Specific Energy Consumption of Heat Pump Drying System

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Abstract

The study developed a heat pump dehumidifier (HPD) dryer prototype incorporating an external condenser. The main feature of the HDP dryer prototype is its capability to adjust the drying air temperature and moisture content depending on the drying requirements of a particular product. It consisted of 90cm x 56cm x 61cm (length, width & height respectively) drying chamber and 4 layers of tray system and each layer has 1 tray. The tray has a dimension of 46cm length and 37cm width respectively. A 1.5 hp (1.12kW) piston compressor. Mango was used in the experiment as a test sample product. Three test sample loads were experimented, namely: 170g, 340g and 510g which were dried in the HPD dryer system for a drying air temperature of 40 ^oC and drying air velocity of 0.7 m/s. The specific moisture evaporation rate (SMER); and the specific energy consumption (E_{kg}) for both wet and dry products were calculated using the measured data. The amount of moisture evaporated to reach the final moisture content of 15% wet basis was calculated and the energy consumed was determined in kilowatt-hour meter from the measured value. The results revealed that there is reduction of energy consumption as product load is increased.

***Keywords**:* energy consumption, heat pump dryer, specific energy consumption, specific moisture evaporation rate

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1. Introduction

Drying is one of the oldest methods of preserving food. It is a process in which moisture is removed from a solid using heat as the energy input. Drying is a common unit operation in food processing facilities to lower the moisture content of foods in order to reduce water activity and prevent spoilage or reduce the weight and the volume of food products for transport and storage. In many agricultural countries large quantities of food products are dried to improve shelf life, reduce packaging costs, lower shipping weights, enhance appearance, retain original flavor, and maintain nutritional value (Sokhansanj and Jayas, 2006).

As an energy intensive process, drying is a complex operation involving combined heat and mass transfer. It is a process with high energy requirement forming about 60 percent of total energy need for production of food products such as cereals. This amount of energy consumption is considerable compared with the average energy consumption figures in tillage (16%), planting and protection (12%), harvest (6%) and transport (6%) (Motevali *et al.*, 2011). A large proportion of the energy required within the food industry is used to remove water from food products. About 6.2×10^9 J energy is used to produce one ton of food crops with current technology. More than 24% of this amount is needed for the drying process (Wang and Chang, 2001).

Heat pumps have been used extensively by industry for many years, but less for drying process. An improved dryer with energy recovery can reduce the total energy requirement. A heat pump is attractive because it can deliver more energy as heat than it consumes in electrical energy (Harchegani *et al.*, 2012). Thus, to increase the benefit of the dried product production, an energy efficient dryer should be applied for food drying. The objective of the study is to determine the energy consumption and the specific energy consumption at each different sample load (i.e., 170g, 340g and 510g) of wet product and dry product in the experiment.

2. Methodology

2.1 Experimental Description/Setup

A closed-loop system laboratory scale heat pump dryer prototype used in this experimental research was fabricated. The schematic diagram of the heat pump dehumidifier (HPD) dryer system is shown in Figure 1. The dryer is a closed insulated chamber which consists of a heat pump dehumidifier unit. It is composed of an evaporator, main condenser and fan. They were located at the lower portion of the enclosure and an external condenser with fan has motor rated at 40W located at the back side of the same level at the lower portion of the enclosure and a drying chamber located at its upper portion of the enclosure.

The compressor (1.5 horsepower), which has fan and motor rated at 40W, is placed at the bottom of the enclosure. Trays were stacked in the drying chamber to support the drying material. The HPD unit, which provided the heating and cooling/dehumidification for the process air, is in the dryer. The fan inside the dryer was used to drive the process air through the coils and fins. It also provided the airflow for the re-circulating circuit. The door of the chamber (i.e. cabinet type) was sealed to avoid air leaks. The refrigerant R-22 was used as the working fluid of the HPD dryer system.

