer bed, tray and combined bed-tray.

Material and Methods

A. Materials

The experiments were conducted to find the drying rate of Curry leaves (Murraya koenigii) which is having a good medicinal characteristics and that was purchased directly from the formers who are doing cultivating curry leaves in and around the Rajapalayam.

B. Sample preparation

The leaves were thoroughly cleansed with fresh water in order to remove any undesired particles that could impact the product's drying rate. After being cleaned with water, the materials are placed for at least 3 minutes in paper that will absorb the water particles from the leaves' surface. The leaves were purchased on the day and prepared for conducting the experiments on the site in order to avoid the natural drying. The sample preparation for each reading weighs 3 kg.

C. Design and Development of Closed-Loop Heat Pump Dryer

1) Design

The heat pump dryer run by 3 ton capacity compressor is designed dry the different types of herbal leaves with three different types of dryer as bed, tray and bed-tray dryer to evaluate its performance at the transient temperature conditions. The inlet velocity to the drying chamber of the circulated air is maintained as 1.5, 2.0 and 2.5 m/s. The schematic diagram of closed loop heat pump dryer is given in Fig.1 and the specification of

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components and measuring instruments in given in table I and II respectively.

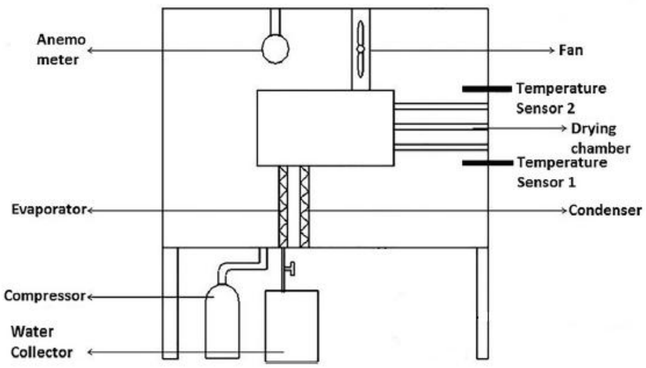

Fig.1 Closed Loop Heat Pump Dryer

TABLE I
SPECIFICATION OF COMPONENTS

Sl. No.	Components	Specifications
1.	Compressor	3-Ton capacity – scroll compressor
2.	Evaporator	3-Ton capacity – Copper coil – vertical finned type
3.	Condenser	3-Ton capacity – Copper coil – vertical finned type
4.	Expansion device	3-Ton capacity expansion valve
5.	Fan	1.5 kW capacity – 2 Nos.
6.	Fabrication plate	G.I Plate with 5 mm thickness
7.	Drying tray	Stainless steel tray with the dimensions of 100 cm x 60 cm

TABLE II
SPECIFICATION OF MEASURING INSTRUMENTS

Sl. No.	Measuring Instrument	Specifications
1.	Anemometer	0 – 45 m/s
2.	Temperature sensor	0 – 99 °C
3.	Humidity sensor	0 – 99 %

2) Operation

The air which is having low Relative humidity can able to absorb the moisture contents in the products. The low relative humidity in air is achieved by the refrigeration system by cooling the air below the dew point temperature and then heated by heat rejected in the condenser. This low-relative-humidity air is directed to the drying chamber, which contains the product to be dried. The high relative humidity air comes out from the drying chamber will be converted to the low relative humidity air by circulating though the evaporator and condenser of the refrigeration system and the process is continuous until the required drying is attained. The drying of products is reached in closed loop heat pump dryer by simultaneous working of two different cycle followed in the heat pump dryer (a) Refrigerant flow circuit and (b) Air flow circuit. The schematic diagram of these two circuit representation is given in Fig.2. [17]

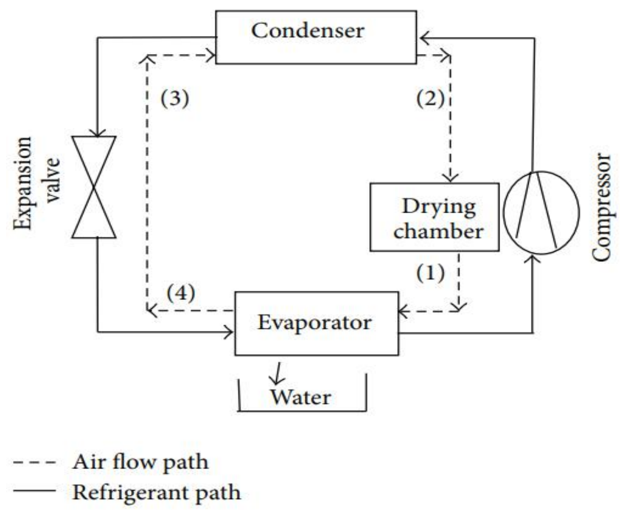

Fig.2 Refrigerant and air flow circuit in Heat pump dryer

Refrigerant flow circuit

The compressor, condenser, expansion device and the evaporator are the main components of the refrigeration flow circuit. The high pressure and high temperature refrigerant comes out from the compressor is entered into the condenser where the condensation of refrigerant is occur and then it is passes through the expansion device and evaporator.

