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Comparative performance of a solar assisted heat pump dryer with a heat pump dryer for *Curcuma*

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ABSTRACT

This study evaluated the performances of solar assisted heat pump dryer (SAHPD) and heat pump dryer (HPD) for drying of *Curcuma xanthorrhiza Roxb*. The HPD and SAHPD reduced mass of *Curcuma* from 30.70 kg to 7.85 kg needed 10.5 hours and 8 hours with average temperature and relative humidity 49.2ºC and 26.5%, and 57.7ºC and 19.8%, for SD and SAHPD respectively. The moisture of *Curcuma* dried from 3.167 db to 0.065 db with an air mass flow rate of 0.121 kg/s. The SAHPD reduced the drying time about 24% compared to HPD. The drying rate and the specific energy consumption were calculated in an average 1.05 kg/h and 1.36kg/h, and 1.17kWh/kg and 2.07kWh/kg for HPD and SAHPD, respectively. The specific moisture extraction rate and the dryer thermal efficiency were calculated in an average 0.931 kg/kWh and 0.521 kg/kWh, and 61.0% and 34.3% for HPD and SAHPD, respectively. Whereas, the pickup efficiency and the coefficient of performance of the heat pump were calculated in an average 57.5% and 59.2%, and 4.03and 4.35 for HPD and SAHPD, respectively. The SAHPD is capable of drying *Curcuma* quickly because of the high pickup efficiency and high drying rate.

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NOMENCLATURE

A_{SC}	Area of solar collector (m^2)
C_{Pair}	Specific heat of air ($Jkg^{-1}C^{-1}$)
H_{fg}	Latent heat of vaporization of water (kJ/kg)
I_T	solar radiation (Wm^{-2})
$\dot{m}_{air}$	Air mass flow rate (kg/s)
m_d	Mass of bone dry (kg)
m_{da}	Mass flow rate of dry air ($kg_{dry\ air}$/s)
$M_{db,t}$	Moisture content dry basis at the time "*t*" (kg mass of water/ kg mass of bone dry)
$M_{db,t+\Delta t}$	Moisture content dry basis at the time "$t+\Delta t$" (kg mass of water/ kg mass of bone dry)
m_{water}	Mass of water evaporation rate (kg/h)
m_{water}	Mass of water evaporated (kg)
m_{wetc}	Mass of wet Curcuma (kg)
t	Drying time (h)
$T_{in, Cond}$	Inlet air temperature of condenser (ºC)
$T_{out, Cond}$	Outlet air temperature of condenser (ºC)
$T_{in, SC}$	Inlet air temperature of solar collector (ºC)

$T_{out, SC}$	Outlet air temperature of solar collector (ºC)
W_b	Electrical energy consumed by blower (kW)
W_{Comp}	Electrical energy consumed by compressor (kW)
Y_{as}	Adiabatic saturation humidity of air entering drying chamber (kg_{water}/kg_{dryair})
Y_i	Absolute humidity of air entering drying chamber (kg_{water}/kg_{dryair})
Δt	Drying time interval (h)

1. INTRODUCTION

Indonesia is rich of medicinal herbs and spices, one of them is *Curcuma xanthorrhiza* Roxb. It is also known as temulawak which widely used in the Indonesian traditional herbal medicine (Jamu). The *Curcuma xanthorrhiza* Roxb. is rich in starch, atsiri oil and curcuminoid that could be used as an antimicrobial, antiseptic anti metastatic, antibiotic, anticancer, anticandidal, antioxidant, and hypolipidemic activies. As a medicine, it could be used to tread stomach diseases, hemorrhoids, liver disorder, constipation, children's fevers, bloody diarrhea, dysentery, and skin eruptions [1, 2].

Commonly, there are three drying methods that have been used for drying medicinal herbs and spices, such as traditional drying method, hot air-drying method, and low temperature drying method. In the traditional drying method such as open sun drying, where the product to be dried by exposing directly to the sun, which has many disadvantages such as long drying time and low quality of the product [3]. In the hot drying method such as solar dryer, where the product to be dried by using thermal energy from the sun. This method has many advantages such as energy saving, free, clean, renewable and is an abundant source of energy that is readily available.