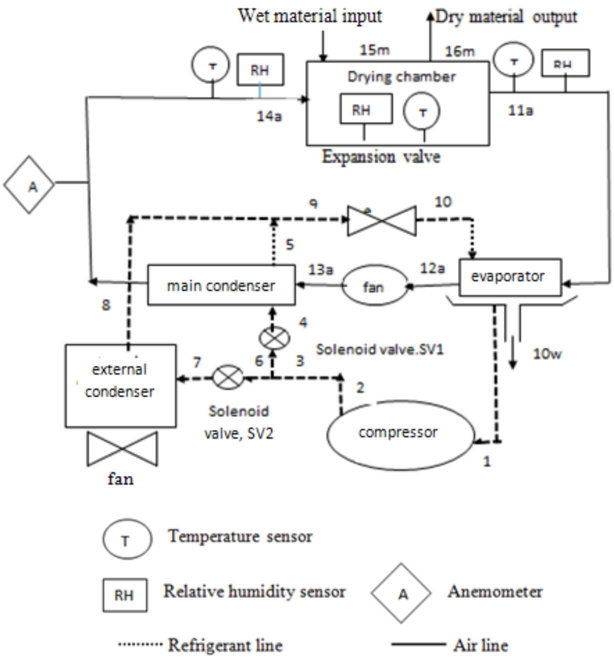

Figure 1. Schematic diagram of a heat pump dryer incorporating external condenser

2.2 Experimental Material

Bought from the local market at Cogon market, Cagayan de Oro City, Philippines, fresh mangoes were used as test sample products. The mango was peeled, sliced with stainless steel knife into different dimensions while its seed and skin were discarded. The thickness of the sliced mango was measured using vernier caliper. The sliced mango was weighed and packed for initial moisture content analysis. The remaining slices of mango were spread uniformly in the perforated plastic trays; they were then placed inside the drying chamber.

2.3 Experimental Apparatus

The developed and fabricated laboratory scale HPD dryer prototype incorporating an external condenser was shown in Figure 1. It has a new air-conditioning unit with a refrigerating capacity of 2 kW. The unit was modified by incorporating an external condenser with fan at rated motor power of 40W. The compressor is 1.5 hp (1.12kW) with cooling fan at rated motor power of 40W. There were two solenoid valves. One solenoid valve was placed before the port of an external condenser and the other one was located before the entrance of the main condenser after the discharge port of the compressor. An insulated drying chamber was built at the upper portion of the heat pump dryer unit. Inside the drying chamber were four perforated plastic trays fastened in a wood frame and air relative humidity and temperature sensors (humidity accuracy ± 2% rh and temperature accuracy ± 0.5 Celsius) and pressure sensor (accuracy ± 1.5% maximum error). Air relative humidity and temperature sensors (humidity accuracy ± 2% rh and temperature accuracy ± 0.5 Celsius) were installed at the entrance and exit of the drying chamber and in between evaporator and main condenser. Digital hot wire anemometer (velocity accuracy ± 5% of reading ± 3 digits) was inserted in the wall through a hole in between the main condenser and entrance of the drying chamber to measure the air velocity. One pressure sensor was installed at the top of the body of the dryer unit to measure the ambient pressure.

A microcontroller connected to a personal computer (PC) was installed on the side of the body for data logging. A digital high precision balance (accuracy 0.01g) was placed near the dryer unit for weight measurement. All electrical wiring connections from the dryer unit and accessories were connected to analog kilowatt-hour meter to measure the energy consumed of the HPD dryer system. The mass of water evaporated from the material being dried was measured using a digital high precision balance, all measurements were taken and recorded manually.

2.4 Experimental Procedure

The drying experiment was performed for each different wet sample load of 170, 340 and 510 gram for four trays inside the drying chamber. The test sample was placed in the perforated plastic tray. The weights of perforated plastic tray and test sample were measured using a high precision balance. The drying air entered the drying chamber at 40 ^{o}C dry bulb temperature with an air mass flow rate of 0.047 kg/s and drying air velocity of 0.7 m/s. Moisture loss was determined by weighing the test sample before and after the drying process of the experimentation. The tray with the test sample was taken out from the drying chamber and weighed on the digital high precision balance. The drying experiment was stopped when the calculated final moisture content of the dried sample reached 15% wet basis or less else continued. It was then repeated in triplicate.

2.5 Data Analysis

In the drying process the moisture content of the material was changing with time and the moisture content was calculated by moisture content, specific moisture evaporation rate, energy consumption and specific energy consumption.

