

## **Drying of *Rhinacanthus nasutus* (Linn.) Kurz. using a solar dryer incorporated with a backup thermal energy storage from wood combustion**

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### **Abstract**

**Kirirat, P., Prateepchaikul, G., Navasut, J., Na Nakorn, N. and Tekasakul, P.  
Drying of *Rhinacanthus nasutus* (Linn.) Kurz. using a solar dryer incorporated  
with a backup thermal energy storage from wood combustion  
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An indirect, natural convection, solar cabinet dryer incorporated with a backup thermal energy storage from wood combustion was designed and tested with the Thai herb, *Rhinacanthus nasutus* (Linn.) Kurz. Most of Thai herbs are widely used as traditional medicine and drying is an initial step in the production process. Solar dryer with a biomass backup heating system is the most feasible solution to drying in Thailand. In this work, a 4 m x 5 m solar collector was used to absorb solar radiation for heating the incoming air during the daytime, while a biomass burner was used to supply heat when solar energy was not possible. Heat from fuelwood combustion was accumulated in the thermal storage system made of bricks, and was used to heat up the incoming air. Results showed that the herb was dried uniformly and the temperature inside the drying cabinet could be maintained above 50°C for more than 10 hours. Thermal efficiency when

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using solar energy was 10.5%, but the value was less than 1% when using the heat from biomass burning. This resulted from the low moisture content of the products after being dried by the solar energy. The dryer is beneficial to the operators, particularly in southern Thailand, where continuous drying is required. This dryer is by no means limited to drying of the herb. Currently, four dryers of the same model have been used by farmer groups in southern Thailand for drying bananas, several types of herbs, fish, and other products. In economic consideration, its payback period is 5.5 years when compared with the LPG-equipped dryer. When the total cost and production capacity are considered, its payback period is about 6 years.

**Key words :** solar dryer, thermal storage, wood combustion, herb drying

### บทคัดย่อ

ไพโรจน์ ศิริรัตน์ กำพล ประทีปชัยกูร จิรพงษ์ นวะสุทธิ ญัฐพงศ์ ณ นคร และ พีระพงศ์ ทิมสกุล การแห้งตัวของสมุนไพรทองพันชั่งด้วยเครื่องอบแห้งพลังงานแสงอาทิตย์แบบผสมผสานกับความร้อนจากไม้ฟืนซึ่งมีระบบเก็บกักพลังงาน

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งานวิจัยนี้ทำการออกแบบและทดสอบเครื่องอบแห้งพลังงานแสงอาทิตย์ผสมผสานกับความร้อนที่ได้จากการเผาไม้ฟืนและมีตัวกักเก็บความร้อนในการอบทองพันชั่งซึ่งเป็นสมุนไพรไทยซึ่งมีคุณค่าในการรักษาโรคซึ่งจำเป็นต้องผ่านการอบแห้งก่อนกระบวนการผลิต โดยเครื่องอบแห้งนี้เป็นแบบรับความร้อนผ่านแผงรับรังสี อาศัยการพาความร้อนอิสระ แผงรับรังสีที่ใช้มีขนาดกว้าง 4 เมตร ยาว 5 เมตร ทำหน้าที่ดูดซับรังสีแสงอาทิตย์และเปลี่ยนรูปเป็นพลังงานความร้อนเพื่อถ่ายเทให้กับอากาศที่ไหลเข้าตู้อบ ส่วนในเวลาที่ไม่ได้มีแสงอาทิตย์จะใช้ความร้อนจากการเผาไหม้ไม้ฟืน โดยความร้อนในส่วนนี้จะถูกเก็บสะสมในชุดเก็บกักความร้อนซึ่งใช้ก้อนอิฐเรียงซ้อนกัน ความร้อนจากชุดเก็บกักนี้จะค่อย ๆ ปล่อยให้กับอากาศที่ไหลเข้าตู้อบ จากผลการทดลองพบว่าสมุนไพรมีการแห้งตัวอย่างสม่ำเสมอ และสามารถรักษาอุณหภูมิในตู้อบให้สูงกว่า 50°C เป็นเวลายาวนานกว่า 10 ชั่วโมง ประสิทธิภาพเชิงความร้อนจากการใช้พลังงานแสงอาทิตย์มีค่า 10.5% ส่วนประสิทธิภาพเชิงความร้อนจากการใช้พลังงานความร้อนจากไม้ฟืนมีค่าต่ำกว่า 1% เนื่องจากเป็นช่วงที่ผลิตภัณฑ์ใกล้แห้งแล้ว เครื่องอบแห้งชนิดนี้มีประโยชน์และสะดวกต่อการใช้งานเป็นอย่างสูงโดยเฉพาะในภาคใต้ซึ่งมีฝนตกชุกและตกต่อเนื่องเป็นเวลานานในฤดูฝน อย่างไรก็ตามเครื่องอบแห้งนี้สามารถใช้อบผลิตภัณฑ์อื่น ๆ นอกเหนือจากสมุนไพร โดยในขณะนี้มีกลุ่มเกษตรกรในภาคใต้จำนวน 4 กลุ่มได้ใช้เครื่องอบชนิดนี้ในการอบกล้วย สมุนไพรต่าง ๆ ปลา และผลิตภัณฑ์อื่น ๆ ระยะคืนทุนของเครื่องอบแห้งนี้ประมาณ 5.5 ปี เมื่อเทียบกับซื้อเครื่องอบแห้งแบบใช้ก๊าซหุงต้ม หรือหากพิจารณาเฉพาะต้นทุนและกำลังผลิตจะมีระยะคืนทุนประมาณ 6 ปี

