Batch uniformity and energy efficiency improvements on a cabinet dryer suitable for smallholder farmers

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Revised: 6 July 2014 / Accepted: 1 September 2014 / Published online: 10 September 2014
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Abstract Drying can add value, facilitate transport and extend the storage life of agro-products; therefore, in developing countries with poorly established cool-chains, drying is particularly effective. Furthermore, drying within small-scale village-based enterprises contributes to rural development. However, most equipment suitable to such operations yields a product of non-uniform quality and shows low levels of energy efficiency. The aim of this research was to improve the batch uniformity and the energy efficiency of a cabinet dryer suitable for smallholder farmers. Experiments were carried out with the cooperation of a dryer manufacturer and a group of users. On each trial 144.5 kg of peeled and deseeded litchis were placed at the dryer's 17 trays, that were stacked atop each other. Moisture content (wet basis) was reduced from 87 to 23 % in about 15.5 h. It was found that a low-cost modification to the dryer chamber's air inlet was able to improve heat distribution and increase the uniformity of the fruit's moisture content. In the original design, at the end of the drying process, moisture content of the fruits on the top tray was 38 % while at the bottom tray was 12 %. The modification to the dryer reduced this disparity and the final moisture content of the fruits placed at the top tray was 25 % while at the bottom tray was 21 %. In addition, the modification reduced the dryer's air mass flow from 0.3 to 0.1 kg s⁻¹ without jeopardizing drying

forces, consequently the dryer energy efficiency increased from 33 to 42 %.

Keywords Convection dryer · Hot-air dryer · Heat consumption · Product homogeneity · Moisture content · Lychee

Notation

A	Area
E_{st}	Isosteric heat of sorption
LPG	Liquefied petroleum gas
m	Mass
$\dot{m}$	Mass flow
$\dot{n}_w$	Drying rate
$\emptyset$	Undefined variable
P	Pressure
Q	Heat
$\dot{Q}$	Power
T	Temperature
v	Air velocity
$\dot{w}$	Evaporation rate
X	Moisture content
Y	Absolute humidity

Greek letters

γ	Uniformity index
η	Energy efficiency
λ	Latent heat of vaporisation
φ	Relative humidity

Subscripts

air	Drying air
dm	Dry matter
duct	Dryer's air duct
in	Input
out	Outlet

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tray Dryer's tray
w Water

Introduction

Drying is a processing technology particularly suitable to developing countries with poorly established cool-chains (Jayaraman and Gupta 2007). Most such countries are primarily agricultural and also important producers of fruit and vegetables, products with a high moisture content and; therefore, highly perishable. As a result, in these countries post-harvest losses tend to be high (Singh 1994). Drying can make the product more stable (Chua and Chou 2003) and cooperative village-based processing activities have been successful in solving economic and social problems in some developing countries (Orsat et al. 2008), as they offer the opportunity for economic activity, employment, and income in rural areas (Raoult-Wack and Bricas 2002). Drying reduces post-harvest losses, and is an effective way of raising the productivity and living standards of the rural poor (Singh 1994), mainly because small-scale processing in rural areas adds value and creates profits which can be retained by the growers (Orsat et al. 2008). However, the equipment suitable for such operations is scarce, though many state-of-the-art industrial-scale dryers are available for the food industry, these are only suitable for commercial companies (Raoult-Wack and Bricas 2002). Most of the small-scale producers cannot afford such high-end technology (Chua and Chou 2003; Patil and Shukla 1988) and the cheaper, easy-to-use dryers, that are suitable for small-scale companies or farmers' cooperatives, generally yield a product of non-uniform quality and have low energy efficiency (Singh 1994; Precoppe et al. 2011). Non-uniform batches lead to deterioration of the products during storage (Müller and Mühlbauer 2011), and the low levels of energy efficiency result in high operating costs (Patil and Shukla 1988). As a consequence, the profit margins of these operations are jeopardized. At present, a low-cost and energy efficient dryer that is able to produce a high quality product is still not widely available on the market (Chua and Chou 2003; Müller and Mühlbauer 2011).