2.5.1 Moisture Content

The equation for calculating moisture content on any drying material based on wet basis (w.b.) is given by:

$$\% \text{ moisture content (w.b.)}, X^{*} = \frac{mass\ of\ moisture}{total\ mass\ of\ moist\ material} = \frac{m_m}{m}$$

$$= \frac{m - m_{bd}}{m} \text{ x } 100 \qquad (2.1)$$

where, m_m is the mass of moisture (kg), m_{bd} is bone dry mass (kg) and m is the total mass of moist material (kg).

and for moisture content on dry basis (d.b.) was given by:

$$\% \text{ moisture content (d.b.)}, X = \frac{mass\ of\ moisture}{bone\ dry\ mass} = \frac{m_m}{m_{bd}} = \frac{m - m_{bd}}{m_{bd}} \text{ x } 100 \qquad (2.2)$$

Calculating the moisture that would be lost during drying from an initial moisture content, X_i to a final moisture content, X_f can be formulated as follows. As an initial mass of a drying material, m can be denoted m_i and it consists of the initial mass of moisture, m_{mi} and bone dry mass, m_{bd}, that is:

$$m_i = m_{mi} + m_{bd} \text{ , while } X_i = \frac{m_{mi}}{m_{bd}} \text{ and } \quad m_{mi} = X_i\, m_{bd} \tag{2.3}$$

Therefore,

$$m_i = m_{mi} + m_{bd} = X_i\, m_{bd} + m_{bd} = m_{bd}\,(1+X_i) \tag{2.4}$$

Similarly, the final mass of material after drying m_f can be stated as:

$$m_f = m_{bd}\,(1+ X_f) \tag{2.5}$$

The moisture loss of the material after drying can be written as:

$$m_i - m_f = m_{bd}\,(1 + X_i) - m_{bd}\,(1 + X_f) = m_{bd}\,(X_i - X_f) \tag{2.6}$$

Therefore, the moisture loss of the drying product is the difference between the weight of the wet product and the weight of the dried product. It is related to the bone dry mass and the moisture content dry basis (d.b.) of the product.

The results related to energy consumption, specific moisture evaporation rate (SMER), amount of moisture evaporated and specific energy consumption can be calculated from the readings obtained from the three air relative humidity and temperature sensors, one digital hot wire anemometer, kilowatt-hour meter, digital high precision balance, psychrometric properties and computer aided- thermodynamic properties.

2.5.2 The Specific Moisture Evaporation Rate

The SMER is a performance indicator that is widely used to define the performance of heat pump dryer system, SMER is defined as

$$\text{SMER} = \frac{\text{Amount of moisture evaporated}}{\text{Energy input to the dryer system}} \text{ , (kg water / kWh)}$$

$$\text{SMER} = m_{w,e} / W \tag{2.7}$$

where, $m_{w,e}$ = amount of moisture evaporated, kg/h

$m_{w,e}$ = measured initial mass of sliced mango before drying minus measured final mass of sliced mango after drying = $m_i - m_f$

W = measured total energy input, or

W= work of compression + fan/blower work; thus, in equation form it can be stated as

$$W = W_c + W_f \tag{2.8}$$

where, W_c is work of compression and W_f is the fan work

2.5.3 Energy Consumption

The total energy consumption denoted as E_t of the heat pump dehumidifier dryer system was determined from the measured reading at the analog kilowatt-hour meter. However, this energy consumption can be calculated using the following relationship:

$$\text{Total energy consumed, } E_t = V \times I \times t \times PF \tag{2.9}$$

where,

where,	E_t	=	Total energy consumed, (kWh)
	V	=	Voltage, (V)
	I	=	Current, (A)
	t	=	operating time, (hour)
	PF	=	Power Factor

2.5.4 Specific Energy Consumption, E_{kg}

The specific energy consumption needed for drying a kilogram (kg) of wet product was calculated using equation 2.10 (Motevali *et al.*, 2011; Koyuncu *et al.*, 2004) as

$$E_{kg} = \frac{E_t}{W_o} \tag{2.10}$$

where, E_{kg} is the required specific energy consumption, kWh/kg and
W_o is the initial weight of wet sample, kg
E_t is the total measured energy consumption, kWh

However, this specific energy consumption could also be calculated using equation 2.11. This is the energy consumed per unit mass of dry product. This parameter has economic significance (Zeki Berk 2009).

$$E_{kg\ dry} = \frac{E_t}{W_f} \tag{2.11}$$

where, W_f is the final weight of dried product, kg

3. Results and Discussion

3.1 Heat Pump Dehumidifier (HPD) Dryer Prototype

The fabricated HPD dryer incorporating an external condenser was built and tested as shown in Figure 2. The body of the unit was made up of plywood and supported with a wood frame. The whole body was insulated with one sided polyethylene foam insulation. It has a new air-conditioning unit with a capacity of 2 kW. The unit was modified by incorporating an external condenser with fan rated 40W and two solenoid valve placed before the port of the main condenser and the other before the port of the external condenser in between the discharge port of the compressor.

