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EFFECT OF PADDY MASS VARIATIONS ON THE DRYING RATE AND EFFICIENCY OF A CONTINUOUS VERTICAL DRYER

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Abstract: An experimental study of a novel dryer is performed. In this current study, paddy drying is carried out using a vertical dryer. The paddy mass is varied as 10, 20, and 30 kg at the air temperature and velocity of 60°C and 5 m/s, respectively. The results indicate that an increase in the paddy mass raises the drying rate and efficiency. However, the large masses of paddy need a long time to reach the required 14% moisture content. The highest efficiency achieved is 3.27% at the paddy mass of 30 kg.

Keywords: paddy mass, drying rate, efficiency, vertical dryer.

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INTRODUCTION

Handling post paddy harvesting is a very important process. Before the paddy is placed in the storage area, it must be dried first to the 14% moisture content. If the moisture content is greater than 14%, then the paddy will be damaged and attacked by fungi or other microorganisms [1, 2]. According to Rahayoe [3], drying (removal of part or most of water from the material using heat energy) is carried out to balance the water content with a particular environment where fungi, enzymes, microorganisms, and insects that can damage become inactive.

The paddy generally has a water content of about 21–26%. The high water content reduces the quality of the paddy. Therefore, the paddy can easily get broken/damaged, rotten, moldy, or changing the color, as reported by Graciafernandy et al. [4]. To avoid paddy damage, the paddy must be dried immediately after harvesting. According to the Indonesian National Standard Agency (No. SNI-01-0224-1987) for the paddy with the quality I, II, and III, the harvested paddy needs to be dried immediately to reach the maximum moisture content of 14%. The paddy quality is classified into several types, as is shown in the table.

Farmers usually conventionally dry the crops using sunlight. Conventional drying is very dependent on the season and land area; it also requires a long time. In the rainy season, the drying process is hampered due to very low sunlight intensity. Therefore, many crops are damaged. The damaged crops make farmers lose because the selling price is cheaper compared to good quality [5]. According to Graciafernandy et al. [4], it generally takes three days for the drying process with a conventional system, but drying under the conditions of a high rainfall takes approximately one week.

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Table 1. Paddy quality in accordance with the SNI 6125:2008 standard

Component	Maximum admissible content in the paddy, %		
	quality I	quality II	quality III
Water	14	14	14
Empty grain	1	2	3
Broken grain and yellow paddy	2	5	7
Chalky grain and young grain	1	5	10
Red grain	1	2	4
Impurities	—	0.5	1
Different variety grain	2	5	10

Along with the increasing demand for rice from time to time, farmers must implement appropriate technologies for better post-harvest processing of agricultural products. Djaeni et al. [6] performed an investigation using an artificial dryer with a fluidized bed. Palled et al. [7] studied an artificial batch-system solar dryer to dry chilies. Mirmanto et al. [8] investigated the drying process of red chili using several types of radiators or heat exchangers. Their device was also an artificial dryer because they used a dryer box where the materials were put inside the box, and the heat energy was obtained from hot water flowing inside the radiators. Similarly, Mirmanto et al. [9] performed experiments using an artificial dryer, but the hot water temperature was varied. Nevertheless, the drying systems used by Mirmanto et al. [8, 9] were batch systems because the dried material was just put in the box, while the hot air flowed through them. Syahrul et al. [10] conducted experiments using a fluidized bed dryer. In their studies, they made the material act as a fluid in a box. Due to the velocity of the hot air coming to the dryer room, the dried materials were lifted up and down again to the bucket. However, the materials were not circulated inside the dryer room. Thus, the continuous drying processes were not investigated.

Margana and Sukmawaty [11] conducted experiments using a continuous dryer, where the material flowed continuously in the dryer room. The materials were lifted using a bucket, and then they were poured down into the dryer room. The experiments were performed with dryer temperature variations.

Artificial dryers offer the following advantages over conventional drying: (1) the operation does not require many humans; (2) the drying process is more efficient; (3) the drying process does not depend on weather conditions; (4) the dryer air temperature can be controlled; (5) there is no contamination by external objects, such as animal dung, gravel, dust, and sand.