Cabinet dryers are the simplest type of convection drying equipment (Grabowski et al. 2003), and are suitable for small-scale production activities such as village-based processing, and the drying of high value crops (Driscoll 2008). Cabinet dryers can dry almost any material that can be placed on a tray (Sokhansanj and Jayas 2007), require low capital inputs and generate low maintenance costs (Jayaraman and Gupta 2007). The low capital cost of a cabinet dryer makes it particularly suitable for seasonal products where dryers are operated only over a fraction of the year (Ratti and Mujumdar 2004). However, cabinet dryers involve long drying times, and incur high labour costs with respect to product handling (Grabowski

et al. 2003). Nevertheless, the main problem with this kind of dryer is the difficulty to achieve a uniform distribution of heated air over the drying material (Patil and Shukla 1988), resulting often in non-uniform drying (Crapiste and Rotstein 1997; Das et al. 2001). The quality of the final product is the most important element to consider when drying food (Araya-Farias and Ratti 2008), and temperature is the main influencing factor (Chua et al. 2000; Araya-Farias and Ratti 2008). When food is exposed to relative high temperatures, undesired structural, organoleptic, and nutritional changes can occur (Crapiste and Rotstein 1997; Das et al. 2001). Another drawback of a cabinet dryer is its low energy efficiency, but that can generally be overcome by reducing the air mass flow and making the exhaust air more humid and, as a result, reducing heat losses via the outlet (Kudra 2009). However, care should be taken to ensure that the air mass flow is still sufficient to remove moisture, otherwise the evaporative capacity is reduced and drying time is extended, jeopardizing energy efficiency (Driscoll 2008).

Litchi (*Litchi chinensis* Sonn.), along with longan (*Dimocarpus longan* Lour.) and rambutan (*Nephelium lappaceum* L.), are the most important members of the Sapindaceae family (Subhadrabandhu and Stern 2005). Litchi is native to southern China and northern Vietnam (Menzel 1984). Southeast Asia alone is responsible for 95 % of the global production of the fruit, which is important for the economies of those countries which grow it (Mitra and Pathak 2010). The litchi fruit has a leathery pericarp and an edible, succulent white aril (Subhadrabandhu and Stern 2005). The fruit is a valuable commodity on the international market and is appreciated for its red pericarp and sweet-acid flavour (Tindall 1994). Litchi is a non-climacteric fruit, and; therefore, needs to be harvested when ripe (Nakasone and Paull 1998); however, the ripe fruits contain more than 80 % water, and so are highly perishable. The storage life of the litchi is very limited due to browning and decay. After 2 days of being harvested the fruit's red pericarp turns brown, reducing the commercial value of the fruit (Cronje 2008). Increasing production levels, domestic market saturation and the very short harvesting season, along with its limited shelf life, bring opportunities to develop the post-harvest processing of litchis (Chakraborty et al. 2010). Drying can convert the fresh fruit into a stable product, one that can be stored for a relatively long period of time, reducing losses. However, there has been little research carried out into the convective drying of litchis. Dried litchis are well known in Asia (Kuhn 1962; Huang et al. 2005), where they are eaten as a snack, like raisins (Small 2011). Litchis are often dried in batch tray dryers with hot air as the drying agent. This is an energy intensive process, because it involves a substantial moisture content reduction, plus the litchi's aril performs strong water bonding forces, which restrain moisture removal (Janjai et al. 2010; Zhao et al. 1999).