ภาควิชาวิศวกรรมเครื่องกล คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์ อำเภอหาดใหญ่ จังหวัดสงขลา 90112

Thailand is an agricultural country, and its products range from world famous jasmine rice to various vegetables, fruits and herbs. Most of the products need some kind of preservation to enhance their shelf life since the production usually exceeds market demand at the harvest season. Drying is one of the most used methods for product preservation, and as a result, it adds higher value to the products. Drying is a mechanism that involves

extraction of moisture from the product by heated air surrounding the product. The air can be heated by any means, e.g. electrical heater, gas burner, or solar heater, and is used to carry away the vapor released from the product until the product is dried to an acceptable moisture content level.

Traditional sun drying on the ground is the most common method for drying the agricultural products in all parts of the country. Drawbacks

of this method include unacceptable hygiene associated with the products, weather dependence, especially the effect of rainfall, inconvenience in operation since the products cannot be dried at night and need to be collected and redistributed, and unpredictable length of drying time. Moreover, the open sun drying rate is slow because of low heat supplied by the ambient air. To increase drying rate, more heat supply is necessary. A dryer can achieve this purpose by supplying more heat which in turn increases the vapor pressure of the moisture in the product, reduces relative humidity of the air, then increases its moisture loading capacity and ensures a sufficiently low equilibrium moisture content (Ekechukwu and Norton, 1999). Electrical or liquefied petroleum gas (LPG)-equipped dryers are commonly used in drying of agricultural products because of their ease of use. However, their operating cost is high due to the escalating price of energy sources. They are, thus, unaffordable to most of the farmers and farmer groups in Thailand.

Solar dryer has, therefore, played an increasingly important role in Thailand. Many types of the solar dryer have been developed by researchers worldwide, and comprehensive reviews of the dryer can be found in the literature (Sharma *et al.*, 1995; Ekechukwu and Norton, 1999; Chua and Chou, 2003). Theoretical studies, design, modeling of the solar dryer can also be found (Ratti and Mujumdar, 1997; Pangavhane *et al.*, 2002; Torres-Reyes *et al.*, 2002). Two of the most common types used are the cabinet dryer and the tunnel dryer. The solar cabinet dryer appears in either active (fan driven) or passive (natural convection) modes. Moreover, the cabinet can be transparent, so that the product inside is directly exposed to the sunlight (direct mode), or it can receive heat via a solar collector (indirect mode). Some solar dryers are designed in mixed type in which the cabinet receives heat from direct exposure and a solar collector (Tiris *et al.*, 1995; Tiris *et al.*, 1996; Ayensu, 1997; Farkas *et al.*, 1999; El-Sebaili *et al.*, 2002; Singh *et al.*, 2004; Lahsasni *et al.*, 2003). The solar collector is merely a flat surface painted black so that it can absorb maximum solar radia-