Air flow circuit

In this circuit the air which is not affected by the atmospheric condition is continuously circulated in the closed chamber in which the main components of the refrigeration system like evaporator and condenser is placed.

Working principle

The air of air flow circuit is passed through the evaporator where the air is attained its dew point temperature because of cooling and the moisture present in the air is condensed and the air which is having 100 % relative humidity after condensation of moisture, it passes through the condenser of the refrigeration circuit where the heat rejected from the condenser will be taken by the air and it relative humidity gets reduced. The low

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relative humidity air passes through the drying chamber and the drying is attained and the process continuous because of circulating the air which is comes out from the drying chamber through the evaporator and condenser of the refrigeration circuit. The process flow diagram is given in Fig.3.

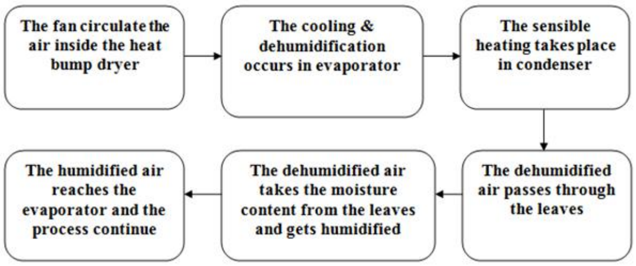

Fig.3 Process flow diagram

D. Methods

1) Evaporation rate

The weight of the dried leaves after 30 minutes of drying in the heat pump dryer is measured immediately taken from the drying chamber to avoid the natural drying. The evaporation rate of the curry leaves can be calculated by the following equation [18].

$$m = \frac{m_i - m_f}{t}$$

Where,
m_i is the mass of product before drying in gram
m_f is the mass of product after drying in gram
t is the drying time in second

RESULTS AND DISCUSSION

The drying characteristics of the closed loop heat pump dryer is analysed with bed drying, tray drying, and compound drying for 1.5 m/s, 2 m/s and 2.5 m/s velocities for curry leaves. The performance parameters of Curry leaves for 30 minutes at inlet velocity 1.5 m/s is tabulated in Table III.

TABLE III
COMPARISON TABLE FOR 30 MINUTES AT VELOCITY 1.5 M/S

Drying Methods	Moisture removal rate (g/s)	Average Temperature (°C)	Average inlet humidity (%)	Average outlet humidity (%)
Bed	0.25	41	30	31
Tray	0.18	43	24	30
Compound	0.28	42	24	33

For various ways of drying Curry leaves, graphs are plotted between inlet and outlet humidity and temperature at 1.5 m/s as shown in Fig 4 a-d.

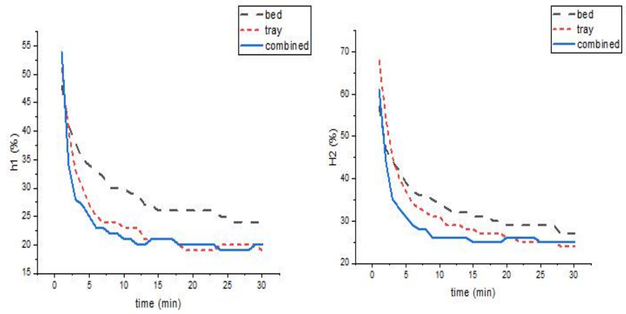

Fig. 4a Time Vs Inlet Humidity Fig. 4b Time Vs Outlet Humidity

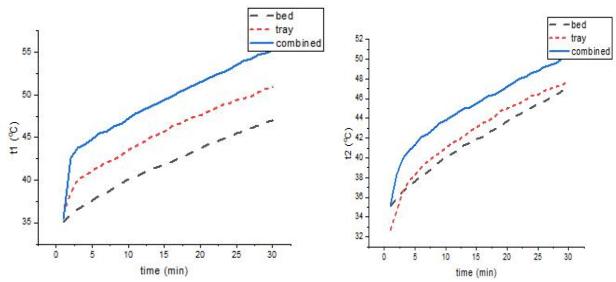

Fig. 4c Time Vs Inlet Temperature Fig. 4d Time Vs Outlet Temperature

In the case of tray drying method the average temperature and outlet humidity for 30 min. is 43°C and 30% and the drying rate is 0.18g/s respectively, bed method, the average temperature and outlet humidity is 41°C and 31% and the drying rate is 0.25g/s respectively and in compound method, the average temperature and humidity is 42°C and 33% and the drying rate is 0.28g/s respectively. The performance parameters of Curry leaves for 30 minutes at inlet velocity 2 m/s is tabulated in Table IV.