Artificial drying is divided into two types, namely, batch systems and continuous systems. In a continuous system, hot air is blown from the bottom of the drying chamber, and the material flows continuously from the bucket elevator to the drying chamber and then back to the bucket elevator again until the moisture reaches the limit value. The continuous flow dryer has several advantages. Margana and Sukmawaty [11] stated that the continuous flow dryer does not require a large space or area, but it has a high capacity; moreover, the drying procedures can be carried out continuously without interruption. Referring to Margana and Sukmawaty [11], this continuous system research needs to be deepened.

1. EXPERIMENTAL FACILITY AND METHOD

The schematic diagram of the experimental facility is shown in Fig. 1. The same facility was also used by Syahrul et al. [12]. The major elements of the testbed are the dryer room, blower, elevator, heater, and hot air pipeline. Hot air flowed in the air duct placed inside the dryer room so that some part of heat came out from the duct into the dryer room by conduction and convection modes. At the end of the duct, there was a blower that sucked air inward the duct and made air flow into the dryer room. In the dryer room, direct contact of hot air with the dried material was ensured. The air velocities measured at the air inlet were kept constant owing to constant blower rotation. The hot air humidity was approximately 35% at $T \approx 60°C$. The 10-gram sample was withdrawn from the testbed every 15 minutes to check its humidity. The number of cycles depended on the mass: the drying process needed around 40 cycles at 10 kg, 55 cycles at 20 kg, and 63 cycles at 30 kg.

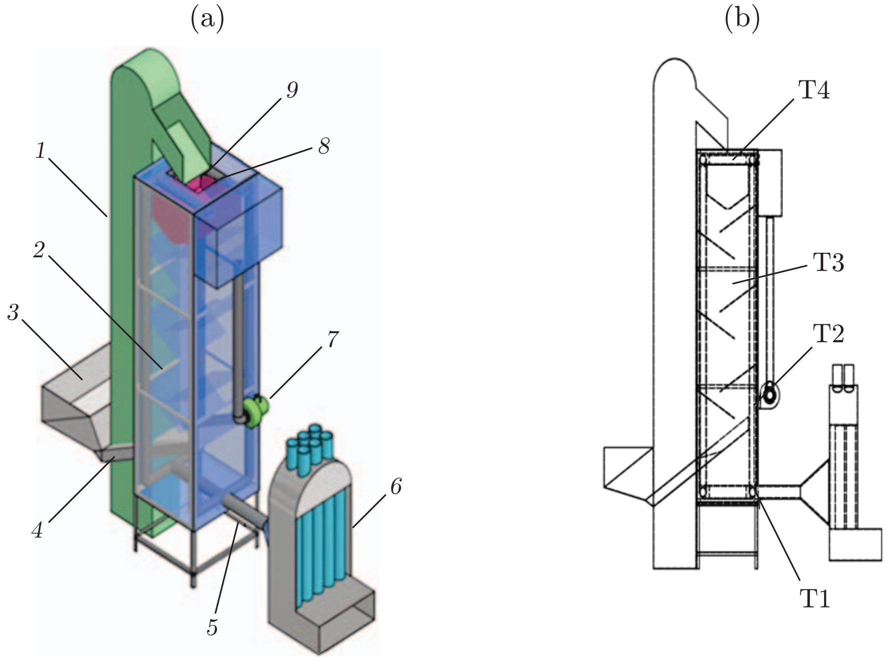

Fig. 1. Schematic diagram of the experimental facility (a) and locations of thermocouples (b): (*1*) elevator; (*2*) dryer room; (*3*) material storage hole; (*4*) material outlet; (*5*) inlet of hot air; (*6*) air heater; (*7*) blower; (*8*) air outlet; (*9*) dryer room inlet; the thermocouples measure the inlet temperature of hot air (T1), the temperature of air flowing into the dryer room (T2), the dryer room temperature (T3), and the outlet temperature of air (T4).

All temperatures were measured using K-type thermocouples with an uncertainty of about ±0.5°C. The paddy mass ranging from 0 to 5 kg was determined using an SF-400c digital balance model within ±0.01 g, while the air velocity ranging from 0 to 30 m/s was estimated using a HoldPeak HP-866B Mini LCD anemometer model within ±0.01 m/s. The water content was determined by a GMK303A moisture tester with a resolution of ±0.01% and an error of ±0.5%.