Figure 2. Fabricated heat pump dehumidifier dryer prototype

3.2 Drying Air Temperature

The developed dryer configuration and its main feature attained low drying air temperature and moisture content depending on the drying requirements of a particular fruit. The temperature profile in which this dryer configuration can attained during drying process or operation is in Figure 3 which exhibits the drying air temperature at 40°C at different sample load (i.e., 170g, 340g and 510g) for four trays per batch drying. Before the start of the drying process the drying air temperatures were set to the desired operating temperature, that is, 40°C. It also indicates the drying air temperature entering the drying chamber (leaving in the main condenser).

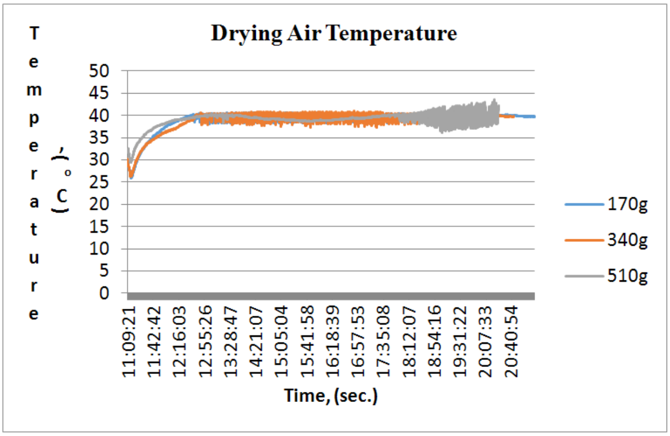

Figure 3. Drying air temperature over time

As shown in Figure 3, less fluctuation can be observed, and the drying air temperature can be maintained at almost constant temperature. It can be noted that the dryer design configuration can attain low drying air temperature in this case 40°C being used during the drying process. The result indicates that the drying time changed for each test load sample (i.e., 170g, 340g and 510g) per batch drying. It was found that the drying time decreased when the weight of the test load sample was increased.

3.3 Drying Air Relative Humidity

Figure 4 shows the graph of drying chamber inlet air relative humidity over time at different test load sample per batch drying at 40°C drying air temperature. The result show that drying chamber inlet air relative humidity has reached below 20% and above 10% for each test sample load per batch drying. It was found that this dryer system can attain an air relative humidity below 20%. Low relative humidity promotes faster drying.

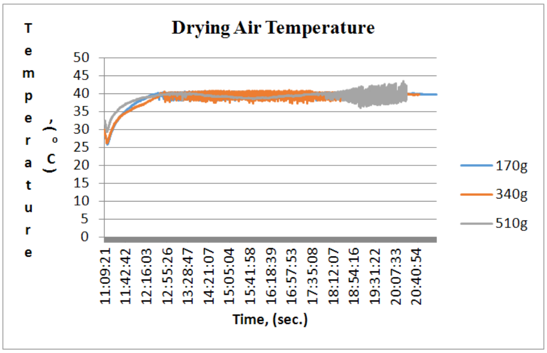

Figure 4. Drying chamber inlet air relative humidity over time

Figure 5 shows the graph of drying chamber outlet air relative humidity over time at different test load sample per batch drying at 40°C drying air temperature. The result reveals that the drying chamber outlet air relative humidity has reached 20% above up to 25%. It was found that there was an increase in the air relative humidity at the exit of the drying chamber due to drying air absorbed moisture from evaporating dried surface.