Recently, various solar dryers with air and water based solar collectors were reviewed [4, 5]. Several types of solar dryers have been developed and tested by some researchers for drying of medicinal herbs and spices such as: solar dryers for chili [6,7], an indirect forced convection solar dryer with a solar air collector for mint leaves [8], a solar-assisted drying system with V-groove solar collector for green tea [9], a roof-integrated solar drying system for rosella flower and chili [10], a solar dryer with forced convection for long green pepper [11], a solar-assisted forced convection dryer for onion [12], a solar tunnel drier for hot chili [13], a roof-integrated solar drying system for rosella flower and lemon-grasses [14]. However, the solar dryer has many disadvantages such as; firstly, if the drying process only uses thermal energy from the sun, the drying rate will be lower when cloudy day and low sunlight, and the drying process cannot be conducted during rainy days. Secondly, if the drying process is done during cloudy day, low sunlight and rainy day, the solar dryer should be assisted with an auxiliary heater. This caused increases the energy consumption. Thirdly, the drying time or drying rate depends on the drying air temperature. The high drying air temperature may remove the important ingredients, which causes color reactions and degradation of the product resulting in low product quality. Meanwhile, in the low temperature drying method such as heat pump dryer, where the product to be dried by using thermal energy from the exhaust gas (condenser) of the heat pump. This method has many advantages such as lower energy consumption, clean, less relative humidity, lower temperature, the relative humidity and drying air temperature are easily controlled and good quality of product.

Various of types the medicinal herb and spice have been dried in the heat pump drying such as; sweet pepper [15], ginger [16], garlic [17], Jew's mallow, spearmint and parsley [18], and onions [19]. However, the heat pump dryer features are not fully operated, this due to the drying air temperature is limited, and it is caused by the limited operating temperature of the refrigerant and compressor operating conditions of the heat pump.

A solar-assisted heat pump dryer (SAHPD) provides an alternative to resolve the disadvantages of the current drying methods for drying medicinal herbs and spices. This dryer consists of a heat pump and a solar drying system. It has many advantages such as low relative humidity, clean, energy saving, low energy consumption, the relative humidity and drying air temperature are easily controlled and the drying processes can be conducted when cloudy and rainy days.

Several studies used SAHPD to dry agricultural products [20]. However, to our best knowledge, the performance of SAHPD for drying of Curcuma chips has not been investigated yet, and limited studies have compared heat pump dryer (HPD) with SAHPD. The purpose of this study was performed to compare the performance of SAHPD with HPD for drying of Curcuma chips.

2. RESEARCH METHOD

2.1. Experimental set-up

The photograph of the solar assisted heat pump dryer (SAHPD) as shown in Figure 1. The drying system consists of heat pump system, solar collector array, drying chamber and blower. The heat pump system consists of compressor, condenser, evaporator, and expansion valve. The working fluid of the heat pump is R-22. Compressor use of electrical capacity of 1 HP. The solar collector equipped with finned double-pass solar collector with black absorber, transparent cover glass material, inside and outside the collector coated with aluminum 1mm thick, angle iron frame, and insulation. Two solar collectors are connected in series with an area of 1.8 m^2 each. The drying chamber uses of the cabinet type and contain the drying trays with adjustable racks to place the *Curcuma xanthorrhiza* Roxb. It walls consist of triple layers, an outside layer uses aluminum sheet, a middle insulated with glass fiber materials and inner layer of uses of aluminum sheet. The drying air is circulated by using blower with electrical capacity of 2 HP.

2.2. Experimental procedure

The sample is fresh *Curcuma xanthorrhiza* Roxb was purchased at the local market in Padang, West Sumatra, Indonesia. The experiments were carried out at Padang Institute of Technology, West Sumatra, Indonesia. After washing, the *Curcuma xanthorrhiza* Roxb was cut into chips of 2-3 mm. As much as 30.7 kg put into the drying chamber for the drying process, shown in Figure 2.