The dimension of the vertical dryer was 3000 × 600 × 600 mm. The blower was used to ensure hot air circulation throughout the testbed. The air velocity was approximately 5 m/s at the hot air temperature $T = 60$°C.

Before conducting the test, the paddy characteristics were determined. The paddy with a water content of $20.0 \pm 0.5\%$ was weighed after each variation of the tested material mass. If the water content of the material was smaller than 20%, then soaking with water was performed. If the water content was greater than 20%, then pre-drying was performed. After material preparation was completed, the drying process was carried out in a continuous vertical dryer.

The water content was measured by a moisture tester. However, it can be also calculated by the following formula [10, 11]:

$$K_a = \frac{m_t - m_k}{m_t} \cdot 100\%. \tag{1}$$

Here K_a [%] is the water content, m_t [kg] is the total mass, m_k [kg] is the dry mass [10] calculated as

$$m_k = m_t(1 - K_{ai}), \tag{2}$$

and K_{ai} [%] is the initial water content of the material.

The drying efficiency is one of the parameters to measure the testbed performance. This parameter is the ratio of the useful energy to the input energy. Some additional operations should be performed for determining the moisture content by Eqs. (1) and (2). For finding the water content of the sample taken from the testbed, it should be dried in the oven until the mass of the sample does not change. For this reason, the water content was measured directly in the present study.

The total energy in the testbed is written as follows [13–15]:

$$E = E_1 + E_2 + E_3. \tag{3}$$

Here E [J] is the total energy inside the testbed, E_1 [J] is the sensible energy of the material, E_2 [J] is the energy used for raising the water temperature inside the material, and E_3 [J] is the latent energy of water evaporation in the material. According to [13], the sensible energy can be expressed as

$$E_1 = m_k c_p (T_p - T_i), \tag{4}$$

where c_p [J/(kg · K)] is the specific heat of the material, T_i [°C] is the final temperature of the material, and T_p [°C] is the initial temperature of the material.

The energy used for heating water in the material can be estimated by the following formula [10, 13]:

$$E_2 = m_a c_{pa} (T_p - T_i). \tag{5}$$

Here m_a is the water mass in the material equal to m_t, and c_{pa} [J/(kg · K)] is the specific heat of water. The energy spent on evaporating water in the material is calculated as follows [10, 13]:

$$E_3 = m_{ar} h_{fg} \tag{6}$$

(h_{fg} [J/kg] is the latent energy, and m_{ar} [kg] is the evaporated water mass).

The volumetric rate of the hot air entering the testbed can be computed by the formula [10]

$$\dot{v} = VA, \qquad A = S^2,$$

where $\dot{v}$ [m^3/s] is the volumetric rate, S [m] is the rectangular side of the cross-sectional area of the dryer room, A [m^2] is the cross-sectional area of the dryer room, and V [m/s] is the air velocity.

The volume of air in the dryer room is calculated by the following formula [10]:

$$v = \dot{v}\,\Delta t$$

(Δt [s] is the drying time). The energy brought by hot air to the drying room can be obtained by using the following formula [10, 11]:

$$E_u = \rho_u v c_{pu} (T_m - T_k). \tag{7}$$

Here ρ_u [kg/m^3] is the density of hot air, c_{pu} [J/(kg · K)] is the specific heat of hot air, T_m [°C] is the average temperature of air entering the dryer room, and T_k [°C] is the average temperature of air leaving the dryer room.

Another parameter considered in the present study was the efficiency

$$\eta = \frac{E}{E_u} \cdot 100\%. \tag{8}$$

The efficiency parameter η can be found in many publications [10, 11, 13–16]. The mass of water evaporated from the material can be estimated as

$$m_{ar} = m_t K_{ai} - m_t K_{af},$$

where K_{af} is the final water content in the material approximately equal to 14%.

2. RESULTS AND DISCUSSION

Figure 2 shows the water content of the material as a function of time. It is seen that these curves are significantly different at $t > 2000$ s.

The time required to reach the water content of 14% is approximately 3000 s for the 10-kg sample, 4250 s for the 20-kg sample, and 4900 s for the 30-kg sample. The water content of the dried material was also studied in [2, 6–9, 16, 17].

