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Investigation on the Performance of Solar Tunnel Dryer during Rainy Season for Cocoa Beans Drying

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Abstract – *In order to help Indonesia cocoa farmers***,** *a solar tunnel dryer had been designed and manufactured. The capacity of the dryer is 500 kg cocoa (wet beans) per batch. The solar tunnel dryer was designed for the use in the dry season with daily solar radiation of 520 W/m^2, but the investigation was conducted to determine its performance in the wet season with solar radiation of 116-798 W/m^2. The mean value of the solar radiation in the wet season was 340 W/m^2. It was found that the thermal efficiency based on the mean value of solar radiation was 31%, the highest temperature in the tunnel dryer was 58.2^{o}C; with mean drying temperature of 38.6^{o}C ± 3.4^{o}C. This condition shows that the temperature was in the range of cocoa beans drying temperature. Therefore, as a conclusion, this dryer equipment could be used during wet or rainy season. The investment and operation cost for the tested solar dryer was relatively low.*

Keywords – Cocoa beans, solar tunnel dryer, sun drying, wet season.

1. INTRODUCTION

The moisture content of cocoa beans after fermentation is 55% (wet basis) and this should be reduced to 6-8% before the beans can be either processed or stored safely. In Indonesia, farmers or small-holders generally dry the cocoa beans by putting them on a platform made of bamboo mats, on a floor, or on plastic material, which is placed in a field. The drying method is called natural sun drying. Some group of farmers use concrete floor, and let the cocoa beans be in the open air. This drying method very often creates some problems, for example, the beans skin is burnt due to overheating condition.

Beside that, drying in the open air is un-hygienic, because it can easily be contaminated with dirt and damaged by animal or insect. Another problem is that in the rainy season, the drying time is too long and the water content of the dried beans is still high, this may promote fungi and mold to grow.

The drying process in the open air is generally carried out without turning the beans bed. This situation causes uneven drying rate and prolonged drying time. As a result, the moisture content of dried beans vary and in-consistent. The final water content is 15 to 20%. This value is far from the standard of dried cocoa beans which is 6-8%.

There are several disadvantages of the natural sun drying:

a. Temperature and airflow is relatively low and cannot be controlled.
b. Drying time is relatively long (around seven days). It is too long compared to that of using an artificial dryer which is usually 20 to 70 hours; depend on drying efficiency [1].
c. Drying on the concrete floor often exposes the cocoa beans to a high temperature, causing the beans' skin color changing from brown to black while inside the beans is still wet.
d. The use of the natural sun drying depends on the climate condition.

The advantage of natural sun drying is that during early morning, the drying process is naturally slow. At noon, the drying process gets faster, and in the afternoon it is back to slow. This condition makes the quality of flavor good, provided that the process is not influenced by contaminating factors [2].

An example of a simple dryer that exposes the beans to direct solar radiation is described in [1]. It consists of a small platform of bamboo (4.9 m x 1.62 m) bounded by wooden edges. This platform is covered with PVC sheet which can be removed to allow access for necessary daily turning of the beans. In good weather it can produce 22.5 kg/m^2 of dry cocoa, and in unfavorable conditions this can only produce 10 - 12.5 kg/m2. It was claimed that this dryer reduced normal sun drying time by two days in adverse weather conditions, as compared to the traditional sun-drying platform. Full drying data of this dryer is not available from the reference.

The use of artificial dryer has also been introduced to plantation industry in Indonesia. The dryers used by this industry are generally forced convection type dryers. This dryer usually consists of wood-fired furnace from which combustion gases flow through horizontal heater tubes before passing through a chimney. This combustion gas heats the air so that the temperature of the air increases. Then the hot air is blown into a plenum chamber in which a single perforated drying floor or platform is placed. The cocoa beans are put on the perforated floor of the platform. This dryer can usually be equipped with a plough type agitator.

Other dryers in Indonesia are called 'uni-dryer'. A uni-dryer is a new model as a replacement of plough type agitators. The dryer has a cylindrical shape with internal diameter of 6.1 meter and a capacity of five tons. It is claimed that the dryer is able to dry five tons of cocoa beans in 40 to 44 hours [1].