tion and convert it into thermal energy, which in turn is transferred to a flowing air. This heated air is then directed into the cabinet where the product that needs to be dried is placed, and then transfers heat to the product until it reaches an acceptable moisture content level. The cabinet dryer needs small space for the cabinet and the solar collector. The tunnel dryer, on the other hand, requires a larger space. It consists of a flat solar collector section, and a product cabinet section, which is directly downstream of the collector. The product is spread on a single layer in the trays. It is usually fan-equipped in order to increase air flow in the dryer, and it has been successfully used to dry several types of fruits (Schirmer *et al.*, 1996; Esper and Mühlbauer, 1996; Esper and Mühlbauer, 1998; Bala *et al.*, 2003).

A dryer using only solar energy may be insufficient in some locations. Most of the products require more than one full sunny day to dry and if it is placed in the dryer at night, it can reabsorb moisture from the ambient air. If excessive amount of the moisture is absorbed, the product quality can deteriorate. Moreover, in some parts where rainfall covers a long period of time, especially in southern Thailand, the use of single solar energy is definitely insufficient. This induces necessity for a backup mode of energy. A use of LPG or electricity is convenient, but this would burden owners with more fuel cost. In Thailand, the highest potential energy source is biomass which is abundant and inexpensive. Cost of rubberwood that is generally used as fuel in southern Thailand is about US\$0.0125/kg (0.5 Baht/kg). Here, 1US\$ is about 40 Baht.

Bena and Fuller (2002) designed a natural convection solar cabinet dryer with a biomass back-up heater. It was a direct type dryer with a biomass burner situated below the cabinet. Brick was employed as a thermal storage for the biomass burning. The cabinet walls were made of clear polyethylene sheet. The trays were made of wire mesh so that air could flow through the trays from the bottom to the vents above the top shelf. Effective drying area for the product is about 3 m<sup>2</sup>. Results showed that the burner and thermal storage

can supply heat for an entire night. However, no details of temperature in the drying cabinet were given. In our previous work (Promtong *et al.*, 2003), a solar cabinet dryer with a biomass backup heat exchanger was built and studied. No thermal storage system was equipped, however. While it can work without disruption from bad weather, it was inconvenient to use since it requires a periodic supply of fuelwood.

In this work, we have designed a solar dryer that incorporates a backup thermal energy storage from wood combustion for drying of a selected herb grown in the south of Thailand named *Rhinacanthus nasutus* (Linn.) Kurz.. This herb is commonly known as Thong-Pan-Chung and it is in the family of ACANTHACEAE. The part of the plant that is used for medication purpose is the leaf. It is used to relieve colds, fever, early stage of tuberculosis, headache from hypertension, constipation and sore throat. It can also refresh the lungs, and reduce blood pressure (Cheeptham and Towers, 2002). Drying is an initial step in the production of the medicine before being ground or subsequently processed. Many of the herbal products are currently promoted by the Thai government as selected products in community project called "One Tambon One Product" or OTOP. Here, a tambon is a community of several villages where groups of farmers initiate their products. The need for solar dryers that can be used conveniently is, thus, inevitable. Solar drying of some herbs were performed in a greenhouse-type solar dryer (Müller *et al.*, 1989) and a wire basket solar dryer (Balladin and Headley, 1999)

