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Effect of Outlet at the Bottom of the Drying Chamber on the Performance of Natural Convection Solar Dryers

***Abstract**. In a closed room, the air gets more humid when the drying process takes place. The increase in air humidity causes the drying rate to decrease. The humidity in the drying chamber needs to be lowered. This study aims to increase the drying rate by keeping the air moist in the drying chamber. The research was conducted by making four outlets at the bottom of the drying chamber. The function of the outlet is to remove the moist air in the drying chamber. Removing moist air occurs by natural convection due to differences in density. This research was carried out in 3 variations. Namely, the outlet is fully closed, half-closed, and fully open. The research was carried out in Makassar, South Sulawesi, Indonesia. The dried material is bananas. The drying process is carried out from 09.00 to 17.00 WIB. The result of this research is that the solar dryer's performance increases when the hole at the bottom of the drying chamber is fully open. On the other hand, the solar dryer's performance decreases when the hole at the bottom of the drying chamber is fully closed.*

Streszczenie. *W zamkniętym pomieszczeniu powietrze staje się bardziej wilgotne podczas procesu suszenia. Wzrost wilgotności powietrza powoduje zmniejszenie szybkości suszenia. Należy obniżyć wilgotność w komorze suszenia. Badanie to ma na celu zwiększenie szybkości suszenia poprzez utrzymywanie wilgotności powietrza w komorze suszenia. Badania przeprowadzono wykonując cztery wyloty w dnie komory suszenia. Zadaniem wylotu jest usuwanie wilgotnego powietrza z komory suszenia. Usuwanie wilgotnego powietrza odbywa się na drodze naturalnej konwekcji z powodu różnic w gęstości. Badanie to przeprowadzono w 3 wariantach. Mianowicie, wylot jest całkowicie zamknięty, półprzymknięty i całkowicie otwarty. Badania przeprowadzono w Makassar w południowym Sulawesi w Indonezji. Suszony materiał to banany. Proces suszenia odbywa się w godzinach od 09.00 do 17.00 WIB. Wynikiem tych badań jest to, że wydajność suszarki słonecznej wzrasta, gdy otwór w dnie komory suszenia jest całkowicie otwarty. Z drugiej strony wydajność suszarki słonecznej spada, gdy otwór w dnie komory suszenia jest całkowicie zamknięty.* (***Wpływ wylotu na dnie komory suszenia na wydajność suszarek słonecznych z konwekcją naturalną***)

Keywords: Drying, Solar, Convection, Natural, Moisture.
Słowa kluczowe: Suszenie, Słoneczne, Konwekcyjne, Naturalne, Wilgotne.

1. Introduction

Drying is one of the post-harvest preservation efforts that can increase the shelf life of agricultural products [1]. Drying is an appropriate preservation process for fruits and vegetables [2]. The drying process requires a large amount of energy, so to be cheap, drying using solar energy is developed [3]. Solar drying is an ancient method of food preservation [4]. The current development of solar dryers uses solar dryers [5]. The advantage of solar energy dryers is that they are environmentally friendly [6]. Another advantage of solar dryers is that they produce products that are clean and free from insects, dust, and so on. Besides that, they can reduce losses in the drying process and improve the quality of drying products [7].

The use of solar dryers is generally to dry agricultural products such as bananas [4, 6], pears [7], carambola [8], mango [9], pineapples [10], bitter gourd [11], potatoes [12], tomato [13], chili [13], asparagus [14], pepper [15], carrot [16], corn [17], locust beans [18], turmeric [19], and cassava [20]. Solar drying can also be used to dry fish [21], Curcuma zedoaria [22], Stevia leaves [23], ebony wood [24], and anti-diabetic medicinal products [25].

The use of solar energy in the drying process continues to grow, in line with the ever-increasing energy needs. The use of solar energy with natural convection systems is often carried out in two fields, namely solar water heaters [26-28] and solar drying [13, 14, 29]. In solar drying, a forced convection system can also be used [9, 11, 19].