Inlet and outlet air temperature of solar collector, heat pump, and drying chamber during the operation of the drying system were measured by using T type copper-constantan thermocouples with an accuracy of ± 0.1ºC, and operating temperature range (-200ºC to 400ºC). The solar radiation was measured by an LI-200 pyranometer in ± 0.1Wm^{-2} accuracy, and with maximum solar radiation of 2000 Wm^{-2}, operating temperature range (-40ºC to 400ºC) and operating relative humidity range (0% to 100%). The air velocity was measured with 0-30 ms^{-1} range an HT-383 anemometer, an accuracy of ± 0.1 ms^{-}1, and with operation temperature range (-10ºC to 45ºC). The solar radiation and air temperature were recorded by an AH4000 data logger with reading accuracy of ± 0.1ºC. The weight change of the *Curcuma xanthorrhiza* Roxb was measured by 0-15 kg range a TKB-0.15 weighing, an accuracy ± 0.05kg. The *Curcuma xanthorrhiza* Roxb was weighed every 30 minutes and temperature was measured every 30 minutes.

The drying experiments were carried out for drying of *Curcuma xanthorrhiza* Roxb chips to study the dryer performance under two different operating modes: (1) heat pump dryer (HPD); (2) combination between heat pump dryer with solar collector (solar assisted heat pump dryer: SAHPD). For the heat pump dryer mode of operation as shown in Figure 3, the solar collector is not operated. For the combination mode as shown in Figure 4 the solar collector and the heat pump operated both.

Figure 1. Photograph of the solar assisted heat pump dryer (SAHPD)

Figure 2. Photograph of Curcuma in drying chamber

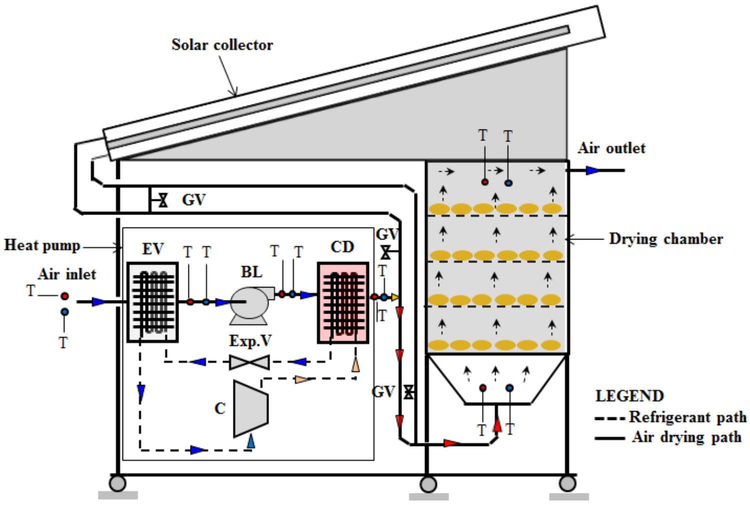

Figure. 3. Mode 1: Schematic diagram of the HPD

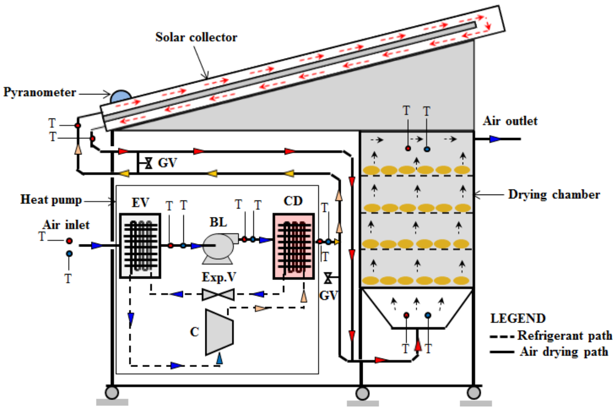

Figure 4. Mode 2: Schematic diagram of the SAHPD
BL: blower, C: compressor, CD: condenser, EV: evaporator, Exp.V: expansion valve, GV: gate valve, T: temperature sensor.

2.3. Experimental data analysis

The performances of the HPD and the SAHPD for drying of *Curcuma xanthorrhiza* Roxb. are characterized by drying rate, specific moisture extraction rate, specific energy consumption, dryer thermal efficiency, and pickup efficiency. It is highly depending on the performance of each of the drying system components such as solar collector and heat pump.

