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Construction and Performance Study of a Rock Bed Integrated Green House Type Solar Air Heater with Solar Dryer

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Abstract : *This paper presents the construction and performance evaluation of a rock bed integrated green house new type solar air heating system gross area of 1m^2. The system is made of locally available materials and installations, operations are conducted in developing country Bangladesh. Rock is used as thermal mass to store heat from solar and release heat in the absence of effective radiation. Drying performances were conducted using the solar dryer with chili products. The performance of solar air heater is evaluated varying the air flow rate and optimum air flow rate is 0.0124 kg/s. The result shows that, solar air heater is able to deliver maximum exit air temperature is 65^{o}C with 1% relative humidity, thermal efficiency is 38% and rate of energy delivered is 4.2 kW. The system is also able to deliver effective hot air during off-sunshine hours and the duration is 6 hours. Performance of dryer shows the maximum moisture extraction efficiency is 36.62%. The overall moisture removal for 9 hours drying is 25% without affecting the quality of product and specific moisture extraction is 7 gm/kWh.*

Keywords: *Construction, Performance study, Solar air heater, Solar dryer, Thermal mass*.

I. Introduction

Supply of hot air is essential to dry vegetable product, fruits, agricultural crops, industrial drying and room heating purposes during winter season as well as the countries survive under cold weather condition [1]. The conventional method of producing hot air is by burning fossil fuel or using fossil based electricity. Researchers are discouraging freedom to consume such limited fossil sources due to rapid depletion, high price and future environmental threats [2]. The effort on research and development to deliver hot air and to avoid the use of fossil sources are growing continuously over the world. Solar air heater is a system used to deliver such hot air and well recognized in tropical and semitropical countries [3]. Though the technology is simple, cost effective, free and eco- friendly [4], the reliable useful output from the solar air heating system is vulnerable due to intermittent solar radiation and the system need to use in off-sunshine hours. The system cannot deliver useful output at night time or during low solar insolation result is poor performance of the system [5]. Energy storage materials can improve the reliability to deliver useful output of the system [6].

Literatures on solar air heating system integrated with solar dryer using different energy storage materials are exists [7-13]. It is found that, solar air heating system with phase change material (PCM) storage is better than sensible storage in the sense of low space required and high heat storage capacity, though sensible heat storage materials are low cost compared to the latent heat storage materials [1]. PCM as well as water based system requires additional auxiliary parts like heat exchanger, circulating pump, storage tank/container, chemicals etc. The system design is also complex and costly. PCM is low thermal conductivity so additives or other materials are usually used with PCM to enhance the heat transfer. Encapsulation of PCM is also undertaken to enhance the heat transfer in a container with encapsulate materials like aluminum powder, graphite, metal/plastic capsule, different geometrical copper capsule etc. Water based system requires tubes/tanks/barrels to store water in addition to solar collector and is usually arranged separately in the system. The rock bed study shows that they use glass cover, absorber plate and insulator separately. They have use storage material like rock, sand, al scrap etc between the glass cover and absorber plate. The critical evaluation of the literatures shows that existing PCM system use significant quantities of materials, chemicals and even the system design is complex due to many auxiliary expensive parts. On the other hand, rock bed system use separate arrangement of component parts which increase the quantities of material used and manufacture cost of the system.

User friendly, easy to install, simple design, less material adaption, better performance in sunshine and off-sunshine hours with minimum cost is preferable to adapt the system for low income countries. Addressing these issues a rock bed integrated greenhouse new type solar air heating system constructed using the local materials and evaluated the thermal and drying performance in a developing country Bangladesh. The objectives of this study are to construct the rock bed integrated air heating system and its thermal and drying performance evaluation during sunshine and off-sunshine hours using the three trays forced convection greenhouse type solar dryer.

II. Materials And Method

This section describes the detail of construction the solar air heating system, data collection, thermal and drying performance evaluation during sunshine and off-sunshine hours of the day in winter season.