Based on the airflow, solar dryers are classified into natural convection and forced convection dryers [30]. In natural convection, the airflow is formed due to differences in buoyancy produced by differences in density due to temperature differences [31]. In forced convection, the airflow is formed due to the use of fans or blowers [32]. The drying rate of forced convection is higher than that of natural convection [20]. Natural convection manufacturing and operating costs are lower than forced convection [33].

Solar drying is constantly evolving, and there are various models. There are three types of solar dryers: direct dryers, indirect dryers, and mixed-mode dryers [5]. Solar energy enters the drying chamber through the glass cover of indirect solar dryers. In an indirect solar dryer, solar energy is collected in the solar collector and then heated into a closed drying chamber (not penetrating solar radiation). In the combined solar dryer, the drying chamber receives solar energy like a direct solar dryer and also has a solar collector that supplies heat to the drying chamber [21].

In a closed room, the air gets more humid when the drying process takes place. The drying rate will decrease if the air in the drying chamber gets humid [34]. In a closed chamber dryer, a humid air outlet is required. Various studies have been carried out using the outlet. Some are above [1, 4, 21] and beside [8, 14, 23].

The research conducted is an indirect solar dryer. The research also uses a natural convection system. The use of natural convection systems is to reduce production and operating costs. Natural convection systems are also so that solar dryers can be used in remote areas where electricity is not yet accessible. Efforts to accelerate the drying rate in this research are to make an outlet at the bottom of the drying chamber. The exhaust duct serves to exhaust moist air, but to a minimum, heat build-up occurs.

2. Materials and metods

2.1. Solar dryer design

The solar dryer consists of two main parts: the solar collector and the drying chamber (figure 1). The solar collector is made of steel plate, the inside is coated with insulation, above the insulation is placed a wave plate [35], the top is covered with glass with a thickness of 3 mm, and the size of the solar collector is 15 cm x 50 cm x 110 cm. The drying chamber is made of steel plate. The inside is coated with insulation, the back has a door to enter the dried material, there are three shelves inside, the bottom has four holes with a diameter of 10 cm, and the size of the drying chamber is 50 cm x 50 cm x 100 cm.

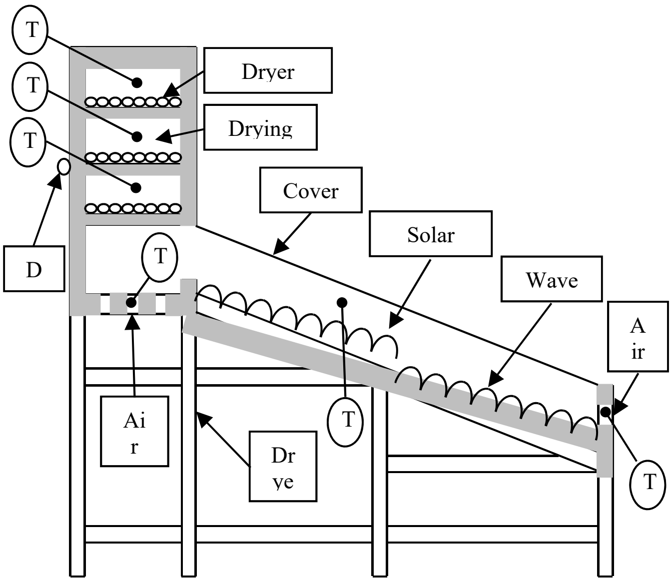

Fig 1. Solar Dryer

The hole at the bottom of the drying chamber removes moist air. The research was conducted to determine the performance of the wet air exhaust hole. The test was carried out with 3 test variations, namely fully closed (no hole), open half (two holes), and fully open (four holes). The test is carried out simultaneously for all test variations to get accurate comparison results.

2.2. Radiation intensity and temperature

Measurement of the intensity of solar radiation using a measuring instrument type Tenmars TM206 Solar Irradiance Meter. Specifications: display: 3½ digits, 2000 readings; range: 2000 W/m2, 634BTU / (ft2xh); resolution: 0.1 W/m^2, 0.1 BTU/ (ft2xh); sampling time: 0.25 second; operating temperature and humidity: 0^oC ~ 50ºC below 80% RH; and power supply: 9V battery x1.