The water mass in the material as a function of time is plotted in Fig. 3. The slope of the curves in Fig. 3 is almost the same as that in Fig. 2. Similar curves were obtained by Yahya [18], who dried the paddy using a hybrid solar and heat pump. A fluidized bed dryer rather than a continuous vertical dryer was used.

From Fig. 3, the amount of water evaporated from the material can be estimated. The mass of evaporated water as a function of time is shown in Fig. 4. At 10 kg, the curve of the evaporated water mass is up and down

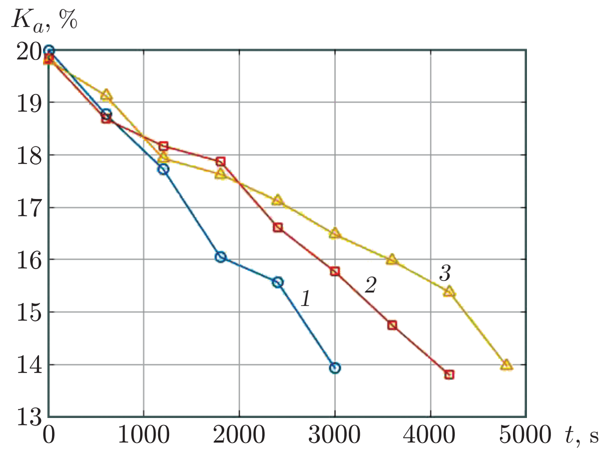

Fig. 2. Water content of the dried material with the mass m_t versus time for $m_t = 10$ (*1*), 20 (*2*), and 30 kg (*3*).

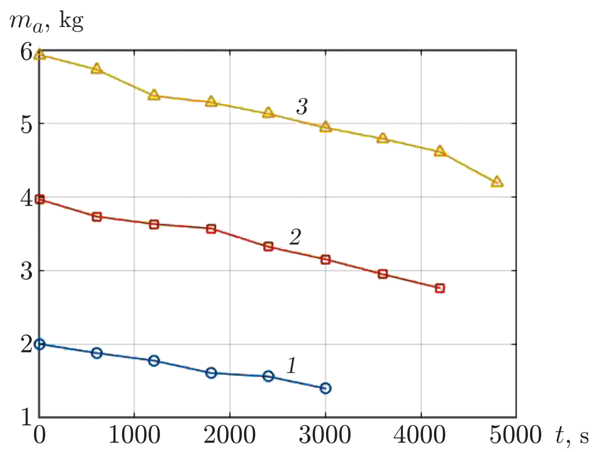

Fig. 3.

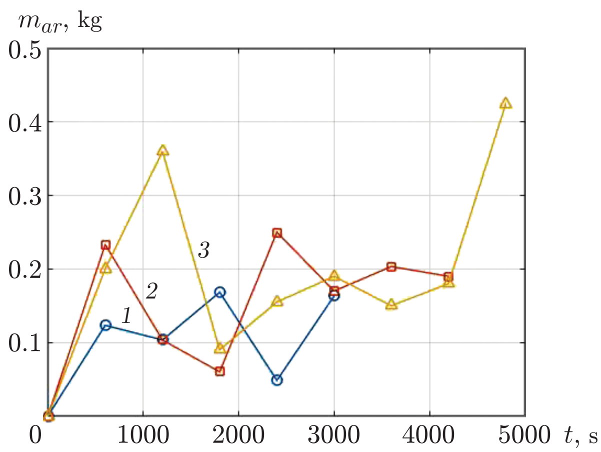

Fig. 4.

Fig. 3. Water mass in the material versus time for $m_t = 10$ (*1*), 20 (*2*), and 30 kg (*3*).

Fig. 4. Water amount evaporated from the material versus time for $m_t = 10$ (*1*), 20 (*2*), and 30 kg (*3*).

from time to time, the average mass of removed water is roughly 0.12 kg, and the total mass of evaporated water is around 0.61 kg. Furthermore, at the material masses of 20 and 30 kg, the curves for the evaporated water mass also have a zigzag character. For the material mass $m_t = 20$ kg, the average mass of evaporated water is 0.17 kg, and the total mass is 1.21 kg. At $m_t = 30$ kg, the average mass of evaporated water is 0.22 kg, and the total mass is 1.75 kg.