Nowadays, Thailand is one of the major, global litchi producers, and litchi sales make an important contribution to the Thai economy (Subhadrabandhu and Yapwattanaphun 2001). About 80 % of litchi orchards are located at the northern part of the country, mainly between Chiang Rai and Chiang Mai (Huang et al. 2005; Subhadrabandhu and Yapwattanaphun 2001). The ‘hong-huay’ variety occupies 70 % of the orchards (Anupunt and Sukhvibul 2005), and the majority of litchi growers in Thailand are smallholders and belong to an ethnic minority group (Subhadrabandhu 1992). Over the last 15 years, the litchi market has reached saturation, the farm-gate price has declined, and farmers have started to cut down trees to plant seasonal crops (Schreinemachers et al. 2010). This substitution has brought with it environmental problems, because the seasonal crops require intensive tillage and the use of large amounts of agrochemicals, worsening soil erosion and water contamination (Delang 2002; Sidle et al. 2006). Aiming to keep the steep mountainous terrain covered with litchi trees, scientists have investigated ways in which to make litchi production more profitable (Sruamsiri and Neidhart 2007). Drying the fresh fruit within the rural community has been proposed as a way to reduce the pressure to sell the fruit soon after harvested and also add value to the product. In 2007, a cabinet dryer was installed in a Hmong community—Mae Sa Mai, and farmers from the Hmong Mae Sa Valley Cooperative there, were trained on food handling and litchi drying techniques (Schreinemachers et al. 2010). The selected dryer was low-cost, easy to operate, and simple to maintain, criteria mentioned by Chua and Chou (2003) as being critical to the acceptance of technology at the rural village level. The dryer was manufactured by Likhitchewan Co., Ltd, a Chiang Mai based company. The Hmong Mae Sa Valley Cooperative is located at the top of the Mae Sa watershed, some 30 km from Chiang Mai. In 2007, the cooperative used this cabinet dryer to add value to the litchis grown there, then in 2008, the entire drying process was evaluated, and it was found that a problem existed with regard to the uniformity of the dried product, as well as with the energy efficiency of the dryer (Precoppe et al. 2011).

Given that state-of-art industrial dryers are no appropriate for smallholder farmers, the objective of this pilot experiment was to create a low-cost dryer suitable for small-scale operation in rural areas. A locally produced cabinet dryer able to dry a variety of food products was selected, with design modifications made to improve batch uniformity and energy efficiency. The idea was to make the modifications low-cost and easy to implement, both by the manufacturer and by the users who already owned such equipment. The research itself was carried out based on close cooperation between the Hmong Mae Sa Valley Cooperative and the Likhitchewan Company.

Material and methods

Drying equipment

The cabinet dryer normally used by the Hmong Mae Sa Valley Cooperative is a multi-purpose batch-operated dryer that encloses 17 square-shaped trays stacked on top of one another, 70 mm apart. The equipment is operated at atmospheric pressure and is 1.7 m high, 1.22 m wide and 1.19 m deep (Fig. 1). Hot air is the drying agent, with ambient air heated by a gas burner located at the rear left-hand side of the unit. Liquefied petroleum gas (LPG) is used as fuel. The heated air and flue gases travel from the burner through a duct to the chamber's air inlet located at the front right-hand side of the dryer. This duct, located at the top of the unit, is 4 m long and connects the rear left-hand side of the dryer to its front right-hand side. Air is induced by an electric-powered radial blower installed at the duct. The heated air enters the chamber via the chamber's air inlet, which runs the entire height of the chamber, and encloses two slits 5 mm wide and 1,700 mm long. At the chamber, heated air flows horizontally across the trays. After passing over the material at the trays, a portion of the moist air is discharged into the atmosphere via the outlet located at the rear right-hand corner of the unit, and the remaining air passes through orifices at the rear left-hand corner of the unit, and then is recycled. The dryer's walls and duct are constructed using 1.4 mm thick steel sheets, but no insulation material. Each tray covers an area of 0.64 m². To overcome the fact that the drying potential of the heated air falls as it passes through the wet material, a mechanism, powered by an electric motor, makes the tray revolve on its central vertical axis at six revolutions per minute.

Fig. 1 Simplified illustration of the cabinet dryer used to process litchi in northern Thailand (dimensions in mm)

Modifications to the dryer and experimental design

In an attempt to improve batch uniformity and energy efficiency with a low-cost modification, a new design for the chamber's air inlet was proposed. In the design manufactured by Likhitchewan, the inlet is composed by two slits, as shown in Fig. 2a. The proposed design changed the chamber's air inlet to a single slit 5 mm wide and 1,700 mm high, as shown in Fig. 2b. Therefore, in this single-slit design, the area that the heated air had to pass to enter the drying chamber was reduced. Experiments were conducted over six consecutive days, alternating one dryer type per day, meaning a total of three replications were carried out using the standard double-slit dryer, and three with the single-slit prototype.