1.1 System description

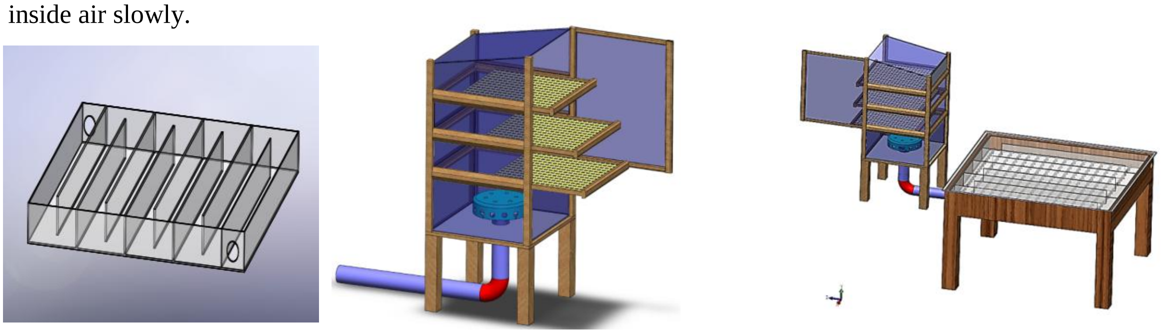
The system in this study consists two major components namely, solar air heater and solar dryer. Their description is given below:

Solar air heater

Solar air heater in this study consist a glass box of thickness is 3 mm (Fig.1a). The area of the box is 1 m^2. There are 9 channel inside the box are partitioned by glass. Metamorphic black rock diameter of 5-6 cm and weight of 42 kg is placed in the channel uniformly with an aim to absorb heat from solar radiation during sunshine hour. The glass box is placed on the wooden board. Insulation is made under the glass box by 0.4 kg cock sheet and 2 kg cotton. The glass box has two opening, one is for input the outside air and other is for exit the hot air. The box containing rock is act as absorber of the system. Hence, there is no need to make separate absorber or cover glass. The system is installed on the base frame made of wood at an angle of 24^o south facing as the country latitude is 24^o.

Solar dryer

The drying chamber is made of wooden frame covered with 3.5 mm glass (Fig. 1 b). The drying chamber is 70 cm height and 35 cm wide. Three trays are made of non corrosive sieve type wire net and mounted inside the drying chamber. The trays were set 20 cm apart to ensure the better circulation of hot air through the drying product. The dryer is connected with solar air heater using well insulated PVC pipe of 3.5 cm in diameter. One end of the pipe connected with solar air heater and other end of the pipe connected with bottom of the dryer. A distributor is installed inside the dryer at the end of the connected pipe to ensure better circulation of the hot air inside. There are small exhaust opening at the top of the side wall to move out the inside air slowly.



(a) (b) (c)

(d)

Figure 1. (a) Schematic of collector channel box (b) Schematic of greenhouse type dryer (c) Schematic of solar collector integrated with dryer (d) Photograph of experimental setup

2.2 Experimental procedure and data collection

The experiments were conducted in mid December. Monthly average solar insolation of this city in December is 3.82 kWh/ m^2.day [13] is a minimum radiation over the year. The system was installed in south facing to receive the maximum radiation and it was confirm that the system is free from shading during effective sunshine hours. A 30W DC fan with regulator was installed at the inlet port of the solar air heater to force the outside air into it. Though the fan was powered by conventional electricity but there was a provision to use solar charged battery to operate the fan. Digital hygrometer was used to measure the temperature and relative humidity of the inlet and exit air. The data was recorded every one hour interval over the effective sunshine and during off-sunshine hours until the exit air condition is same as inlet. The data was measured for several days and for varying air flow rate to find the optimum parameters. The hot air at optimum condition is supplied in the drying chamber to dry red chilies. The chilies are distributed in three trays to measure the performance of individual trays. The drying operation was undertaken until the effective hot air delivered from the solar air heater. Finally the weight loss was measured for the product of each trays and overall drying performance were estimated. The raw data for the analysis is presented in Table 1.