Temperature measurement using a measuring instrument type RS PRO RS42 Handheld Digital Thermometer. Using an external K-type thermocouple bead probe as a temperature sensor. Fast response and laboratory accuracy, following National Bureau of Standards and IEC584 temperature/voltage tables for K-type thermocouples.

2.3. Moisture content

Initial moisture content was tested using open hot air at (105±1) C for 24 h. The water content is calculated using equation [2]:

$$(1) \qquad Moisture\ content\ (\%) = \frac{W_1 - W_2}{W_2}$$

With: W_1 = sample weight before drying (g); W_2 = sample weight after drying (g).

2.4. Drying rate and efficiency

Drying rate is calculated using equation [36]:

$$(2) \qquad Drying\ rate\ \left(\frac{kg}{s}\right) = \frac{M_{(t)} - M_{(t+\Delta t)}}{\Delta t}$$

With: $M_{(t)}$ = weight of material before drying (kg); $M_{(t+\Delta t)}$ = weight of material after drying (kg); Δt = drying time(s).

Efficiency is calculated using equation [37]:

$$(3) \quad Efficiency\ (\%) = \frac{Q_{out}}{Q_{in}} x100\%$$

$$(4) \quad Q_{in}\ (kW) = G.A$$

$$(5) \quad Q_{out}\ (kW) = D_R.h_{fg}$$

With: G = radiation intensity (kW/m^2); A = Solar collector cross-sectional area m^2; D_R = drying rate (kg/s); h_{fg} = enthalpi of evaporation (kJ/kg).

2.5. Drying process

The research was carried out in Makassar, South Sulawesi, Indonesia. The dried material is a sliced banana with a thickness of 5 mm. The drying process is carried out from 09.00 to 17.00 Central Indonesian Time.

The working principle of the solar dryer (figure 1) is to utilize air circulation by natural convection. Dry air enters the solar collector through the inlet. The air is heated in the solar collector chamber, which causes its density to decrease. The hot air then, by natural convection, moves to the drying chamber. In the drying chamber, a drying process occurs, causing the air to become humid. The density of moist air increases, so by natural convection, the moist air moves out of the drying chamber through the outlet.

3. Results and discussions

3.1. Decrease in moisture content

In Figure 2, it can be seen that a drying process occurs in each test condition. This can be seen by the dried material's decreasing water content (MC). The test results in the fully closed condition obtained a decrease in the water content of the material on shelf 3 (R3) by 27.27%, on shelf 2 (R2) by 16.73%, and on shelf 1 (R1) by 11.64%.

In Figure 2, it can also be seen that the highest decrease in the water content of the material occurred in the open full test conditions. The average decreased by 23.73%, then the open half test conditions decreased by 21.27%, and the lowest occurred in the closed test conditions entire average decreased by 18.55%.

In Figure 2, it can also be seen that the highest decrease in the water content of the material occurred on shelf 3. On average, it decreased by 30.04%. On shelf 2, the average decreased by 20.34%, and the lowest occurred on shelf one on average; it decreased by 11,16%.

As a comparison, the research of solar dryers by Noutfia [38] obtained a decrease in water content from 73.3% to 66.2%. Noutfia's research had a lower water content drop than the research conducted.

In other studies of solar dryers, there was also a decrease in water content, such as the research of Dhalsamant [12], which decreased from 82.12% to 10%; the Shalaby study [39] dropped from 86% to 48.12%; Islamic research [40] decreased by 46.8%; the Musembi study [41] dropped from 86% to 8.12%, and Babar's study [42] dropped from 90% to 38%. The water content decrease in the abovementioned research is higher than in the research conducted. The higher the decrease in water content, the faster the drying process.