The thermal efficiency of a solar collector is the ratio of useful heat gain by solar collector to the energy incident in the plane of the collector. It was determined using the following equation [21],

$$\eta_{coll} = \frac{\dot{m}_{air} C_{Pair} (T_{out,\,SC} - T_{in,SC})}{I_T\, A_{SC}} \times 100\% \quad (1)$$

Where I_T is solar radiation incident in the collector, A_{SC} is an area of collector, $T_{in,\,SC}$ and $T_{out,\,SC}$ are inlet and outlet air temperatures of solar collector, respectively. $\dot{m}_{air}$ is air mass flow rate, C_{pair} is specific heat of air.

The coefficient of performance of a heat pump (COP) is the ratio of useful heat or heat energy released by the refrigerant in the condenser to the electrical energy consumed by compressor. It was determined using the following equation [18],

$$COP_{hp} = \frac{\dot{m}_{air} C_{Pair} (T_{out,\,Cond} - T_{in,\,Cond})}{W_{Comp}} \quad (2)$$

Where $T_{\text{in, Cond}}$ and $T_{\text{out, Cond}}$ are inlet and outlet air temperatures of condenser, respectively, and W_{Comp} is the electrical energy consumed by the compressor.

The moisture content of the Curcuma was calculated by two methods such as wet and dry basis as [22], The moisture content wet basis was calculated as

$$M_{\text{wb}} = \frac{m_{\text{wetc}} - m_d}{m_{\text{wetc}}} \tag{3}$$

The moisture content dry basis was calculated as

$$M_{\text{db}} = \frac{m_{\text{wetc}} - m_d}{m_d} \tag{4}$$

where m_d the mass of bone is dry of the Curcuma, and m_{wtc} is mass of wet Curcuma.

The drying rate is the mass of water evaporated from the wet Curcuma per unit time. It was determined as [6],

$$\text{DR} = \dot{m}_{\text{water}} = \frac{m_{\text{water}}}{t} = \frac{M_{\text{db,t+}\Delta\text{t}} - M_{\text{db,t}}}{\Delta \text{t}} \tag{5}$$

Where $M_{db,t}$ is moisture content dry basis of curcuma at the time "t", $M_{\text{db,t+}\Delta\text{t}}$ is moisture content dry basis of curcuma at the time "$t + \Delta$t", m_{water} is the mass of water evaporated, t is drying time, and Δt is drying time interval.

The mass of the water evaporated (m_{water}) from the wet Curcuma was calculated as [21],

$$m_{\text{water}} = \frac{m_{\text{wetc}}(M_{\text{wb,i}} - M_{\text{wb,f}})}{(100 - M_{\text{wb,f}})} \tag{6}$$

Where m_{wetc} is initial mass of wet curcuma, $M_{wb,f}$ is final moisture content on the wet basis, and $M_{wb,i}$ is initial moisture content on wet basis.

Specific moisture extraction rate (SMER) is ratio of the moisture evaporated from wet product to the energy input to drying system. The specific moisture extraction rate of the HPD and the SAHPD were calculated using the following equations [23],
for the HPD,

$$\text{SMER}_{\text{HPD}} = \frac{\dot{m}_{\text{water}}}{W_{\text{Comp}} + W_b} \tag{7}$$

for the SAHPD,

$$\text{SMER}_{\text{SAHPD}} = \frac{\dot{m}_{\text{water}}}{I_T\, \text{A}_{\text{SC}} + W_{\text{Comp}} + W_b} \tag{8}$$

where W_b is the electrical energy consumed by blower

Specific energy consumption (SEC) is the measure of the energy used to remove 1 kg of water in the drying process. The specific energy consumption of the HPD and the SAHPD were calculated using the following equations,
for the HPD,

$$\text{SEC}_{\text{HPD}} = \frac{W_{\text{Comp}} + W_b}{\dot{m}_{\text{water}}} \tag{9}$$

for the SAHPD,

$$\text{SEC}_{\text{SAHPD}} = \frac{I_T\, \text{A}_{\text{SC}} + W_{\text{Comp}} + W_b}{\dot{m}_{\text{water}}} \tag{10}$$

Thermal efficiency of drying system is ratio of the energy used for moisture evaporation to the energy input to drying system. The thermal efficiency of the HPD and the SAHPD were calculated using the following equations [24],
for the HPD,

$$\eta_{\text{th,HPD}} = \frac{\dot{m}_{\text{water}} H_{\text{fg}}}{W_{\text{Comp}} + W_b} \quad (11)$$

for the SAHPD,

$$\eta_{\text{th,SAHPD}} = \frac{\dot{m}_{\text{water}} H_{\text{fg}}}{I_T \, A_{\text{SC}} + W_{\text{Comp}} + W_b} \quad (12)$$

where $H_{\text{fg}}$is latent heat of vaporization of water (kJ/kg).