Table 1. Experimental data of the solar air heater and solar dryer

Time of the day	Solar air heater (at 0.0124 kg/s air flow)			Solar dryer			
	Exit air temperature (ºC)	Exit relative humidity (%)	Thermal efficiency (%)	Weight of the product (gm)			
				Lowertray	Middle tray	Upper tray	Open sun
10:30 AM	37	13	17.21	1000	1000	1000	1000
11:00 AM	44.5	7	21.77				
11:30 AM	50	2	26.83	968	979	959	993
12:00 PM	54	1	31.08				
12:30 PM	56	1	32.4	940	943	909	980
1:00 PM	58.3	1	34.12				
1:30 PM	62.4	1	37.97	909	907	857	957
2:00 PM	60.2	1	35.94				
2:30 PM	58	1	33.41	859	872	815	939
3:00 PM	57	1	31.49				
3:30 PM	53	1	28.55	824	843	786	919
4:00 PM	50	3	27.34				
4:30 PM	46.3	5	24.6	792	827	760	913
5:00 PM	43.5	7	23.29				
5:30 PM	39.7	10	22.58	769	813	743	910
6:00 PM	37.3	17	20.86				
6:30 PM	32.4	20	16	755	797	729	906
7:00 PM	29.5	23	13.57				
7:30 PM	28.4	29	12.76	747	789	721	906
8:00 PM	25.4	36	10.02				
8:30 PM	24	40	8.81				
9:00 PM	22.3	44	6.68				
9.30 PM	20.8	48	5.77				

III. Results And Discussion

This section describes the experimental results of the system. The experiments were conducted for solar air heater and with solar dryer in winter season using chili product. The thermal condition of solar air heater is optimized varying the air flow rate of 0.0124 kg/s, 0.0089 kg/s, 0.0053 kg/s. The details of the results are described below.

1.2 Performance analysis of the solar air heater

Fig. 2 shows the variation of ambient air temperature, relative humidity and solar insolation with sunshine and off-sunshine duration in winter season (December, 2015). Temperature and relative humidity trends are made using the actual measured data for the duration. The hourly solar insolation data for the location and for the month of December were adopted from Ref. [14]. The effective sunshine hours are considered from 9.30 AM to 3.00 PM (about 5.5 hrs) and roughly 6 hours off-sunshine data were measured to make the off-sunshine trends in the figure. It is seen that the solar insolation is increasing from the morning and reached to maximum at 12.00 PM and then decreasing. The atmospheric temperature is increasing until 3.00 PM and then decreasing slowly. The relative humidity is decreasing with increasing atmospheric temperature until 3.00 PM and then starts to increase due to addition of moisture content in the atmosphere.