3.2. Temperature at solar drying

Figure 3 shows the results of temperature measurements on a solar dryer. Temperature measurements were carried out at 7 points, namely ambient temperature (T~); collector intake air temperature (Tin); the temperature of the air exiting the drying chamber (Tout); air temperature in the collector chamber (Tc); air temperature on rack 1 in the drying chamber (TR1); air temperature on rack 2 in the drying chamber (TR2); and the air temperature on rack 3 in the drying chamber (TR3). The temperature graph is entirely parabolic. This is due to the radiation energy entering the solar collector, which is also parabolic in size (figure 4).

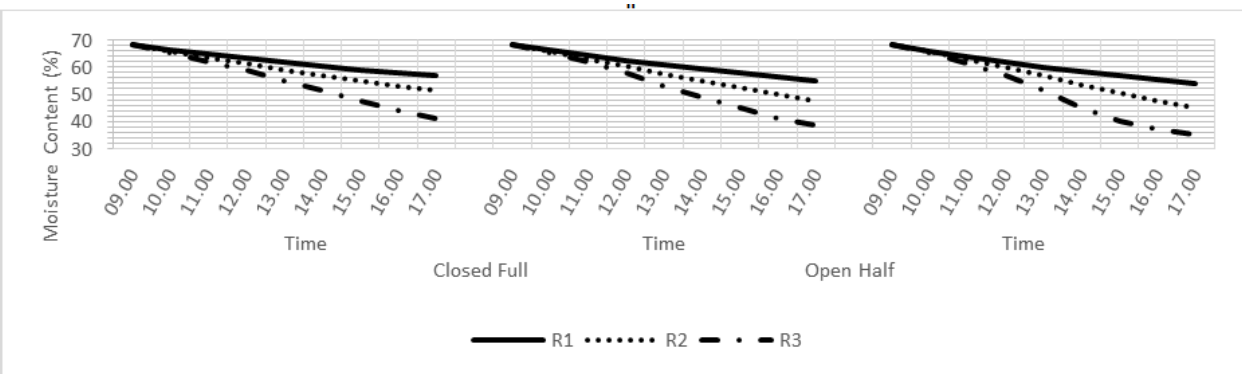

Fig 2. Decreasing the mass of the material during the drying process

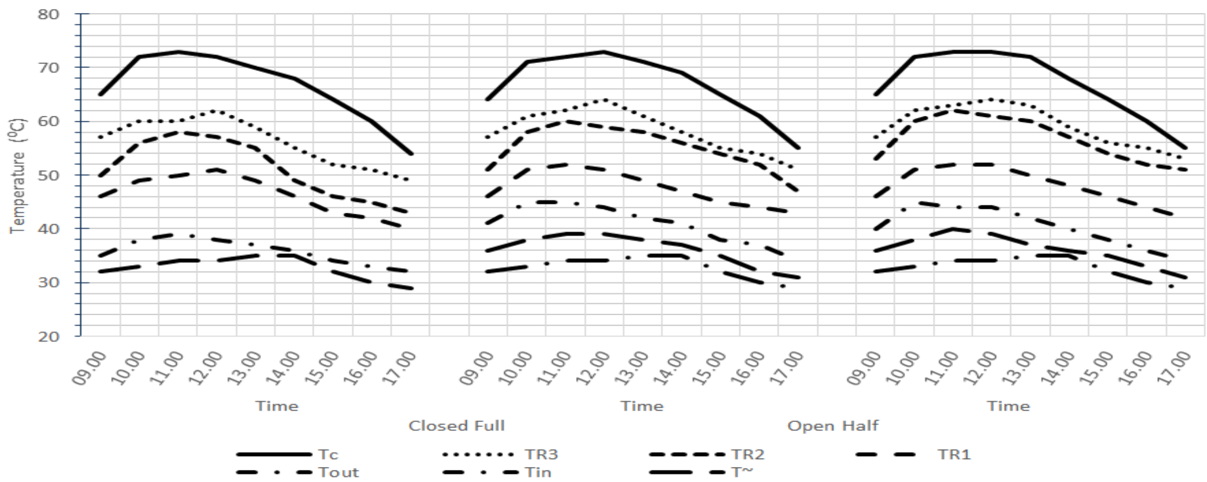

Fig 3. Temperature of the solar dryer

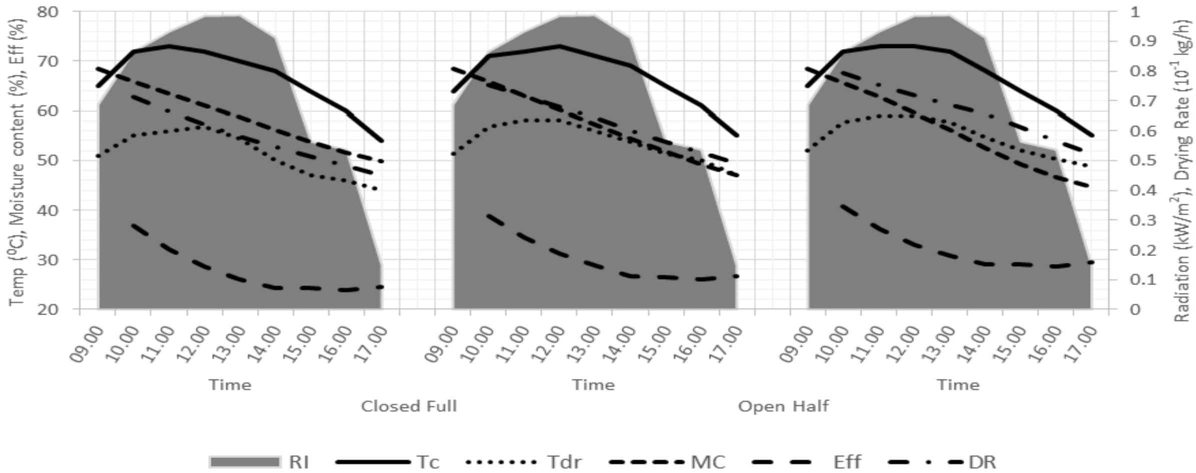

Fig 4. Performance of a solar dryer

Figure 3 shows that the T~ in each condition is the same because the tests are carried out simultaneously, and the T~ measurement is only carried out once for each data collection. The magnitude of T~ is 29 - 35°C with an average of 32.67°C. Tests with fully closed conditions obtained Tc of 54 - 73°C with an average of 66.44°C, and Tin of 32 - 39°C with an average of 35.78°C. Tests with open half conditions obtained Tc of 55 - 73°C with an average of 66.78°C; Tin is 31 - 39°C with an average of 36.11°C, and Tout of 34 - 45°C with an average of 40.78°C. Tests with fully open