Pick-up efficiency as the ratio of the moisture evaporated from wet product or the moisture picked-up by the air in the drying chamber to the theoretical capacity of the air to absorb moisture. The pickup efficiency of the HPD and the SAHPD were calculated using the following equation [25],

$$\eta_{\text{Pickup}} = \frac{m_{\text{water}}}{\dot{m}_{\text{da}} t (Y_{\text{as}} - Y_i)} \quad (13)$$

Where $\dot{m}_{da}$ is mass flow rate of dry air ($kg_{dry\ air}/s$), Y_i is absolute humidity of air entering drying chamber (kg_{water}/kg_{dryair}) and Y_{as} adiabatic saturation humidity of air entering drying chamber (kg_{water}/kg_{dryair}).

2.4. Experimental uncertainty

In the drying experiments of the *Curcuma* the data was obtained by appropriate instrument, however, errors and uncertainties can arise because of the situations such as instrument selection, condition, environment, observation, reading, and test planning. Uncertainty was calculated using the following equation [20,26],

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (14)$$

3. RESULTS AND ANALYSIS

The variations of solar radiation and solar collector efficiency with time of the day are shown in Figure 5. As seen from the figure the weather is quite sunny, the solar radiation is varied from 607.4 Wm^{-2} to 962.7 Wm^{-2} and in average is 801.1 Wm^{-2} was recorded. The solar collector efficiency is varied from 31.1% to 49.2%, and in average is 39.2%, with an air mass flow rate of 0.121 kgs^{-1}. As observed from the Figure 5 the efficiency of solar collector is depending on the solar radiation. The solar radiation fluctuates, then the solar collector efficiency also fluctuates. The evaluation of the uncertainty of experiment as shown in Table 1.

Table 1. Uncertainties of the parameters during drying experiment of Curcuma

Parameters	Unit	Uncertainty comment	
		SAHPD	HPD
Air temperatures	ºC	± 0.17	± 0.17
Air relative humidities	%	± 0.22	± 0.22
Air absolute humidities	kg water/kg dry air	± 0.26	± 0.26
Air adiabtic saturation humidities	kg water/kg dry air	± 0.26	± 0.26
Solar radiation	W/m^2	± 0.14	-
Air velocity	m/s	± 0.24	± 0.24
Mass loss of samples	g	± 0.014	± 0.014
Mass loss of products	kg	± 0.11	± 0.11
Reading values of table (ρ, C_p, and H_{fg})	-	± 0.1-0.2	± 0.1-0.2
Time measurement	min	± 0.1	± 0.1

The variation of inlet and outlet air temperature of condenser and COP of the heat pump with time of the day for SAHPD and HPD are shown in Figure 6. The average inlet and outlet temperature of the condenser are 27.5oC and 51.6oC, and 24.9oC and 50.9oC for HPD and SAHPD were recorded, respectively. Whereas, the averages of the COP of the heat pump were calculated of about 4.03and 4.35 for HPD and SAHPD, respectively, with an air mass flow rate is about 0.121 kgs-1.

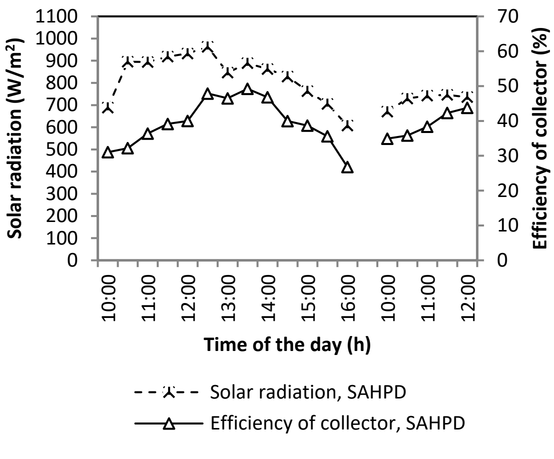

Figure 5. Variation in solar radiation and efficiency of collector with time of the day