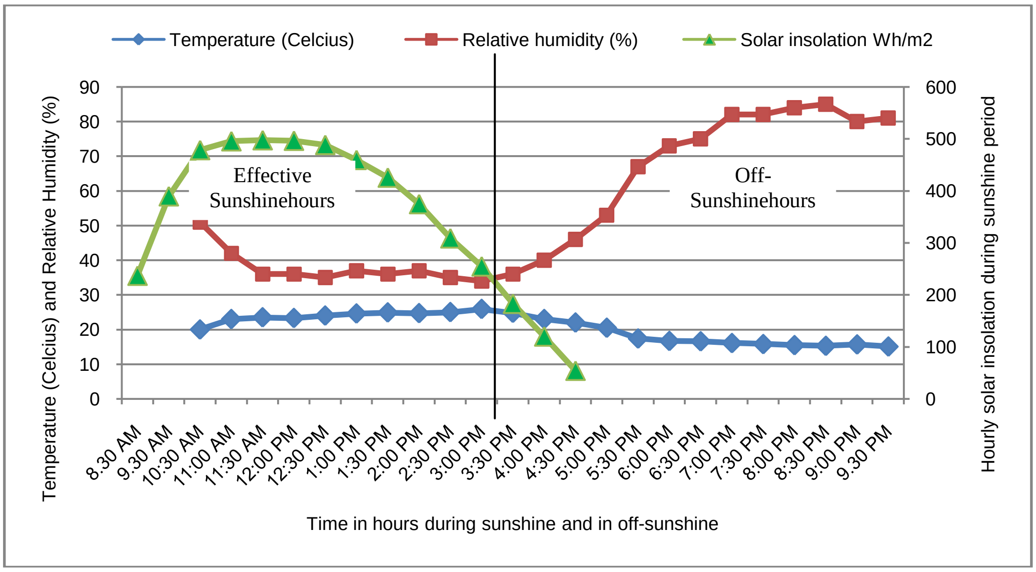


Figure 2. Change of ambient temperature, relative humidity and solar insolation with time

Fig. 3 shows the change of rate of heat energy delivered by the air heater with time at varying air flow rate. The aim of this study is to receive maximum heat energy from the system with maximum hour of heat storage capacity during off-sunshine at optimum air flow rate. From the figure it is seen that, heat energy delivered during effective sunshine hours is increasing for all three air flow rate and the magnitude of the rate of energy delivered at 0.0124 kg/s flow rate is higher compared to other two flow rate. The trend of energy delivered is declining in a similar nature during off-sunshine hour for all three air flow rate. Hence, air flow rate of 0.0124 kg/s is better to deliver heat energy magnitude of 3.60 to 4.20 kW.

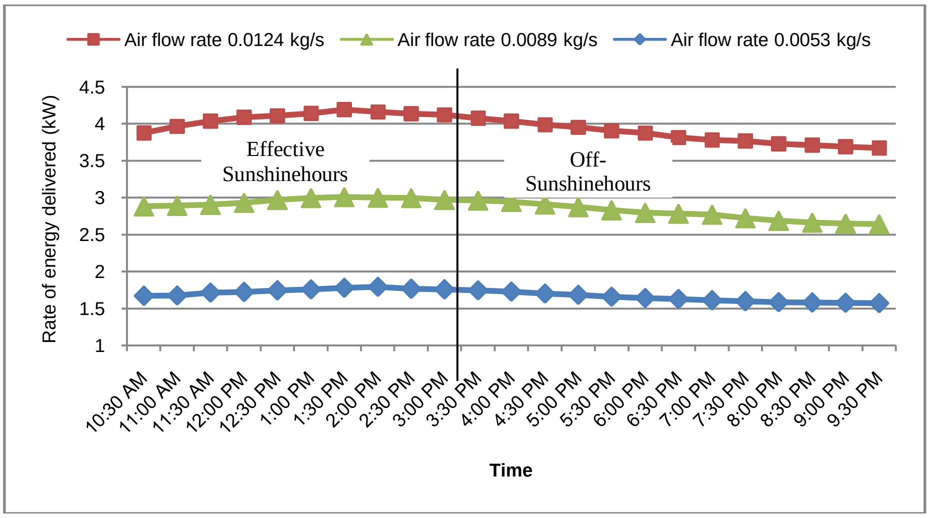


Figure 3. Change of heat energy delivered with time at varying flow rate

Fig. 4 shows the change of exit air temperature with time at varying air flow rate. It is seen that the trends are similar in nature and the deviation of their magnitude is insignificant for all three air flow rate in both effective sunshine and off-sunshine hours of the duration. Though, highest exit air temperature was measured 65^0C at air flow rate of 0.0089 kg/s, but heat energy delivered is higher at 0.0124 kg/s flow rate. Exit air temperature is actually varied with the variation of radiation intensity and flow rate. The temperature at the end of off-sunshine duration at 9.30 PM was measured $20\text{-}22^0$C with 50% relative humidity where the ambient air temperature was 15^0C with 80% relative humidity. This $5\text{-}7^0$C difference was assumed to be effective for the heating or drying purposes. The rock bed storage unit is able to deliver the effective hot air for 6 hours in the off-sunshine duration. Hence, the optimum rate of energy delivered for the system is 3.60-4.20 kW, air flow rate is 0.0124 kg/s and heat storage capacity to deliver the effective hot air during off-sunshine is 6 hours.