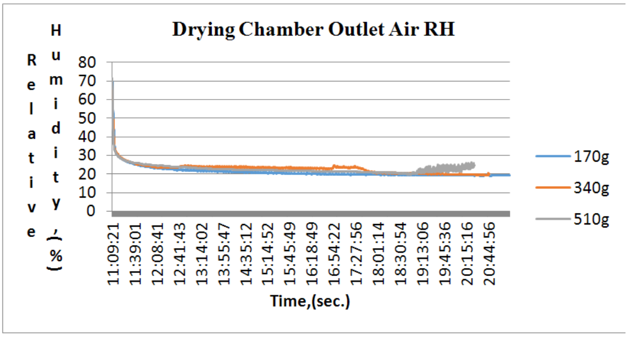

Figure 5. Drying chamber outlet air relative humidity over time

3.4 Moisture Content

The drying process was well represented by the drying curve that gives information about the variation of the moisture content of the product with time. Figure 6 shows the variation of the average sample weight over drying time per batch drying and the general trend of the curves with the influence of the operating conditions.

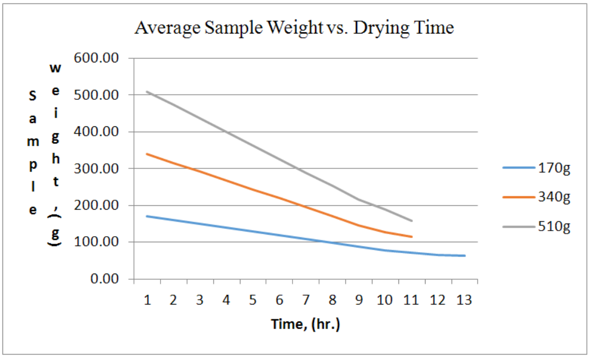

Figure 6. Average sample weight over drying time

It was found from the experiment that the sample weight reduced gradually over drying time. This was caused by the loss of water from the sample. The moisture removal decreased as the drying process progressed due to the decrease of moisture content of the sample to reach the final moisture content.

3.5 Calculation of SMER

The SMER is a parameter used to describe the performance number that considers both dryer and heat pump system. It is defined as the mass of water evaporated or removed from the product, (kg), and the required input energy, (kWh). The SMER is a specific way to describe the drying efficiency. The SMER of the dryer system can be determined using equations 2.7 and 2.8. The total energy input was taken from the actual reading of the analog kilowatt-hour meter.

The reduction of the moisture or water content of the sample for 40^{o}C drying air temperature for different test sample load was shown in Fig. 3.5. The recorded heat pump dehumidifier dryer system average energy consumed from the start of drying to the end were 14.9 kWh, 13.2 kWh and 12.5 kWh for 170g, 340g and 510g, respectively . The average amount of moisture loss or water evaporated from the sample was calculated using equation (2.6) and the value were 408.58g, 835.11g and 1342.43 for 170 g, 340g and 510g test sample load, respectively. Also, the result shows that by using equation (2.7), the calculated heat pump dehumidified dryer system average SMER were 0.0274 kg/kWh , 0.0633 and 0.1074 kg/kWh for 170g, 340g and 510g sample load, respectively.

It can be observed in Table 1 that the SMER incurred an increased amount of moisture evaporated. This result agrees to the findings of Marnoto *et al.* (2012) and Karabacak and Atalay (2010) who conducted drying test of curcuma and tomatoe, respectively. To increase the value of SMER more water should be removed during the drying process, that is, increasing the material mass flow rate through the dryer and relatively increased the relative humidity of the process air. The SMER increases with an increase in humidity in the dryer (Rahman and Perera, 2007). The value of SMER at 40^{o}C drying air temperature for 170g, 340g and 510g sample load and the amount of water evaporated and the energy consumed during the drying process are shown in Table 1.

Table 1. Specific moisture evaporation rate

Sample Load, (g)	Amount Water Evaporated, (g)	Energy Consumed, (kWh)	SMER, (kg/kWh)
170	408.58	14.9	0.0274
340	835.11	13.2	0.0633
510	1342.43	12.5	0.1074

3.6 Energy Consumption

The energy consumption of the heat pump dehumidifier dryer was determined from the actual reading measured in the analog kilowatt-hour meter. The energy consumption during the experiment at different sample load per batch drying was shown in Figure 7 below. It showed that there was a decreased in the energy consumption when the sample load per batch drying was increased. The values were 14.9, 13.2 and 12.5 kWh for sample load 170, 340 and 510g, respectively.