### Design of the dryer

The solar dryer designed and used in this project is an indirect type as shown in Figure 1. It is sturdy and rugged. The solar collector (1) with an area of 4.5 m<sup>2</sup> is made of a corrugated steel sheet painted solid black. A burner (2) for fuelwood combustion is equipped to supply heat so that continuous drying is made possible when solar radiation is insufficient. Two slots for air flow into the drying cabinet are located directly below the

collector. The slot that is adjacent to the collector (3) is used to heat the air flowing into the cabinet by the solar collector while the slot at the bottom (4) is used for the air to receive heat from the thermal storage system (5) directly below it. This storage system consists of about 1,500 pieces of construction brick ( $C_p = 960$  J/kg K). It accumulates heat from the combustion of fuelwood in the burner and slowly radiates it to the flowing air and the drying cabinet (6). The flowing air that picks up moisture from the product in the cabinet is exhausted to the surroundings via a 6-m-high chimney (7) by natural convection. This chimney is also used for the exhaust of the combusted gas. Part of the exhaust gas is used to heat the cabinet via the space around it (8) except the bottom surface and the door side. The inside wall of the drying cabinet is lined with stainless steel sheet to meet food safety criteria. The shelves and trays are all made of stainless steel as well. The cabinet is insulated by 2-inch-thick fiberglass and its outside wall is covered with aluminum sheets. The drying cabinet is designed so that the air can flow over the product in the tray in a staggering manner as shown in Figure 1. This is different from most of the dryers where the trays are porous and air flows from the bottom shelf to the top. This induces a high pressure drop in the cabinet and can retard the drying rate. Moreover, it is not suitable for some products that are soaking wet initially, such as fish, since water in the product will drip down and cause a moisture pickup for the product at the lower shelves, and result in an undesirable accumulation of water at the bottom of the cabinet. The dryer designed in this research avoids these problems.

The passage of the hot gas in the thermal storage system is shown in Figure 2. The combusted gas is forced to flow in a groove on one side of the storage, and then flow across the stack of bricks through the channels to the passage on the other side before exhausting through the chimney, also by natural convection. At the beginning of the combustion, the butterfly valve (9) is fully open in order to enhance the combustion and flow of the combusted gas. After the fuelwood is well

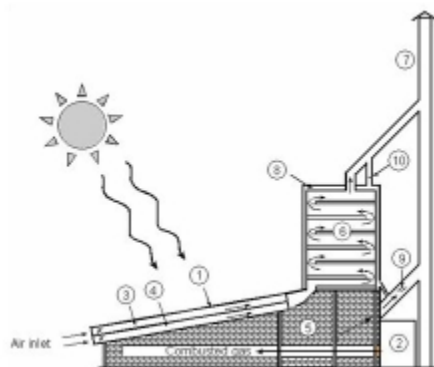


Figure 1. A solar dryer with backup thermal energy storage used in this work.

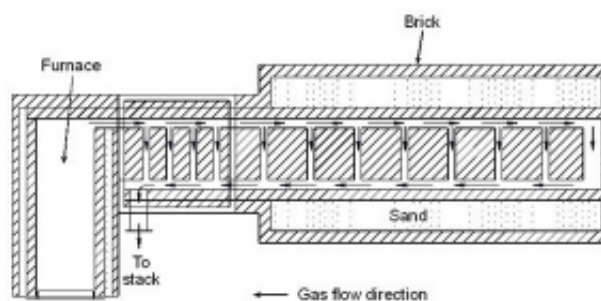


Figure 2. Cross section of the thermal storage system showing passage of the combusted gas.

combusted, this valve will then be closed, and the gas will only exhaust through the stack via the space in the cabinet and valve (10). This is to minimize heat loss and to keep the temperature in the drying cabinet high for long periods of time.

### Experiments

Typical parameters in studying the drying characteristics of the products and the dryer performance includes (Leon *et al.*, 2002)

- Product mass or moisture content
- Relative humidity
- Temperature
- Air flowrate
- Solar radiation
- Mass of fuelwood
- Solar collector efficiency
- Thermal efficiency of the dryer
- Specific moisture extraction rate