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Energy is required to evaporate water from the goods. It needs about 2400 kJ to evaporate one kilogram of water [3]. The energy required for the drying process can be divided into energy for driving the fans and for raising the temperature of the drying air. In this investigation, solar energy was used as the energy source of drying, and photovoltaics (PV) as source of energy for driving the fans. According to [4], the energy required for driving the fan is less than 3% of total energy requirement.

Drying rate can be accelerated by increasing the air flow rate and or by increasing the drying air temperature, but the air drying temperature must be kept below the maximum value of drying temperature. Maximum drying temperature for some agricultural products is below 80 to 85^{o}C [5]. Many researchers, for example Duncan, Faborode, and Bravo, determined maximum temperature for drying is 60^{o}C, while Gosh and Devos started to dry cacao beans with a higher temperature, i.e. 70 to 75^{o}C, and then the temperature was decreased to 60^{o}C in the end period of drying as cited in [6].

There are two methods of drying, slow and fast drying. Fast drying can be done when acidity (pH) of cocoa beans after fermentation is high (more than six) and the beans is wet. Slow drying can be done when pH of the beans is low (less than five) and the beans are rather dry [2].

Almost all dryer equipments are expensive and need high operation cost, because of the high price of the fuel and long operation time (up to 35 hours). The fuel is usually petroleum or biomass. The price of a dryer with a capacity of 500 kg wet beans per batch is about US$ 4,000, and the operation cost is US$ 0.07 to US$ 0.1 per kg dry beans.

Cocoa farmers need cheaper dryers. As an effort to help Indonesian cocoa farmers to overcome the above-mentioned situation, a solar tunnel dryer has been designed, manufactured, and tested. The dryer was designed to use solar energy as its energy source either for raising temperature of drying air or driving the fan. The dryer capacity was designed for 500 kg wet beans per batch.

With such a capacity the operation cost was about US$ 0.025 to 0.035 per kg dry beans. The price of the dryer was US$ 2,000. The total investment was Rp. 33.500.00 or US$ 3,700. Economic analysis showed that Internal Rate of Return (IRR) was 49%, Pay Back Period (PBP) was 2 years, Benefit and Cost ratio (B/C) was 1.13, and Return on Investment (ROI) was 15%.

The solar tunnel dryer was designed for the use in the dry season. The investigation was conducted to determine the performance of the dryer if it was used in the wet or rainy season. The investigation therefore was done in the rainy season.

There are two seasons in Indonesia; these are dry and wet seasons. The average daily solar radiation in the dry season at the investigated place is 5 to 6 kWh/m^2 and in the wet season is 2.5 to 4 kWh/m^2 [7]. The relative humidity is high; it may reach 95% in the wet season. In the day, the relative humidity decreases with the increasing temperature. The local ambient temperature is 20 to 35^{o}C and the relative humidity is in range 60 to 99%.

For calculating the size of the tunnel dryer, it was assumed that the equipment would be used in the dry season, and the average daily solar radiation was 15 MJ/m^2 per day [3] or 520 W/m^2. With this assumption it was predicted that the dryer would not work well in the wet season, because the mean of solar radiation was only 340 W/m^2.

The aims of this work were:

a. To find the best design for the dryer that could be used in all seasons.
b. To find the cheapest in both of investment and operation cost.

2. MATERIALS AND METHODS

Equipment

The solar tunnel dryer developed at the Science and Technology Research Centre (PUSPIPTEK) in Serpong Indonesia was used in this work. It consisted of plastic foil-covered flat solar collector, a drying tunnel and three small axial flow fans. The dimension of the tunnel dryer is 20 meters in length and two meters in width. The solar energy absorption area of the collector is 20 m^2, and the drying area is approximately the same. Black carpet was used for both the floor of solar collector and the drying area, therefore the floor of the tunnel dryer functioned as a solar collector. Figure 1 shows design of the tunnel dryer, which was adapted from the Hohenheim design.

K-type thermocouples were used to measure drying air temperature along the flow direction in the dryer; and a pyranometer was used for measuring global solar radiation at the middle of the dryer. Signal from these sensors were connected to a data acquisition unit (Fluke Hydra), and controlled by a computer. The data were collected in every 10 minutes.

Method

The thermocouples for measuring the drying air temperature were installed in the dryer at six points. These were at two, five, 10, 14, 16 meters from entry point of the dryer, respectively. Each point had three sensors at left, right, and middle side of the floor.