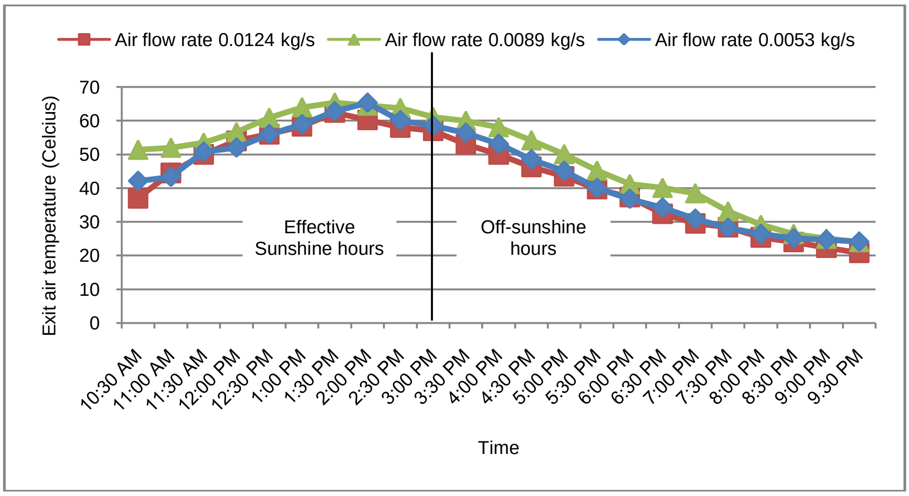


Figure 4. Change of exit air temperature with time at varying flow rate

Fig. 5 shows the change of exit relative humidity and thermal efficiency of the solar air heater with time at 0.0124 kg/s flow rate. As much as lower the relative humidity in the air is effective for heating or drying purpose. Figure shows that the relative humidity in the exit air is declining with time and is become 1% at 11.30 AM and continue until 3.30 PM then start to increase due to increase the moisture content in the atmosphere. The acceptable relative humidity for the purpose of heating or dryings is considered to 55% recorded at the end of off-sunshine duration. Similarly, the thermal efficiency of the air heater is increasing and reached maximum to 38% at 1.00 PM as the rate of energy delivered at this time is maximum. The efficiency declining during the off-sunshine hours due to magnitude of energy deliver is decreasing.

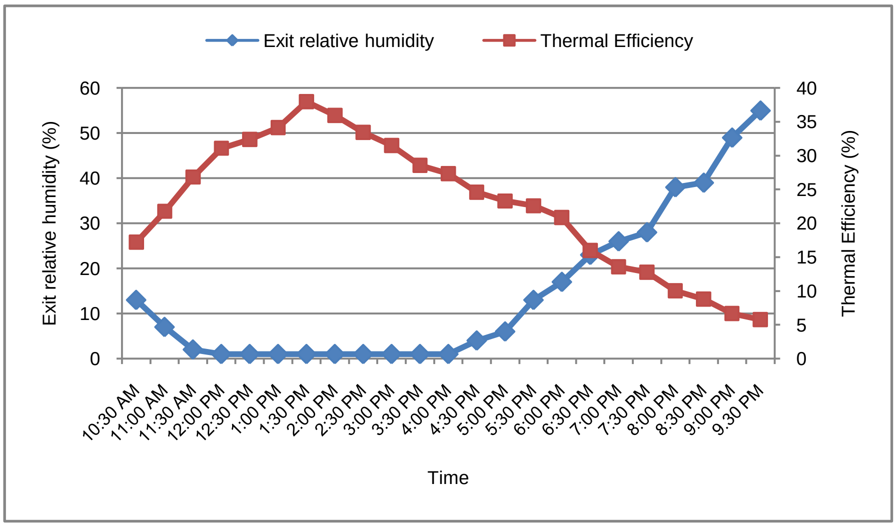


Figure 5. Change of exit relative humidity and efficiency with time at 0.0124 kg/s air flow rate