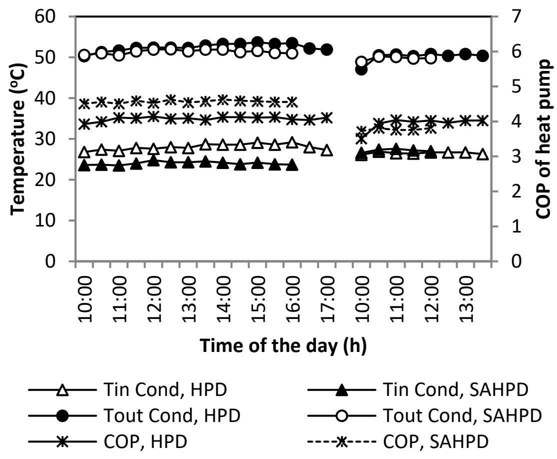

Figure 6. Variation in temperature and COP of the heat pump with time of the day.

The variation of ambient temperature, and air temperature inlet and outlet of drying chamber with drying time for SAHPD and HPD are shown in Figure 7. For the HPD, the ambient temperature, and air temperature inlet and outlet of the drying chamber are varied from 29.0oC to 34.3oC, 43.5oC to 51.3oC, and 30.1oC to 39.6oC, respectively, with corresponding average values of 32.3oC, 49.2oC and 32.8oC. Whereas, for the SAHPD, the ambient temperature, and air temperature inlet and outlet of the drying chamber are varied from 33.1oC to 35.1oC, 53.4oC to 61.7oC, and 32.0oC to 47.2oC, respectively, with corresponding average values of 34.3oC, 57.7oC and 36.9oC. The results indicated that the air-drying temperature in the SAHPD was higher than the HPD. The difference value is 8.5°C, this can be stated that the drying rate in the SAHPD is higher than the in HPD. As seen from figure that the drying chamber outlet air temperature increased with increasing in drying time. This due to, the heat transfer coefficient decreased in the drying time.

The variation of ambient relative humidity, and air relative humidity inlet and outlet of the drying chamber with drying time for SAHPD and HPD are shown in Figure 8. For the HPD, the ambient relative humidity, and air relative humidity inlet and outlet of the drying chamber are varied from 58.9% to 80.4%, 24.7% to 28.8%, and 48.2% to 92.3%, respectively, with corresponding average values of 68.9%, 26.5% and 72.7%. Whereas, for SAHPD, the ambient relative humidity, and air relative humidity inlet and outlet of the drying chamber are varied from 56.2% to 70.9%, 17.7% to 23.9%, and 37.1% to 88.3%, respectively, with corresponding average values of 64.0%, 19.8%, and 68.6%. The results indicated that the air-drying relative humidity in the SAHPD was lower than the HPD. The difference value is 6.7%. As seen from figure that the drying chamber outlet air relative humidity decreased with increasing in drying time. This due to, the mass transfer coefficient decreased in the drying time.

The variation of moisture content of Curcuma xanthorrhiza Roxb with drying time for SAHPD and HPD are shown in Figure 9. The moisture content of Curcuma xanthorrhiza Roxb was reduced from 3.167 dry basis to final moisture content of about 0.065 dry basis. The time to reach the final moisture content was found of about 10.5 hours and 8hours for HPD and SAHPD, respectively. The SAHPD had a shorter drying time compared to the HPD. In other words, the SAHPD reduced the drying time 24% compared to the HPD. This due to, its moisture content transfer rate is higher than the HPD, this caused by the difference in the partial vapour pressure between Curcuma xanthorrhiza Roxb and the drying air obtained in the SAHPD is higher than in the HPD. This difference value is very dependent on the drying air temperature and relative humidity, when drying air temperature is high and relative humidity is low, the difference in the partial vapour pressure between Curcuma xanthorrhiza Roxb and the drying air is also high, and vice versa.