The drying rate is defined as the mass of water evaporated per unit time. It can be determined by using the curves in Fig. 3. The drying rate is $\dot{m}_{ar} = 0.728$ kg/h for the material mass $m_t = 10$ kg, $\dot{m}_{ar} = 1.04$ kg/h for $m_t = 20$ kg, and $\dot{m}_{ar} = 1.3$ kg/h for $m_t = 30$ kg. Thus, an increase in the material mass does not increase the drying rate linearly. Increasing the material mass by about 100% raises the drying rate approximately by 42.5%, while elevating the material mass from 20 to 30 kg makes the drying rate increase approximately by 26.5%. When each drying rate is divided by the dry material mass, then the drying rate per 1 kg of the dry material is 0.091 kg/h for the material mass of 10 kg, 0.065 kg/h per 1 kg of the dry material for 20 kg, and 0.055 kg/h per 1 kg of the dry material mass for the sample mass of 30 kg. It can be interpreted that increasing the material mass decreases the drying rate per kg of the dry material mass.

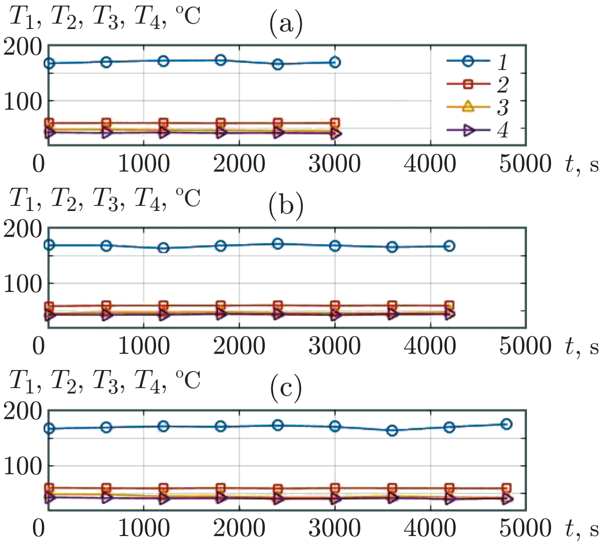

Fig. 5.

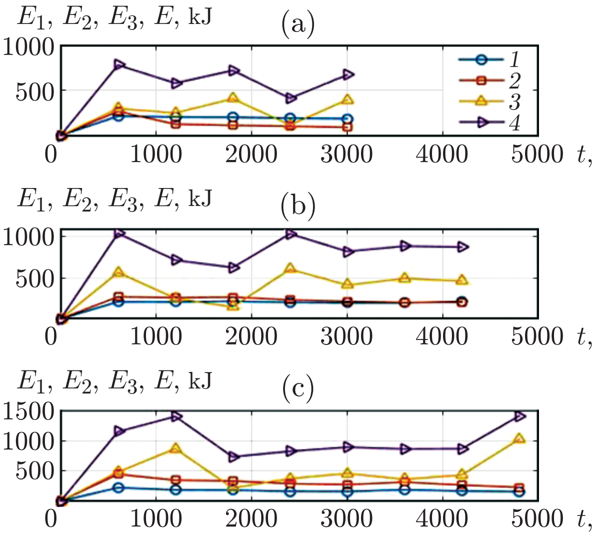

Fig. 6.

Fig. 5. Temperatures T_1 (*1*), T_2 (*2*), T_3 (*3*), and T_4 (*4*) for $m_t = 10$ (a), 20 (b), and 30 kg (c).

Fig. 6. Energies E_1 (*1*), E_2 (*2*), and E_3 (*3*), and total energy E (*4*) required for material drying versus time for $m_t = 10$ (a), 20 (b), and 30 kg (c).

The heat transfer in this study depends on the energies E, E_1, E_2, E_3, and E_u. Figure 5 shows the temperature as a function of time. The inlet temperature of hot air T_1 fluctuates only slightly with time due to problems in controlling the stove as a heater. The temperature of air entering the dryer room T_2, the temperature in the dryer room T_3, and the outlet temperature of air leaving the dryer room T_4 are almost constant and almost independent of the mass of the dried material.