1.3 Performance of the dryer

Fig. 6 shows the change of moisture contents of the product with duration of drying for three tray dryer and drying under open sun. It is seen that the moisture content of the product is decreasing with time for three trays dryer and drying under open sun. The declining slope using the dryer is higher than that of open sun drying. Higher the slope means higher the moisture removes from the product. The moisture remove in the upper tray is much higher than that of other two trays because of upper tray receive heat from air heater and also from sun during effective sunshine hour directly through the glass, since the top of the dryer is made of glass. The declining trend for middle tray and upper tray is similar until the end of effective sunshine at 3.30 PM since within this period the middle tray receives part of the heat from both top and bottom of the dryer. During off-sunshine hours, the middle tray receive part of the heat only from bottom of the dryer result is lower the weight loss than that of lower tray. Since, lower tray receives heating effect effectively from the air heater during off-sunshine hours and the moisture remove is continuing similar as the trend of effective sunshine hours. The overall moisture remove from the product using dryer with three trays is about 25% for 9 hours duration of drying where only 9% found using the open sun drying. Hence, product drying using the dryer is about 3 times effective compared with open sun drying method.

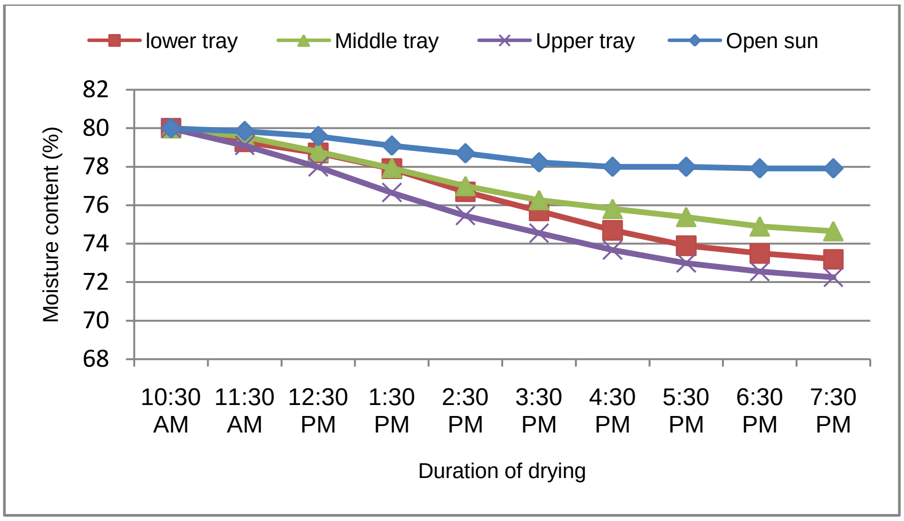


Figure 6. Change of moisture contents with duration of drying

Fig. 7 shows the rate of change of weight loss of the product with duration of drying. It is seen that the rate of weight loss is increasing with time and maximum at noon and then decreasing. The magnitude of the rate change for open sun drying is significantly lower than that of using dryer. Among three trays, rate change of weight loss for upper tray is higher than that of other tray magnitude of 5.67%. Upper tray and middle tray shows the similar change pattern compared to lower tray. This may be due to the non uniform distribution of hot air first time in the lower tray that comes from the air heater. It needs more distance between tray and distributor to ensure the better distribution of hot air. The average moisture extraction per unit energy input is 7, 6, 8 and 3 gm/kWh estimated for lower, middle, upper trays and open sun drying method respectively.

Fig. 8 shows the change of moisture extraction efficiency with duration of drying. The efficiency is increasing with time for all trays until mid of the day and then decreasing. The peak efficiency found at different time for three trays due to the trays are set at different position in the dryer. The maximum efficiency of upper tray and middle tray is 48% and 35% respectively at 12.30 pm where 43% for lower tray at 2.30 pm. The efficiency of open sun drying is much lower than that the drying chamber. The average extraction efficiency for a particular time is estimated using the value of three trays and shown in the figure. It is seen that the maximum average extraction efficiency is 36.62% at 12.30 pm.