TABLE IV
COMPARISON TABLE FOR 30 MINUTES AT VELOCITY 2 M/S

Drying Methods	Moisture removal rate (g/s)	Average Temperature (°C)	Average inlet humidity (%)	Average outlet humidity (%)
Bed	0.28	44	24	32
Tray	0.21	45	25	28
Compound	0.31	45	25	34

For various ways of drying Curry leaves, graphs are plotted between inlet and outlet humidity and temperature at 2 m/s as shown in Fig 5 a-d.

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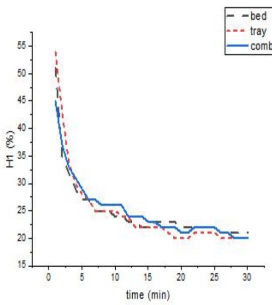


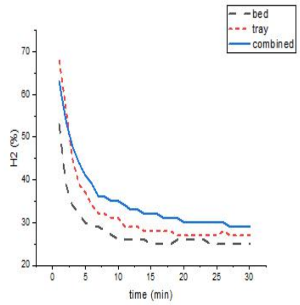
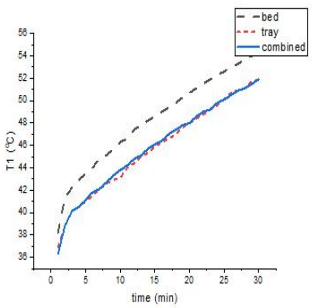


Fig. 5a Time Vs Inlet Humidity Fig. 5b Time Vs Outlet Humidity



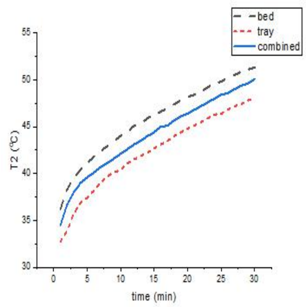


Fig. 5c Time Vs Inlet Temperature Fig. 5d Time Vs Outlet Temperature

The readings were taken for the duration of 30 min. at 2 m/s. In the case of tray drying method the average temperature and outlet humidity for 30 min. is 45ºC and 28% and the drying rate is 0.21g/s respectively, bed method, the average temperature and outlet humidity is 44ºC and 32% and the drying rate is 0.28g/s respectively and in compound method, the average temperature and humidity is 45ºC and 34% and the drying rate is 0.31g/s respectively. At 2 m/s velocity, Compound method removes 18% of moisture, Bed method removes 16% of moisture and Tray method removes 13% moisture from the leaves in 30 minutes. Therefore, the moisture extraction rate in compound method is 11% greater than bed method and moisture extraction rate in bed method is 33% greater than tray method.

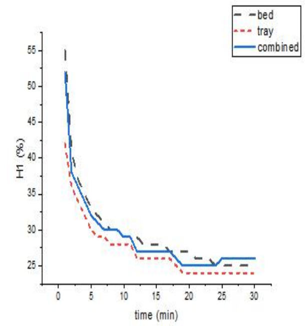
The performance parameters of Curry leaves for 30 minutes at inlet velocity 2.5 m/s is tabulated in Table IV.

TABLE V

COMPARISON TABLE FOR 30 MINUTES AT VELOCITY 2.5 M/S

Drying Methods	Moisture removal rate (g/s)	Average Temperature (°C)	Average inlet humidity (%)	Average outlet humidity (%)
Bed	0.33	44	29	40
Tray	0.23	43	30	35
Compound	0.34	45	27	43

For various ways of drying Curry leaves, graphs are plotted between inlet and outlet humidity and temperature at 2.5 m/s as shown in Fig 6 a-d.