Measurement positions of temperature, relative humidity, and product mass are indicated in Figure 3. Temperature of air inside the drying cabinet was measured at the bottom, middle and top shelves (positions 1-7) while the temperature inside the thermal mass storage was measured at position 8 and 9 using type-K thermocouples connected to a selector switch and a temperature readout. Ambient temperature was also measured in the same manner. Relative humidity in the cabinet was measured at the center positions of the bottom, middle and top shelves (positions 1, 2 and 7) using a relative humidity probe (Wm Model HTA4200). Product mass of the sample was measured at positions 1-7 as shown in Figure 3 using a digital balance (UWE Model DB-600). Moisture content ( $MC_{db}$ ) on a dry basis was then calculated from the mass of the product:

$$MC_{db} = \frac{m_p - m_d}{m_d} \times 100\% \quad (1)$$

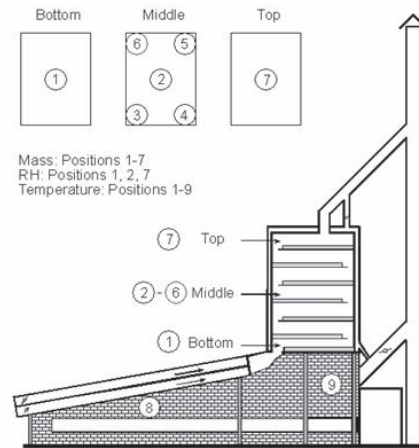


Figure 3. Positions for data measurements in the cabinet and the thermal storage system.

where  $m_p$  is the product mass at any instant, and  $m_d$  is the mass of the dry product which was evaluated when it was totally dried using a lab-scale electric heater (Mammert Model 400). Both the temperature and product moisture content at the middle shelf were measured at five positions in order to investigate spatial variations in the drying cabinet at the same shelf. Air flowrate was calculated from air velocity measured at the collector inlet using a hot-wire anemometer (Airflow developments Model TA400T). Solar radiation was measured at the center of the solar collector using a pyranometer with integrator (KMUTT). This pyranometer could read the radiation intensity, in  $W/m^2$ , and accumulate solar energy, in  $kW-h/m^2$ , using an integrator. In this experiment, radiation intensity was recorded once every hour. Solar collector efficiency ( $\eta_{sc}$ ) can then be calculated from

$$\eta_{sc} = \frac{q}{IA} \tag{2}$$

where  $I$  is the solar radiation energy flux,  $A$  is the collector area, and  $q$  is the thermal energy transferred to the flowing air which can be determined from

$$q = m_a C_p (T_i - T_o) \tag{3}$$

Here  $m_a$  is the amount of air flowing into the cabinet during the period of drying and can be

determined from the air flowrate,  $C_p$  is the specific heat of air,  $T_i$  is air inlet (ambient) temperature, and  $T_o$  is the temperature of air leaving the collector surface and flowing into the drying cabinet.

Since there was no standard parameters used in performance analysis (Bena and Fuller, 2002), thermal efficiency was employed in this work. Because this dryer could operate in two modes, i.e. solar energy and thermal energy from fuelwood combustion, the thermal efficiency can be considered as thermal efficiency using solar energy ( $\eta_{th,solar}$ ), thermal efficiency using fuelwood ( $\eta_{th,wood}$ ), and overall thermal efficiency ( $\eta_{th,all}$ ). These can be calculated, respectively, from

$$\eta_{th,solar} = \frac{m_{L,solar} L}{IA} \tag{4}$$

$$\eta_{th,wood} = \frac{m_{L,wood} L}{m_{wood} HV_{wood}} \tag{5}$$

and

$$\eta_{all} = \frac{m_L L}{IA + HV_{wood} m_{wood}} \tag{6}$$

where  $m_{L,solar}$  is the moisture removed from the product by solar energy,  $m_{L,wood}$  is the moisture removed from the product by wood combustion,  $m_L$  is the total moisture removed from the product,  $L$  is the latent heat of vaporization,  $m_{wood}$  is the mass of the fuelwood, and  $HV_{wood}$  is the (lower)

heating value of the fuelwood, which is dependent on its moisture content (Khullar, 1995).

One parameter that is usually used to evaluate performance of the dryer is the specific moisture extraction rate (SMER) that is defined as the ratio between moisture removed to the total energy input (Ratti and Mujumdar, 1997). This can be determined, for each mode or overall, as in the case of thermal efficiency, by removing the latent heat of vaporization term from Eqs. (4) to (6). Inverse of the specific moisture extraction rate is called *specific energy consumption*.