Drying procedure

The six experiments were conducted in the village of Mae Sa Mai, in which the Hmong Mae Sa Valley Cooperative has its drying facility. Their usual drying procedure was followed: litchis of the 'hong-huay' variety were harvested by hand, sorted for their size and for defects, then deseeded, peeled and soaked in a 0.03 % (w/v) citric acid solution, followed by immersion in 0.05 % (w/v) potassium metabisulphite. After that, the fruits were placed on the trays in a single layer using a load density of 13.3 kg m⁻², leading to a load of 8.5 kg per tray. Tray loadings were controlled using a digital balance (T23P; Ohaus, Pine Brook, USA). The dryers were switched-on when containing a total of 144.5 kg of fresh material, and were switched-off after 120.0 kg of water had evaporated. The dryers were placed on a set of three load cells (LCM-501; OMEGA Engineering, Stamford, USA), allowing the research team to continuously measure the reduction in mass of the unit, referring to the mass of evaporated water (m_w). A 3-phase stepwise temperature regime was employed with no preheating step. When the dryers were switched-on, the thermostat was adjusted to 70 °C, then after 3 h it was reduced to 65 °C, and after 6 h reduced again to 60 °C. It was then kept at this temperature level until the end of the drying process.

Fig. 2 Details of the chamber's air inlet: **a** double-slit design, as normally produced by the manufacturer, and **b** single-slit design installed at the prototype dryer

Batch uniformity evaluation

Air velocity above the trays (v_{tray}) was measured with an 8-point miniature hot-wire anemometer (TVS-1008; OMEGA Engineering, Stamford, USA). Data was collected from trays 1 (top), 5, 9, 13 and 17 (bottom). Above each of those trays, eight sensors were placed systematically on a grid and v_{tray} was measured for a period of 2 min, recording data every 100 milliseconds. Measurements were made in triplicate, without fruits, with the rotation mechanism disabled, and the gas-burner switched-off.

Air temperature above the trays (T_{tray}) was recorded every 10 s at trays 1, 5, 9, 13 and 17 throughout the entire drying process over the six experiments. For each of these trays, three miniature temperature data loggers (OM-EL-USB-1-PRO-A, OMEGA Engineering, Stamford, USA) were placed between fruits and arranged equally spaced in a straight line from the centre to the edge of the tray.

In each of the six experiments, fresh samples—taken before switching-on the dryer, and dried samples—taken at the end of the drying process, were collected from trays 1, 5, 9, 13 and 17. The fruits were sampled systematically using a grid structure. At the Central Laboratory of the Faculty of Agriculture, Chiang Mai University, samples were evaluated for their moisture content (X). The static gravimetric method (ASABE 2008) was employed; samples were kept at 103 °C for 24 h using a laboratory convection oven (UFB 400; Memmert Co., Schwabach, Germany). Moisture content was evaluated in quadruplicates for each tray.

Differential pressure (P) was measured at the corner where the dryer's wall and the chamber's air inlet met. Measurements were performed in triplicate for each dryer. A digital manometer (GDH 200-07; GREISINGER electronic, Regenstauf, Germany) was employed and measurements were taken at different heights: at the bottom, at 0.5 m, 1.0 m, 1.5 m and at the top, as well as 2.0 m from the bottom of the dryer. At each of these points, the pressure was recorded every 5 s over a period of 1 min.