The variation of drying rate with drying time for SAHPD and HPD are shown in Figure 10. The drying rate of Curcuma xanthorrhiza Roxb was calculated, for the HPD, the drying rate is varied from 0.60 kg/h to 1.65 kg/h and in average is 1.05kg/h. whereas, for the SAHPD, the drying rate is varied from 0.85 kg/h to 1.85 kg/hand in average is 1.36kg/h. Referring to Figure 10, the drying rate decreased with increase by time. Then, the evaporation rate of moisture decreased by time.

The variation of SMER and SEC with drying time for SAHPD and HPD are shown in Figure 11. The SMER is varied from 0.533 kg/kWh to 1.467 kg/kWh and 0.327 kg/kWh to 0.676 kg/kWh and in an average of about 0.931 kg/kWh and 0.521 kg/kWh for HPD and SAHPD, respectively were calculated.

Whereas, the SEC are varied from 0.68 kWh/kg to 1.88 kWh/kg and 1.27 kWh/kg to 3.53 kWh/kg, and in an average of about 1.17 kWh/kg and 2.07 kWh/kg for HPD and SAHPD, respectively were calculated. As observed from the figure that the SMER decreased and SEC increased with increase by time. This due to, the drying rate decreased in time, and also the SMER of the HPD is higher that the SAHPD, this due to the total energy input to the HPD is lower than to the SAHPD.

The variation of dryer thermal efficiency and pickup efficiency with drying time for SAHPD and HPD are shown in Figure 12. The dryer thermal efficiency is varied from 33.50% to 97.07% and 21.45% to 44.39%, and in an average of about 61.03% and 34.28% for HPD and SAHPD, respectively were calculated. The pickup efficiency is varied from 34.04% to 93.37%and 30.30% to 92.78%, and in an average of about 57.51% and 59.21% for HPD and SAHPD, respectively were calculated. As observed from the figure that the pickup efficiency of the SAHPD is higher than the HPD. This due to, the evaporation rate of moisture in the SAHPD is higher than the HPD.