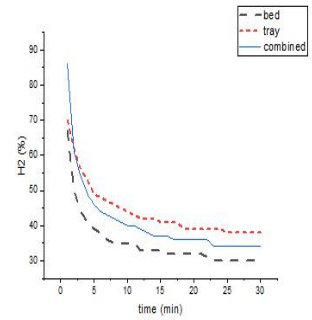
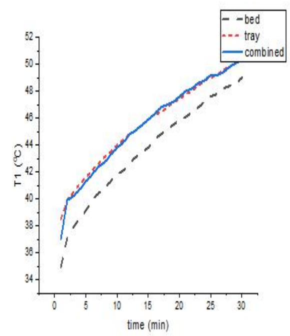


Fig. 6a Time Vs Inlet Humidity Fig. 6b Time Vs Outlet Humidity



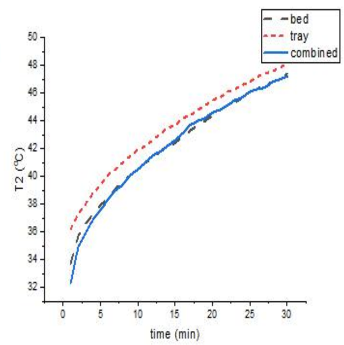


Fig. 6c Time Vs Inlet Temperature Fig. 6d Time Vs Outlet Temperature

The readings were taken for the duration of 30 min. at 2.5 m/s. In the case of tray drying method the average temperature and outlet humidity for 30 min. is 43ºC and 35% and the drying rate is 0.23g/s respectively, bed method, the average temperature and outlet humidity is 44ºC and 40% and the drying rate is 0.33g/s respectively and in compound method, the average temperature and humidity is 45ºC and 43% and the drying rate is 0.34g/s respectively. At 2.5 m/s velocity, Compound method removes 21% of moisture, bed method removes 20% of moisture and Tray method removes 14% moisture from the leaves in 30 minutes. Therefore, the moisture extraction rate in compound method is 3% greater than bed method and moisture extraction rate in bed method is 43% greater than tray method.

The Fig 7 shows the graphical representation of performance comparison of bed, tray and compound method at 1.5, 2.0 and 2.5 m/s velocities. Moisture extraction of Curry leaves is in peak at the velocity 2.5 m/s. Therefore, on comparing the three methods of drying at 2.5 m/s velocity, the moisture extraction rate in compound method is 36% greater than in bed method.

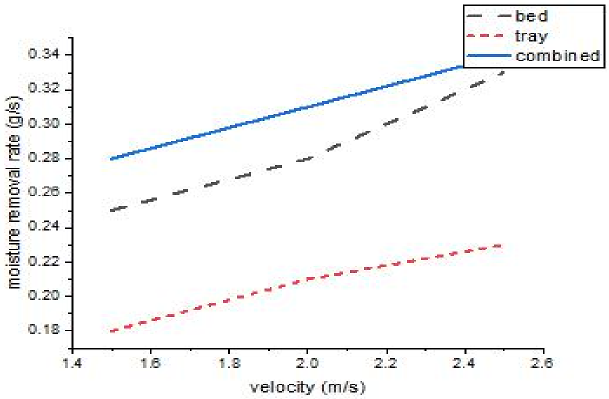


Fig. 7 Inlet Velocity Vs Moisture removal rate

Then moisture extraction rate in bed method is 6% greater than moisture extraction rate in tray method. And moisture extraction rate in compound method is 48% greater than in tray method. Regarding the above discussion, at 2.5m/s drying air velocity, the compound method or combined method has the maximum moisture extraction rate, followed by bed and tray methods.

Conclusion

Heat pump dryer is designed and fabricated in this proposed work. This is a promising technology for maintaining the product quality with lower energy consumption and higher drying rate. It is especially applicable for high-value products such as herbs and vegetables. The experiments is conducted to investigate the drying characteristics for Curry leaves at three different velocities and in three different drying chamber in a closed loop heat pump dryer is conducted. Based on the results, the combined drying chamber (bed-tray) produces highest evaporation rates 0.28, 0.31 and 0.34 g/s for the air velocities of 1.5, 2.0 and 2.5 m/s respectively compared to the tray and bed drying chamber. The evaporation rate of bed-tray dryer is 12 % and 55.5 % higher than the bed and tray drying chamber at the velocity of 1.5 m/s. Similarly the evaporation rate is 10.71 % and 47.61 % higher at the velocity of 2.0 m/s and 3.03 % and 47.82 % higher at 2.5 m/s. The evaporation rate is 38.8 % higher in the bed dryer compared to tray at the velocity of 1.5 m/s. Similarly for the evaporation is 33.33 % and 43.47 % higher in the bed dryer than the tray dryer.

Based on the results the following points are concluded.

- The inlet and outlet temperature of air before and after drying chamber is increases continuously while operating at transient temperature conditions.
- The relative humidity of air is continuously decreased at inlet and outlet of the drying chamber with respect to time.
- In the case of drying curry leaves the best evaporation rate is attained in the bed-tray drying chamber.
- The lowest evaporation rate is attained in tray chamber irrespective of inlet velocity of air.

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