The energy E_1 is determined by Eq. (4) dependent on T_p and T_i. The temperature T_i is obtained before the material is placed into the testbed, while T_p is measured directly and coincides with T_3. The energy E_2 used for heating water contained in the material is estimated by Eq. (5). Finally, the energy E_3 spent on water evaporation depends on the mass of water evaporated during the drying process and can be determined by Eq. (6). The time evolution of the energies E_1, E_2, and E_3, and the total energy E spent on material drying obtained by Eqs. (3)–(6) is illustrated in Fig. 6. The energies required for raising the material temperature for three material masses are almost identical and almost constant in time. However, the energy for evaporating water in the material depends on time and on the dried material mass. Consequently, the total energy is also time-dependent. This dependence is due to the evaporated water mass (see Fig. 3).

The energy E_u transferred by hot air to the testbed is evaluated by Eq. (7). The calculated results are shown in Fig. 7. For the three different material masses, the energies transported by air are almost the same due to the temperature setting in the air inlet. Nevertheless, a constant inlet temperature of air can be set only by using an electrical heater controlled by a proportional-integral-derivative (PID) controller. In this study, air heating was provided by using a gas stove. In this case, the heat transfer rate of air decreases with time. The heat transfer rate in Fig. 7 can be obtained by using the general equation [13, 14]:

$$Q_u = E_u/t.$$

The experimental efficiency is calculated by Eq. (8). The time evolution of the device efficiency is illustrated in Fig. 8. By using these curves, one can obtain the average efficiency values: 3.17% for the material mass $m_t = 10$ kg, 4.6% for $m_t = 20$ kg, and 4.8% for $m_t = 30$ kg. Thus, the dryer efficiency is not high. Additional studies are needed to increase this efficiency.

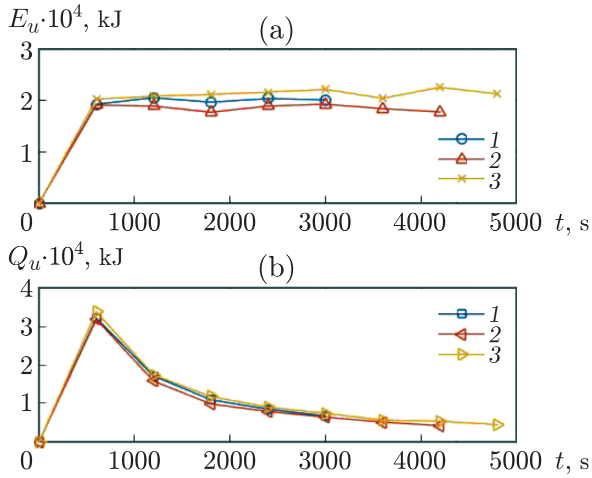

Fig. 7.

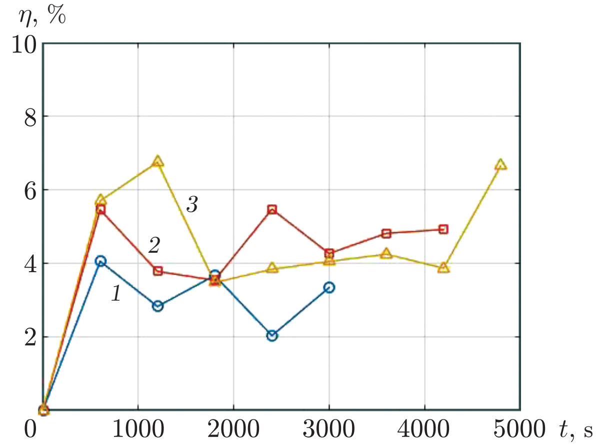

Fig. 8.

Fig. 7. Time evolution of the energy E_u transferred by hot air (a) and heat transfer rate Q_u (b): $m_t = 10$ (*1*), 20 (*2*), and 30 kg (*3*).

Fig. 8. Efficiency of the device versus time for $m_t = 10$ (*1*), 20 (*2*), and 30 kg (*3*).

CONCLUSIONS

An experimental study on the use of a continuous vertical dryer for paddy drying was performed. The water content was found to decrease with time for all material masses. Increasing the material mass raised the drying time and reduced the drying rate per kg of dry material. Additional investigations are needed to determine the effect of the material mass on the dryer efficiency.

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