The result of measurement was recorded and processed in a computer, and displayed as a curve. The investigation was held in the rainy season (May 2004), where the sunshine was not optimum. Average daily solar radiation was 11.7 MJ/m^2/day. According to [3] tropical monsoon insolation is 5 to 25 MJ/m^2 per day. The tropical monsoon insolation used in the design calculation was 15 MJ/m^2 per day or 520 W/m^2.

The ventilations system in this tunnel dryer was cross-draught ventilation. It was done by using three little fans producing pressure of approximately 10 N/m^2, and airflow rate through the cocoa beans of 0.1 m^3/s.

For measuring the change of moisture content, samples were taken from nine positions along the tunnel dryer, and in each position three little baskets were installed for the samples. To monitor the weight loss of the product during the drying process, the samples were weighed every 2 hours.

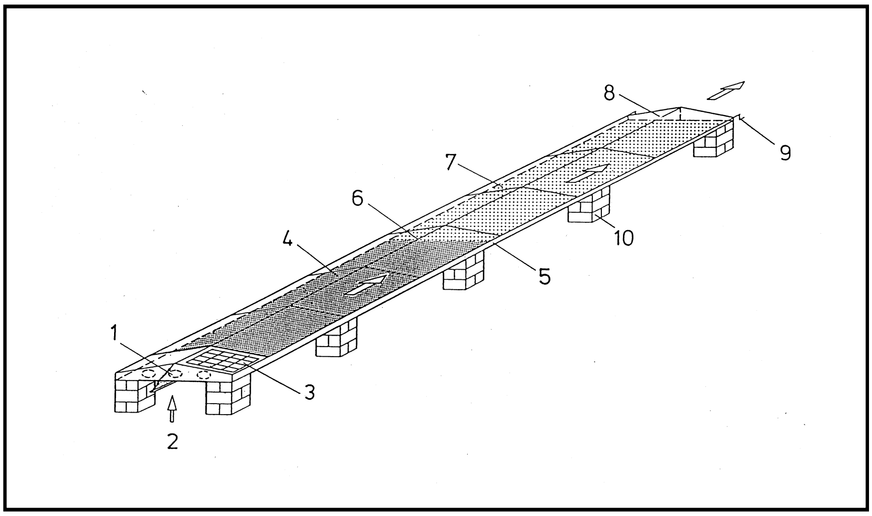

Fig. 1. Solar tunnel dryer:
(1) fan, (2) inlet air, (3) solar cell module, (4) solar collector, (5) metal frame, (6) outlet of the collector, (7).drying floor, (8) outlet of the drying tunnel, (9) rolling bar, (10) concrete block substructure

Materials

Cocoa beans from PT. Intergreen Estate in Cianjur, Indonesia were used in this experiment. The initial weight of cocoa beans was 500 kg of wet beans, and it was spread out on the floor of the dryer with density of 15 to 25 kg/m^2.

3. DESIGN OF THE TUNNEL DRYER

m_{ci} = 55% and m_{cf} = 7%
T_{max} = 70^{o}C and T_a = about 30^{o}C
Rh = about 70%
Drying time = 56 hours or 7 days
m_B = 500 kg (batch capacity)

$$M_w = m_B\ (m_{ci} - m_{cf}) / (100 - m_{cf}) \quad (1)$$

M_w = 258 kg or M_{av} =4.6 kg per hour
m_d = 500 kg – 258 kg = 242 kg

$$Q = (h_f - h_i)\ m_{ci} / 3600 \text{ kW} \quad (2)$$

According to h-x diagram:
h_i = 90 kJ/kg and h_f = 125 kJ/kg
w_i = 24 g/kg and w_f = 34 g/kg

$$M_i = M_{av} / (w_f - w_i) \quad (3)$$

M_i = 460 kg/hour
Q = 4.47 kW

The thermal efficiency was assumed to be 30% and I = 520 W/m^2, hence the area of the solar collector, A = 28.6 m^2. If the area of the dryer was calculated based on latent heat of vaporization, the area of the solar collector, A = 23 m^2.

In the manufacturing of the dryer, the area of both solar collector and drying floor was 40 m^2. The size of the tunnel dryer was two meters in width, and 20 meters in length.

With the condition mentioned above, maximum air temperature at the end part of collector was expected to be 68.2^{o}C.

4. RESULT AND DISCUSSION

The water content of the cacao beans after fermentation was 50 to 55%. It should be reduced to about 8%, in order to prevent the mold, fungi and or other microorganisms to develop, so that the beans could be stored for long time without damage.