conditions obtained Tc of 55 - 73°C with an average of 66.89°C; Tin is 31 - 40°C with an average of 36.11°C; and Tout of 34 - 45°C with an average of 40.33°C. The size of Tc and Tin for all conditions tends to be the same, while the size of Tout also tends to be the same. The Tout measurement in the fully closed test condition was not carried out because there was no air duct out of the solar drying chamber.

As a comparison, the research of solar dryers by Noutfia [38] obtained an exit temperature of 26 - 48°C. Noutfia's research has an exit temperature equivalent to the research conducted. In other solar dryer studies, the exit temperature, as in Lingayat's study [6], was 28 - 52°C, and in Yassen's study [43] at 33 - 50°C. The exit temperature in the above research is greater than the research conducted. The greater the exit temperature, the greater the energy wasted from the drying chamber.

Collector temperature was also obtained in other studies, namely the Asnaz study [1] of 42 - 78.2°C; research by Dhalsamant [12] of 38.46 - 56.35°C; Babar's study [42] was 56 - 57°C; Baniasadi's study [44] was 25–48°C; and the Srinivasan study [45] at 30-44°C. The collector temperature in the above research is lower than the research conducted. The low temperature of the collector chamber can be caused by low heat absorption or fast heat supply.

In the research of solar dryers by Lingayat [4], the collector temperature is 37 - 80°C. Lingayat's research has a collector temperature equivalent to the research conducted.