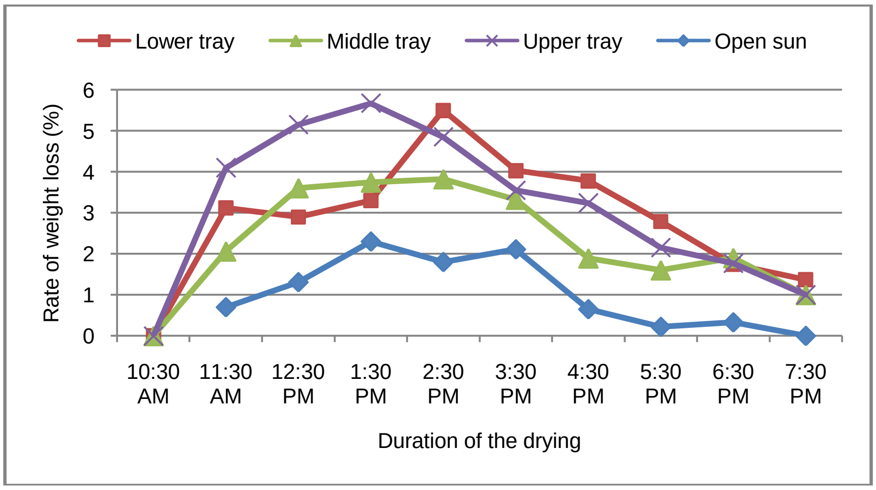


Figure 7. Rate of weight loss of the product with duration of drying

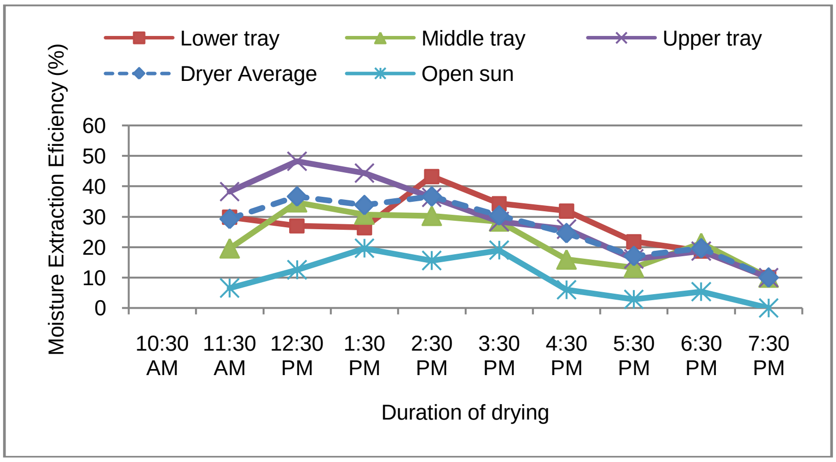


Figure 8. Moisture extraction efficiency with duration of drying

IV. Conclusions

Forced convection solar dryer with rock bed integrated new type greenhouse solar air heater has been constructed using the local material and experimental performances were evaluated in this study. The performance of solar air heater was optimized varying the air flow rate. The optimum condition of air heater was used to dry chilies in the dryer. The solar air heater is capable to deliver the hot air at 65°C and 1% relative humidity under maximum condition at 0.0124 kg/s air flow rate. The maximum thermal efficiency is 38% and the rate of energy delivered is 4.2 kW. The system is capable to deliver hot air for effective drying during off-sunshine hours and the duration is 6 hours. The maximum moisture extraction efficiency of dryer is 36.62%. The overall moisture removal for 9 hours drying is 25% without affecting the quality of product and specific moisture extraction is 7 gm/kWh. The system consumes less quantities low cost materials and simple design required low space for the installation. The study is useful in tropical and semitropical countries of the world. The countries have the solar availability and facing shortage of modern energy access can benefited using this study to minimize the energy crisis and to earn carbon credit using this technology. The system could be manufacture in any countries as it uses local materials available over the world. To implement such technology it needs proper technician and its importance in renewable energy plan to the policy maker.

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