Based on experiences and literatures, the drying temperature should be up to 65^{o}C [1]-[2]. Drying temperature of more than 65^{o}C, caused fast drying and unfavorable flavor, which was unexpected by consumers. Fast drying could be done, when the pH of the beans after fermentation is more than 5.2.

Average temperature during drying time was 37.9^{o}C. The average temperature of each point of measurement was:

1. Point one (two meters from the entry point): 32.5^{o}C.
2. Point two (five meters from the entry point): 36.9^{o}C.
3. Point three (10 meters from the entry point): 36.5^{o}C.
4. Point four (14 meters from the entry point): 38.6^{o}C.
5. Point five (16 meters from the entry point): 41.1^{o}C.
6. Point six (18 meters from the entry point): 41.8^{o}C.

Figure 2 shows the distribution of temperature along the tunnel during investigation.

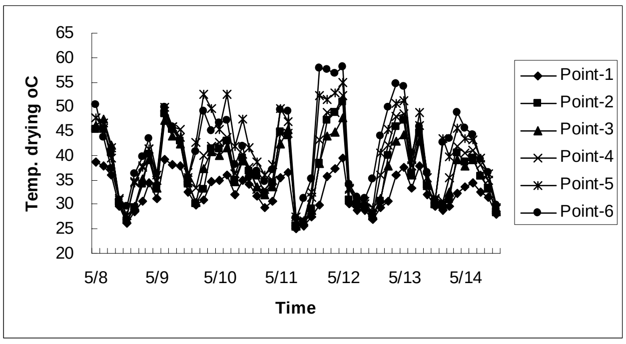

Fig. 2. Distribution of temperature along the tunnel dryer

The maximum temperature was 58.2°C at point six, it was found when the sunshine brightly, and the minimum temperature was 25°C at point one.

During the investigation, the weather condition changed frequently from cloudy to sunny or rain. The variation of solar radiation and the ambient temperature is shown in Figure 3.

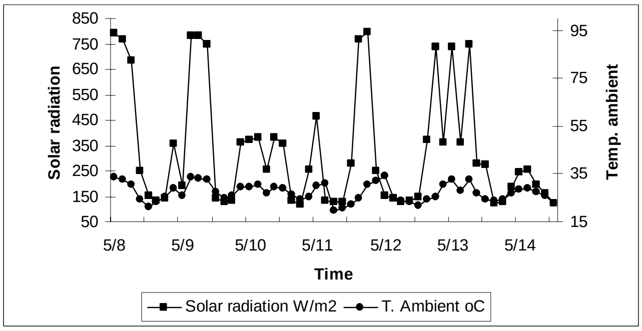

Fig. 3. Solar radiation, $T_{ambient}$ vs. time

A comparison of the tested solar tunnel dryer and natural sun dryer in terms of drying time was also done in this investigation. This was done in the same time and weather condition. It was found that the drying using solar tunnel dryer was shorter compared to that of using natural sun dryer. The drying time using the tested solar tunnel dryer was seven days while that of using natural sun dryer was 13 days. In addition, the product of natural sun drying was dirty because of the growing mold and fungi.

If the tested solar tunnel dryer was compared to other dryer [3], the tested solar tunnel dryer was less efficient. The tested solar tunnel dryer was able to reduce the water content by 36.8 kg per day, while the other dryer was able to reduce 53.3 kg per day. The season condition of the other dryer however was not mentioned.

Figure 4 shows the average air temperature at the entry point and exit point of the tunnel dryer.

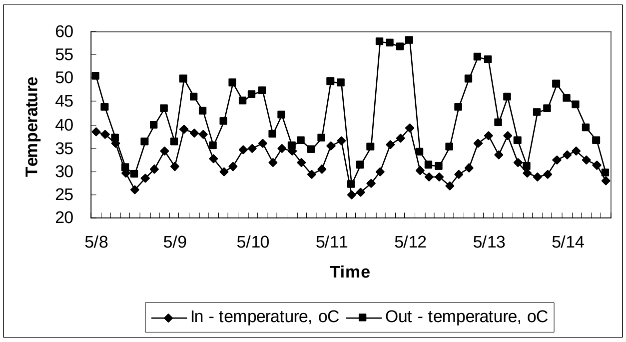

Fig. 4. Average air temperature at the entry point and exit point of the tunnel dryer

From Figure 2, and Figure 4, it is known that;

a. Average temperature of the air in the entry point increased along the tunnel dryer. The highest temperature was 58.2°C. It was reached at the end point of the dryer on 12th May, 13:12 o'clock.
b. The temperature difference between the entry and exit point was about 10 to 20°C. The biggest difference was reached on 13th May, 11:23 o'clock about 20°C.
c. The mean temperature at the collector and drying floor was 38.6°C.