In this experiment, each parameter was measured every three hours, except the solar radiation energy flux which was recorded once every hour. When using the fuelwood as a heat supply, 41.8 kg of wood was initially loaded and burned. No additional wood was needed to keep the temperature in the drying cabinet at the desired level for the period of 10 to 14 hours.

## Results and Discussions

### Drying conditions and characteristics

Drying of *Rhinacanthus nasutus* (Linn.) Kurz. was accomplished in 23 hours when solar energy was used for nine hours and fuelwood was used afterwards. A total of 41.8 kg of fuelwood was used. Average moisture content of the fuelwood was 13.1% dry basis. Total initial mass of the herb prior to drying was 5.2 kg.

The solar radiation pattern during the drying of *Rhinacanthus nasutus* (Linn.) Kurz. is shown in

Figure 4. Total insolation for nine hours of drying was  $3.97 \text{ kW-h/m}^2$  which was equal to total energy of 64.3 MJ for a  $1.5 \text{ m} \times 3.0 \text{ m}$  solar collector. The collector efficiency was found to be 23.0% for an average air flowrate of  $0.035 \text{ m}^3/\text{s}$ . Air temperatures at different positions are shown in Figure 5. Ambient temperature was highest at  $35^\circ\text{C}$  during the daytime, and the nighttime ambient temperature was slightly below  $30^\circ\text{C}$ . The temperature at the bottom shelf (position 1) was found to be highest during the daytime while the temperature at the top shelf (position 7) was lowest. This could be expected since the air had transferred heat to the herbs as it flowed in the cabinet. During the nighttime when the fuelwood was used, the temperature at the bottom shelf was slightly less than that of the middle shelf. This was because the inlet air relative humidity was higher at night (Figure 6). The temperature at the top shelf was, however, still lowest until at the end of the drying when all the temperatures in the drying cabinet were nearly identical. At the middle shelf, where temperature was measured at five positions, it could be seen that temperatures at all positions were almost identical. This indicated the minimal spatial variation of temperature, and that non-uniform drying at the same shelf could be prevented. The relative humidity of air in the cabinet was nearly identical for all shelves measured during the daytime as also shown in Figure 6. However, the humidity at the bottom shelf was highest during the nighttime, as expected.

Moisture content (dry basis) of the herb as

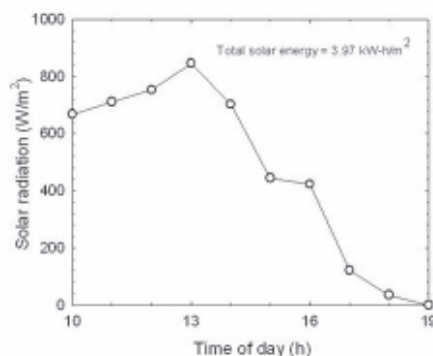


Figure 4. Pattern of solar radiation during the drying of *Rhinacanthus nasutus* (Linn.) Kurz.

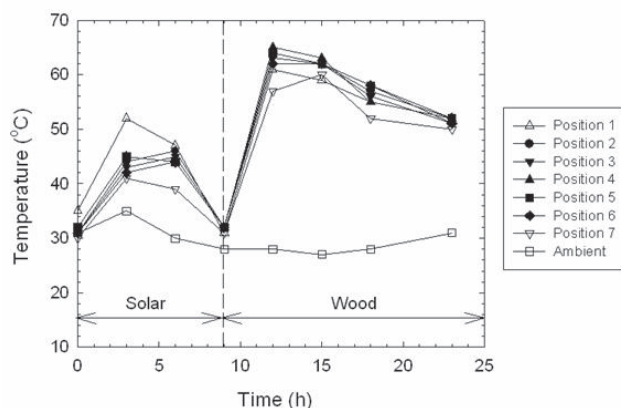


Figure 5. Variations of temperature in the cabinet and ambient temperature during the drying of *Rhinacanthus nasutus* (Linn.) Kurz.