In the study of solar dryers by Sharma [13], the collector room temperature was 67 - 94°C. Sharma's research has a higher collector chamber temperature than the research conducted. The high temperature of the collector chamber can be caused by high heat absorption or slow heat supply.

The results of the drying chamber temperature test can be seen in Figure 3. Tests with fully closed conditions obtained TR3 of 49 - 62°C with an average of 56.11°C; TR2 of 43 - 58°C with an average of 51.00°C; and TR1 of 40 - 51°C with an average of 46.22°C. Tests with open half conditions obtained TR3 of 51 - 64°C with an average of 58.11°C; TR2 of 47 - 60°C with an average of 55.00°C; and TR1 of 43 - 52°C with an average of 47.56°C. Tests with fully open conditions obtained TR3 of 53 - 64°C with an average of 59.11°C; TR2 of 51 - 62°C with an average of 56.67°C; and TR1 of 42 - 52°C with an average of 47.89°C.

Figure 3 also shows that the highest drying room temperature (TDR) occurs in the fully open test conditions of 42 - 64°C with an average of 54.56°C, then the open half test conditions of 43 - 64°C with an average of 53 .56°C, and the lowest occurred in fully closed test conditions of 40 - 62°C with an average of 51.11°C.

Figure 3 also shows that in all test conditions, the highest drying chamber temperature is TR3 of 49 - 64°C with an average of 57.78°C, then TR2 of 43 - 62°C with an average of 54.22°C, and the lowest TR1 is 40 - 52°C with an average of 47.22°C.

As a comparison, the drying room temperature in other solar dryer studies is in the Asnaz study [1] at 40 - 52.8°C; research by Dhalsamant [12] of 32.76 - 52.14°C; Sharma's study [13] was 46 - 55°C; Swami's study [21] was 34 - 54°C; Téllez's study [23] was 42 - 53°C; Shalaby's study [39] was 34 - 40°C; Yassen's study [43] was 33 - 45°C; and the Srinivasan study [45] at 31 - 50°C. The drying chamber temperature in the above study was lower than the research conducted. The low temperature of the drying room can be caused by the low energy supply received and can be caused by the high humidity of the air in the drying room.

The drying chamber temperature was also obtained in other studies, namely in the Lingayat study [4] at 28 - 66°C; and Zoukit's study [46] at 31 - 66°C. The drying chamber temperature in the above study is equivalent to the research conducted.

Meanwhile, other studies that obtained the drying room temperature were Lingayat research [6] at 28 - 70°C, research by Owusu [14] at 42 - 69°C; Mahapatra's study [15] was 47.53 – 54.86°C; Seetapong's study [29] averaged 63.19°C, and research by Mugi [47] at 34 - 69°C. The drying chamber temperature in the above study was higher than the research conducted. The high temperature of the drying room can be caused by the high energy supply received and can be caused by the low humidity of sthe air in the drying room.

3.3. Solar dryer performance

The tests were carried out simultaneously so that the intensity of solar radiation entering the dryer was the same for all test conditions. In Figure 4, the radiation intensity (RI) is 147 - 987 W/m^2 with an average of 734.89 W/m^2.

Figure 4 shows that the drying rate (DR) graph has decreased. The results of the calculation of the average drying rate obtained the highest in the fully open test conditions of 0.052 - 0.079 kg/h with an average of 0.066 kg/h, then the open half test conditions of 0.049 - 0.075 kg/h with an average of 0.062 kg/h, and the lowest occurred in the fully closed test conditions of 0.045 – 0.071 kg/h with an average of 0.057 kg/h.

As a comparison, the drying rate in other solar dryer studies is the Islamic study [40] which is 0.04 – 0.058 kg/h; and Baniasadi's study [44] was 0.0005 - 0.002 kg/h. The drying rate in the above research is lower than the research conducted. In the solar dryer research by Asnaz [1], the drying rate was 0.07 - 0.34 kg/h. Asnaz's research has a higher drying rate than the research conducted. The higher the drying rate, the faster it will take to reach the desired dryness level.