Figure 5 shows relative humidity, drying temperature during investigation.

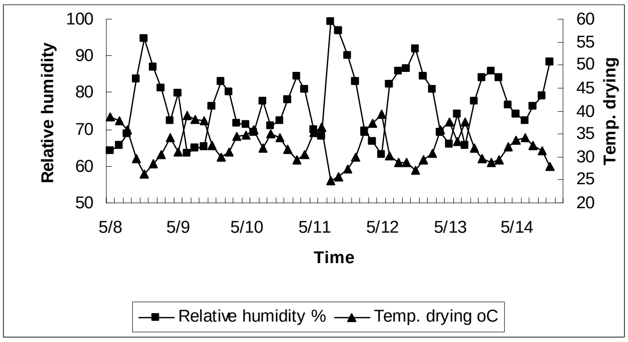

Fig. 5. Relative humidity, T_{drying} vs. time

The reduction of the cocoa beans water content in the tested solar tunnel dryer, in the left, right, and middle side (position 1st, 2nd, 3rd, and position 4th, 5th, 6th, and position 7th, 8th, 9th) were not significantly different. Even, after the 3rd day of drying process, the water content curves were close together. On the 7th day of drying the moisture content reached 8.1 % dry basis. **Figure 6** shows the reduction of the cocoa beans water content during investigation.

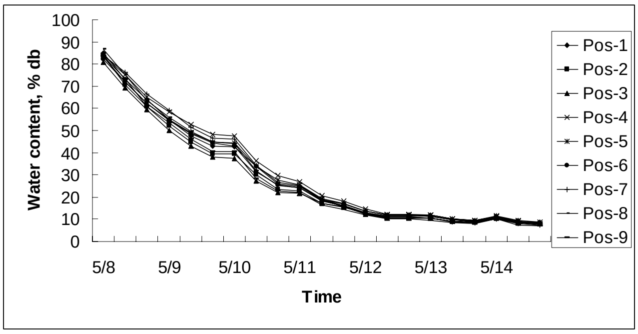

Fig. 6. Reduction of cocoa bean water content during drying

Error Analysis

There are two types of experimental errors i.e. determinate, and indeterminate or systematic error [8]. In another paper, the error can be divided into two i.e. broad and rough but in practice the terminology used is systematic and random [9].

Systematic errors are errors which tend to shift all measurement in a systematic way. This may be due to such things as incorrect calibration of equipment, consistent improper use of equipment, or failure to properly account for some effects. Other source of systematic errors are external effects which can change the result of the experiment, but for which the corrections are not well known. Random errors are errors which fluctuate from one measurement to the next. They yield results distributed about some mean value [9].

To eliminate the measurement error in this experimental, the temperature sensors were installed at six points along the drying floor. Each point had three sensors, one was at the right side, the second one was in the middle, and the last one was at the left side. Result of the drying temperature was the average of the three sensors measurement.

To eliminate systematic errors, the equipment was calibrated before performing measurement. The measurement accuracy of the equipment was high (about ± 0.02), but there was a little delay between the actual time and the recorded time of the changing in solar radiation. The delay time was only about three seconds and could be neglected.

For errors analysis calculation, the mean and standard deviation methods were used. The mean $\overline{X}$ of a series of measurements is equal to the sum of the individual measurements divided by the total number of measurements (N):

$$\sum_{j=1}^{N} x_i = x_1 + x_2 + x_3 + ... + x_N \tag{4}$$

$$\overline{X} = \frac{\sum X_i}{N} \tag{5}$$

where: $N = 52$

$\sum xi = 2008$ and $(\sum xi)^2 = 4{,}033{,}170$

$\sum xi^2 = 78147$

The mean temperature = 38.6°C

$V_x = 11.48$

$S = 3.4$

Therefore the mean drying temperature is $T = 38.6 \pm 3.4$°C.