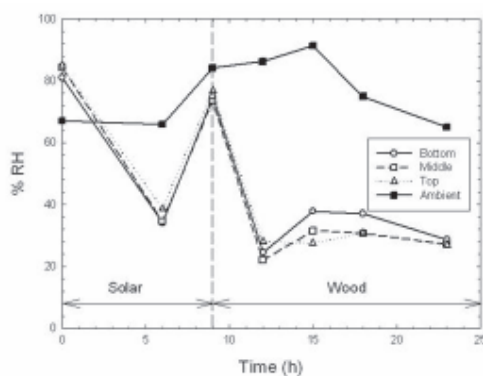


Figure 6. Variations of relative humidity in the cabinet and ambient humidity during the drying of *Rhinacanthus nasutus* (Linn.) Kurz.

a function of time is shown in Figure 7 for the samples at seven positions. Initial moisture content of the samples varied from about 215 to 360% with an average of 268%. The reason for high variation of the initial moisture content is that the herb was washed prior to drying and only the moisture content at position 5 was distinctively high. Most of the herb was dried (moisture content less than 16% d.b.) after 12 hours except at the top shelf (position 7). It was, however, all dried after 15 hours. The herb was dried continuously overnight for a total drying time of 23 hours where the average final moisture content was 3.7%. The herb at the bottom shelf dried fastest while the herb at the top shelf dried slowest. This suggested that switching of the herb between the top and bottom

shelves after six hours should give a more uniform drying in a shorter time. Two drying modes, i.e. the falling rate period, and the saturated period, were obviously seen.

### Performance of the dryer

The thermal efficiency when using solar energy ( $\eta_{th,solar}$ ) calculated from Eq. (4) was 10.5%. The efficiency using fuelwood ( $\eta_{th,wood}$ ) following solar energy drying calculated from Eq. (5) was 0.23%. This is particularly low and is misleading since drying was almost complete when using solar energy alone, but the drying was allowed to continue until the moisture content was considerably lower than the necessary level (16% d.b.). Only small amount of moisture was removed after



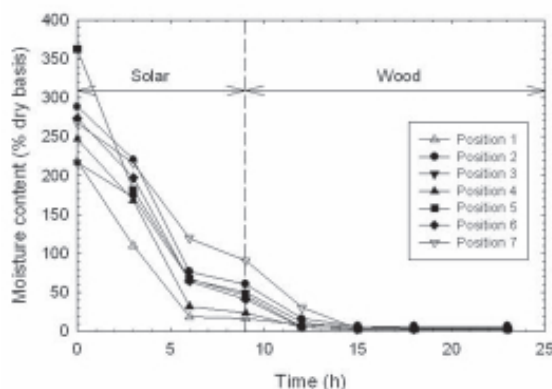


Figure 7. Variations of moisture content of *Rhinacanthus nasutus* (Linn.) Kurz. at seven positions in the cabinet during the entire drying period.

9 hours. This resulted in a low overall thermal efficiency ( $\eta_{th,all}$ ) of 1.1%. These can be increased by immediately replacing the herb after 12-15 hours of drying to prevent using the heat to unnecessarily dry the already dried herb. The specific moisture extraction rate was found to be 4.66 g/MJ.