Figure 4 shows the efficiency (Eff) graph in a parabolic shape. The results of the calculation of the average efficiency, the highest was obtained in the fully open test conditions of 27.86 - 40.80 % with an average of 31.86%, then the open half test conditions of 26 - 38.81 % with an average of 29.92%, and the lowest occurred in the fully closed test conditions of 23.89 - 36.83% with an average of 27.59%.

As a comparison of efficiency in other solar dryer studies, the Lingayat study [6] was 17.28 - 38.23%; Sharma's study [13] was 13.4 - 13.9%; Ullah's research [16] was 14.97 - 16.14 %; Musembi's study [41] was 17.89%; Srinivasan's study [45] was a maximum of 14%; Seetapong's study [29] averaged 2.59%; Mugi study [47] an average of 20.13%; and research by Abi Mathew [25] by 7.9%.

In the solar dryer research by Yassen [43], 46-71% efficiency was obtained. Yassen's research has a higher efficiency than the research conducted.

4. Conclusions

The tests are carried out simultaneously so that T~ and the radiation intensity are the same for all test conditions. The amount of radiation intensity that enters the dryer is an average of 734.89 W/m2. The amount of T~ around the dryer is an average of 32.67 C.

In the fully closed test conditions, the results obtained are a decrease in the water content of the material on rack 3 by 27.27%; on shelf 2 by 16.73%; and on shelf 1 of 11.64%. Also obtained the results of an average Tc of 66.44^{o}C; Tin average is 35.78^{o}C; The average TR3 is 56.11^{o}C; The average TR2 is 51.00^{o}C, and the average TR1 is 46.22^{o}C. Other results obtained were an average drying rate of 0.057 kg/s; the average efficiency is 27.59%.

In the open half test conditions, the results obtained were a decrease in the water content of the material on shelf 3 by 29.67%; on shelf 2 of 20.91%; and on shelf 1 of 13.24%. Also obtained the results of an average Tc of 66.78^{o}C; Tin average is 36.11^{o}C; The average tout is 40.78^{o}C; The average TR3 is 58.11^{o}C; The average TR2 is 55.00^{o}C; and an average TR1 of 47.56^{o}C. Other results obtained were an average drying rate of 0.062 kg/s; the average efficiency is 29.92%.

In the fully open test conditions, the results obtained are a decrease in the water content of the material on rack 3 by 33.19%; on shelf 2 by 23.38%; and on shelf 1 of 14.61%. Also obtained the results of an average Tc of 66.89^{o}C; Tin with an average of 36.11^{o}C; The average tout is 40.33^{o}C; The average TR3 is 59.11^{o}C; The average TR2 is 56.67^{o}C; and an average TR1 of 47.89^{o}C. Other results obtained were an average drying rate of 0.066 kg/s; the average efficiency is 31.86%.

Based on the decrease in moisture content, the results obtained that the open full test condition occurs evaporation of the most water content in the material and the fully closed test condition occurs evaporation of the least water content in the material. Based on the decrease in moisture content, it was also found that on shelf 3 there was the evaporation of the most water content in the material, and on shelf 1 there was the evaporation of water content in the least material.

Based on the temperature in the drying chamber, the results obtained that the test conditions are fully open the highest heat absorption occurs and the test conditions are fully closed conditions where the heat absorption is the lowest. Based on the temperature in the drying chamber, the results also show that on rack 3 the highest heat absorption occurs, and on rack 1 the lowest heat absorption occurs. While the input temperature, output temperature, and collector temperature tend to be the same for all test conditions.

Based on the drying rate and efficiency, the results obtained that the open full test conditions obtained the highest dray rate and efficiency and the fully closed test conditions obtained the lowest dray rate and efficiency.

In general, the result of this research is that there is an increase in the performance of the solar dryer when the hole at the bottom of the drying chamber is fully open, on the contrary, there is a decrease in the performance of the solar dryer when the hole at the bottom of the drying chamber is fully closed.

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