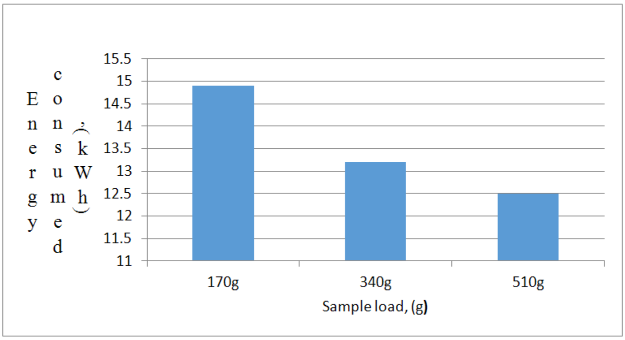

Figure 7. Energy consumption for a charge of the dryer at different sample load

3.7 Specific Energy Consumption

3.7.1 The specific energy consumption needed for drying a kilogram of wet product

The specific energy consumption for drying a kilogram of wet product were determined for all sample loads using equation 2.10. Figure 8 showed the specific energy consumption was decreasing when the sample load increased per batch drying.

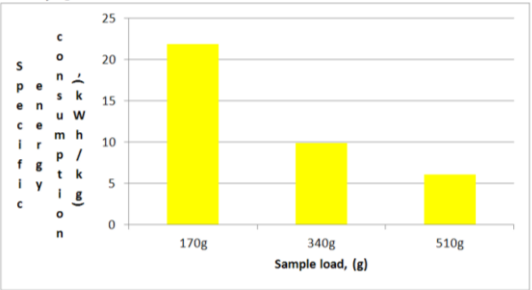

Figure 8. Specific energy consumption for drying a kilogram of wet product

It was found that the values were 21.9, 9.9 and 6.1 kWh/kg wet product for 170g, 340g and 510g sample loads, respectively.

3.7.2 The specific energy requirement for drying a kilogram of dry product

The specific energy requirement for drying a kilogram of dry product was determined for all sample loads using equation 2.11. Figure 9 shows the specific energy requirement was decreasing when the sample load increased per batch drying. It was found that the values were 54.8, 26.8 and 17.9 kWh/kg dry product for 170g, 340g and 510g sample loads respectively.

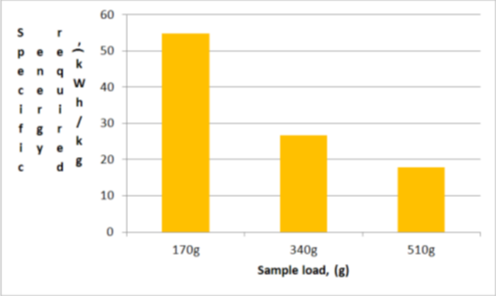

Figure 9. Specific energy requirement for drying a kilogram of dry product at different sample loads

The total energy consumption for a charge of the dryer and the specific energy requirement needed for drying a kilogram of products can be seen in Figs. 3.6, 3.7 and 3.8. There was a strong correlation between these three figures because of the fact that the values of Figs. 3.7 and 3.8 were obtained from the value of Fig. 3.6 by calculating equations 2.10 and 2.11. It was found that from these figures, the minimum energy required (6.1 kWh/kg of wet product and 17.9 kWh/kg of dry product) is needed for drying a kilogram of products at sample load of 510g. The maximum energy required (21.9 kWh/kg wet product and 54.8 kWh/kg dry product) is needed at 170g sample load. The results show that the energy consumption is decreasing with increasing sample load per batch drying.

4. Conclusions and Recommendation

The experimental investigation of the mango fruit drying performance of an HPD dryer prototype incorporating an external condenser leads to the following conclusions and recommendations:

4.1 Conclusions

The experimentation yielded the following key results:

1. The (HPD) dryer prototype incorporating an external condenser was effectively developed, experimentally tested and successfully operated.
2. The drying air temperature of 40^{o}C was attained and controlled successfully.
3. The results clearly indicate that the energy consumption was reduced as the product load increased.

4.2 Recommendation

Based on the findings and conclusions reached, the dryer successfully dried an amount of product load and it is further recommends that the size of the drying chamber and the number of trays be increased so that the product load capacity will also increase for optimal energy use.

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