Thermal Efficiency

Thermal efficiency of solar collector was calculated using Equation 6.

$$E = M_i \ x \ cp \ (T_o - T_i) \ / \ A \ x \ I \tag{6}$$

E= 460 x 1.004 (41.8-32.5) / (40 x 340) = 31%.

The collector efficiency or thermal efficiency of this equipment was 31%.

Another solar tunnel dryer, adapting the Hohenheim design and scaled down to fit the local condition and requirements has been constructed at the Asian Institute of Technology (AIT) Bangkok [10]. The test result of AIT dryer was compared with that of the tested solar tunnel dryer. It was known that both dryers showed the same characteristic, in that the fluctuations of solar radiation caused the temperature to fluctuate.

The collector efficiency of the AIT dryer for DC/PV operation was estimated at 14.2% against 9.3% for AC operation. The solar collector area was 7.20 m^2, and solar radiation was about 300-600 W/m^2 [10].

A passive solar tunnel dryer was designed and constructed at Department of Mechanical Engineering University of Moratuwa, Sri Lanka. The dryer consists of collector, drying chamber, metal duct, and chimney. Two chimneys were designed to compare their effectiveness upon the performance of the dryer. Chimney-1 was made by rolling a thin sheet to from a cylinder; while chimney-2 is a wooden frame covered with polyethylene to form a cylinder. The dryer was designed to operate with passive ventilation mechanism. The collector and drying chamber had about 0.9 meters in width, and about 1.8 meters in length. Efficiency of the collector for chimney-1 was found to be 64%, while for chimney-2 was 68% [11]. But the value of global insolation on the collector surface was not mentioned.

Another solar tunnel dryer was developed and tested at Research Centre for Applied Science and Technology (RECAST). The maximum value of efficiency calculated for their forced convection solar tunnel dryer with collector area of 24 m^2 was 21.7%, and the average solar radiation is 655 W/m^2 [12].

The design of a simple solar dryer with biomass back-up heater had been built by Benon Bena and Bob Fuller of the University of Melbourne Australia, as cited in [13]. The dryer consisted of a drying cabinet mounted on top of a brick chamber that enclosed a 200-liter drum burner. The overall thermal efficiency of the dryer (solar and biomass) was found to be about 9%. The efficiency of the dryer when operating on solar energy or biomass alone was 22% and 6%, respectively [13].

5. CONCLUSIONS

1. The investigation results show that the temperature reached using the tested solar tunnel dryer was in the range of drying temperature for cocoa beans.
2. The efficiency of the tested solar tunnel dyer was 31%. Although the dryer was designed for operating in dry season, it was able to work in good performance in the wet season in which the investigation was carried out.
3. The drying time was shorter compared to that of the natural sun drying.
4. The operation cost and investment is relative low.

ACKNOWLEDGEMENT

Thanks to Mr. Gigih Atmaji, and Mr. Yusni Anis from the Agency for the Assessment and Application of Technology (BPPT) in Jakarta Indonesia, who helped in the construction and measurement of this study. Dr.Ing Tilman Pass and Prof. Dr. Ing W. Mühlbauer from Hohenheim University, Stuttgart, Germany, and Dr. Ing Sri Mulato from Cocoa and Coffee Research Centre in Jember, Indonesia for their valuable comments in designing the equipment. The author also give thanks to Mr. Drs. H. Sunaryo the founder of Technical University (STT) of Duta Bangsa, and founder of Indoteknokrasi Foundation in Bekasi, Indonesia, for the support for this experiment.

NOMENCLATURE

$\overline{X}$	mean value
Xi	a series of measurements
N	total number of measurements
V_x	variance
S	standard deviation
m_{ci}	initial moisture content
m_{cf}	final moisture content
T_{max}	maximum temperature
T_a	ambient air temperature
Rh	relative humidity
m_B	mass of wet material
M_w	mass of water to be evaporated
M_{av}	mass of water to be evaporated per hour
m_d	mass of dry material
Q	energy for drying
h_i	initial enthalpy

h_f final enthalpy
w_i initial humidity ratio
w_f final humidity ratio
M_i air flow rate
A area of the solar collector
I global insolation
E thermal efficiency, %
cp specific heat of air: 1.004 kJ/kg ^oC or W h/kg ^oC
T_o average temperature of air exit from dryer
T_i average temperature of air entry to dryer

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