**Effect of the thermal storage system**

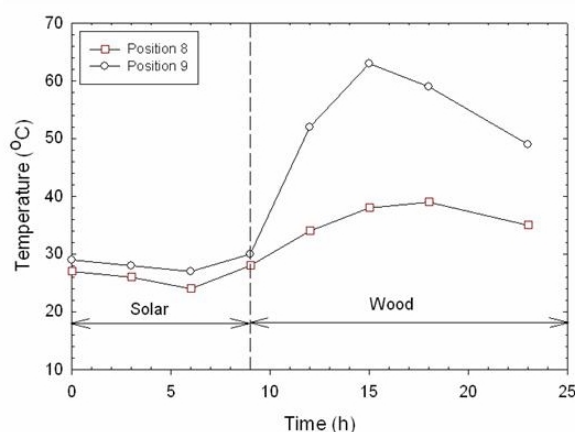
The effect of the thermal storage system located under the solar collector and cabinet is shown in Figure 8. Temperature in the middle of the storage under the mid point of the solar collector (position 8) during the nighttime rose to about 10-15°C above its temperature during the daytime when solar energy was used. This played a part in the relative humidity reduction of flowing air, which is quite high during the night. Note that the temperatures in the thermal storage during the daytime are about 4-8°C lower than the ambient temperature. This is because the experiment began several days after it was last operated which resulted in the low temperature of the bricks since they are quite a good insulating material. The temperature under the cabinet (position 9) using fuelwood was about 30°C above its temperature during the daytime, and it dropped by only 10°C after 12 hours. This indicated that plenty of heat still remained in the storage. This is beneficial to the operators, particularly in southern Thailand

where rainfall can at times continue for many days without a glimpse of sunlight. Drying period could, thus, be greater than 12 hours for a single supply of fuelwood. However, when using fuelwood together with solar energy, the amount of fuelwood supplied may be reduced to increase the overall thermal efficiency.

**Economics consideration**

In this section payback periods of the solar dryer have been considered. The payback period based on the comparison with the popular LPG-equipped dryer, as well as that based on the total cost and production capacity are calculated. The capacity for one period of drying was 5.2 kg of fresh product.

Total cost of the solar dryer was about US\$ 2,750 (US\$1 = 40 Baht). When using the solar dryer, we assumed that the product required 9 hours of operation using solar energy and 6 hours using fuelwood. The solar energy cost was zero. Fuelwood consumption was about 3 kg/hr. The cost of fuelwood in Thailand was about US\$0.0125/kg. Then, the cost of fuelwood was about US\$0.04325/kg of product. Assuming year-round drying of 365 days in which the total amount of product was about 1,900 kg, the total annual cost of fuelwood would be about US\$82.25. The annual maintenance was assumed to be about US\$25. Hence, the total annual operating cost was US\$107.25.



**Figure 8.** Variations of temperature in the storage system during the drying of *Rhinacanthus nasutus* (Linn.) Kurz.

The cost of LPG-equipped dryer of the same capacity was US\$1,625. The drying of the same capacity product required 12 hours. Using the LPG lower heating value of 47,310 kJ/kg, and assuming that the dryer overall thermal efficiency was 15% in general, the total annual cost of LPG was US\$ 308.75. Here the cost of LPG was US\$7.50/ container of 15 kg. The annual maintenance was about US\$2.50. Then the annual operating cost was US\$311.25. Finally, the payback period of the solar dryer compared with the LPG-equipped dryer was calculated to be about 5.5 years. The financial internal rate of return (FIRR) was calculated to be 15.07% while the economics internal rate of return (EIRR) was 33.01%. These values were based on the equal life time of 10 years for both dryers.

The payback period based on the total cost and production capacity can also be calculated. The profit from drying the herb is about US\$0.25/ kg of fresh product (figures from discussion with farmers). Using the same figures in the calculation, the annual profit of drying the herb is about US\$ 475 and the payback period is about 6 years.

### Conclusion

The solar dryer incorporated with a backup thermal energy storage from wood combustion presented in this work is appropriate in the drying of herbs or other agricultural products because of

its convenience of use. Single supply of fuelwood of about 40 kg can maintain the temperature in the cabinet above 50°C for more than 10 hours. Even though its overall thermal efficiency is quite low, it is beneficial to the operators, particularly in southern Thailand where continuous drying is required during rainy season when rainfall can spread over a long period of time. However, when using fuelwood together with solar energy, the amount of fuelwood supplied should be reduced in order to increase the overall thermal efficiency. This dryer is by no means limited to the drying of the herb. Currently, four dryers of the same model have been used by farmer groups in southern Thailand for drying bananas, several types of herbs, fish, and other products. Its payback period is 5.5 years based on the equivalent LPG-equipped dryer, and 6 years based on the total and production capacity.

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