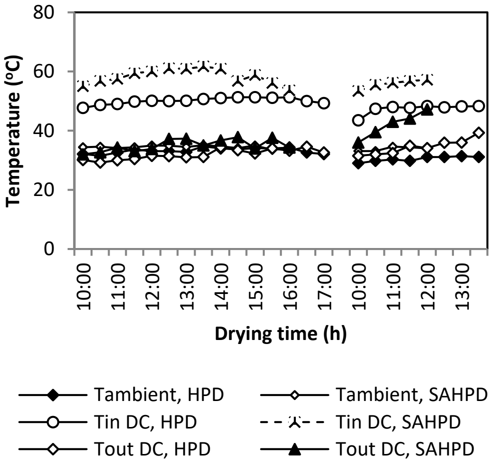

Figure 7. Variation in temperature with drying time

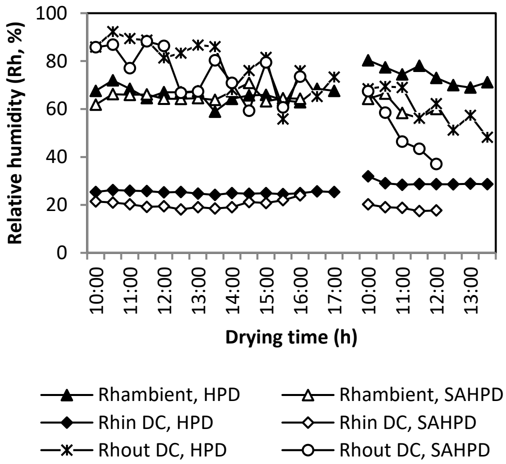

Figure 8. Variation in relative humidity with drying time

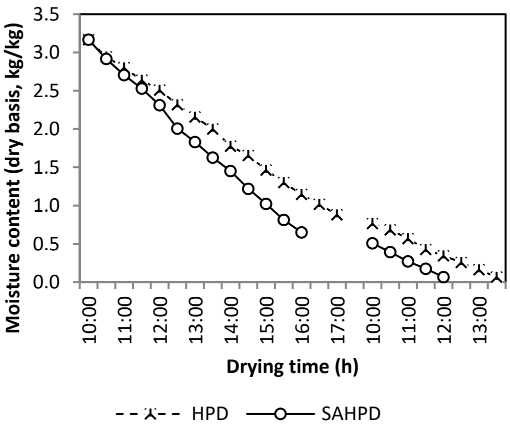

Figure 9. Variation of moisture content with drying time

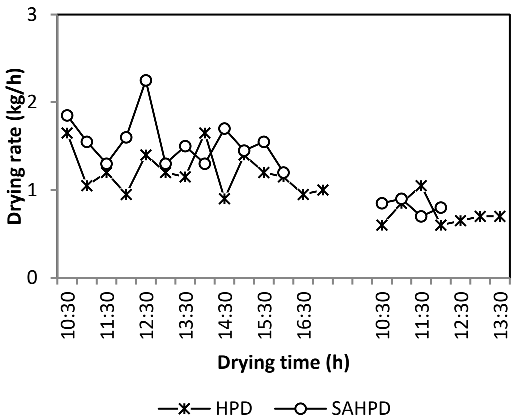

Figure 10. Variation in drying rate with drying time

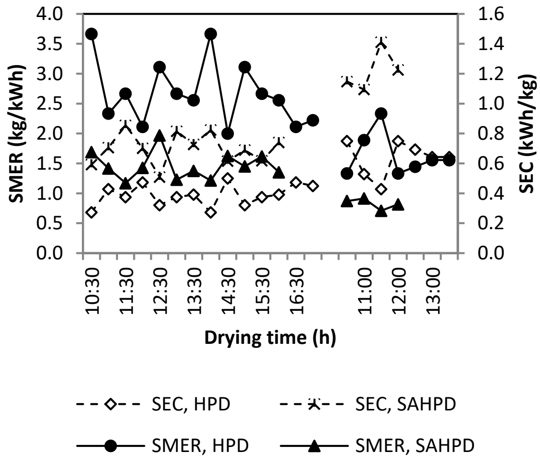

Figure 11. Variation in SMER and SEC with drying time

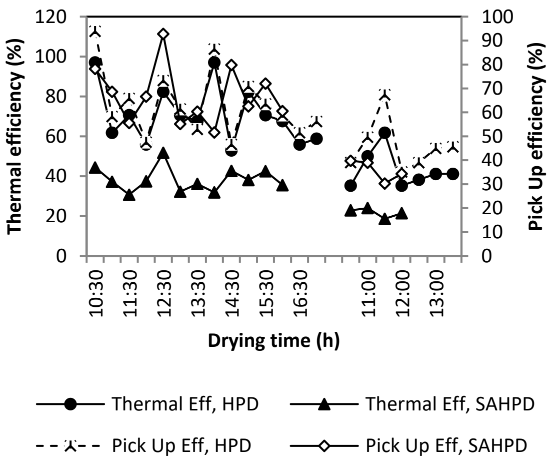

Figure 12. Variation in thermal efficiency and pickUp efficiency with drying time

4. CONCLUSIONS

The performances of a SAHPD and a HPD have been evaluated for drying of *Curcuma xanthorrhiza* Roxb. The HPD and SAHPD reduced mass of *Curcuma xanthorrhiza* Roxb from 30.70 kg to 7.85 kg needed 10.5 hours and 8 hours with averages temperature and relative humidity of about 49.2^{o}C and 26.5%, and 57.7^{o}C and 19.8%, for SD and SAHPD respectively. The moisture of *Curcuma* dried from 3.167 db to 0.065 db with an air mass flow rate of 0.121 kg/s. The SAHPD reduced the drying time of about 24% compared to the HPD. The drying rate and the specific energy consumption rate were calculated in an average of about 1.05 kg/h and 1.36kg/h, and 1.17kWh/kg and 2.07kWh/kg for HPD and SAHPD, respectively. The specific moisture extraction rate and dryer thermal efficiency were calculated in an average of about 0.931 kg/kWh and 0.521 kg/kWh, and 61.03% and 34.28% for HPD and SAHPD, respectively. Whereas, the pickup efficiency and coefficient of performance of the heat pump were calculated in an average of about 57.5% and 59.2%, and 4.03and 4.35 for HPD and SAHPD, respectively. Whereas, the average of the solar collector efficiency was calculated to be about 39.2%. The result shows that the SAHPD is capable of drying *Curcuma* quickly because of the high drying rate and high pickup efficiency.

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