For the quantification of the uniformity of v_{trays} , T_{trays} , X and the P , uniformity index (γ) were used. The index γ represents how a parameter varies over a cross sectional plane, allowing measuring how the proposed modification at the chamber's air inlet affected uniformity. In this metric, a value of 1 indicates the highest uniformity:

$$\gamma = 1 - \frac{\sum_{i=1}^n [(|\phi_i - \bar{\phi}|) A_i]}{2|\bar{\phi}| \sum_{i=1}^n A_i} \quad (1)$$

Where A is the area of a cross sectional plane, n is the number of measurements points at the cross sectional plane

and $\bar{\phi}$ is the variable analysed for uniformity (e.g. v_{trays} , T_{trays} , X or P). The notation $\bar{\phi}$ represents the average value of the variable over the cross sectional plane.

Energy performance evaluation

Instantaneous indices were used to evaluate the energy performance of the dryers, as suggested by Kudra (2009), allowing to account for the influence of changes over time in the product moisture content. In order to calculate instantaneous indices, data was recorded throughout the entire drying process at 10 s intervals. Cumulative values were obtained by integration.

The properties of the fresh air entering the dryer were measured by placing a humidity-temperature probe (HygroClip S3; ROTRONIC, Bassersdorf, Switzerland) at the dryer inlet. Humidity-temperature probes (HygroClip IC1; ROTRONIC, Bassersdorf, Switzerland), pressure transducers (PAA35X-V-3; OMEGA Engineering, Stamford, USA), and hot wire anemometers (FMA-904; OMEGA Engineering, Stamford, USA) were also installed at the duct and at the dryer's outlet. Air density was calculated using the CIPM-2007 formula (Picard et al. 2008) by entering the recorded relative humidity (ϕ), temperature (T), and pressure (P). Air volume flow was obtained by multiplying the air velocity measurements by the respective cross-section area. At the outlet, a 1 m long tube with a diameter of 0.12 m was installed to assist volume flow calculations. The product of the volume flow and air density yielded the mass flow at the duct ($\dot{m}_{\text{duct}}$) and at the outlet ($\dot{m}_{\text{out}}$). In addition, absolute humidity at the outlet (Y_{out}) was calculated according to WMO (2008), by entering ϕ_{out} , T_{out} and P_{out} . Figure 3 shows a schematic of the dryer and the location of the installed sensors.

The LPG consumption rate ($\dot{m}_{\text{LPG}}$) was measured using a digital gas flow meter (MASS-STREAM D-6360; M+W Instruments, Leonhardsbuch, Germany), while the thermal power input ($\dot{Q}_{\text{in}}$) was obtained by multiplying the LPG consumption rate by its higher heating value (H_{LPG}): $\dot{Q}_{\text{in}} = \dot{m}_{\text{LPG}} \cdot H_{\text{LPG}}$. Heat input (Q_{in}) was calculated by

Fig. 3 Schematic diagram of the dryers showing measurements points (T , temperature; ϕ , relative humidity; P , pressure; v , air velocity; $\dot{m}$, mass flow)

multiplying the mass of the LPG consumed (m_{LPG}) by the LPG higher heating value: $Q_{\text{in}} = m_{\text{LPG}} \cdot H_{\text{LPG}}$. In Thailand, LPG is mixture of 70 % propane and 30 % butane, and; therefore, H_{LPG} was entered as 50.1 MJ kg^{-1} (Moran 1999). Electricity consumption was measured with a digital kilowatt-hour meter (Energy Logger 4000; Voltcraft, Hirschau, Germany) placed at the power socket.

The evaporation rate ($\dot{w}$) was calculated by dividing the mass of evaporated water (m_w) obtained from the load cells by the measuring interval. The drying rate ($\dot{n}_w$) was obtained by dividing $\dot{w}$ by the dry matter of the litchi (m_{dm}) loaded into the dryer: $\dot{n}_w = \dot{w}/m_{\text{dm}}$. Dry matter was calculated from the product's final moisture content.

Moisture content during drying (X) was calculated from the litchi's final moisture content and the cumulative mass of evaporated water (m_w). Then, X (dry basis) was used to calculate the litchi's isosteric heat of sorption (E_{st}) during the drying process, as modelled by Janjai et al. (2010):

$$E_{\text{st}} = (50.892e^{-0.023X})55.5087 \quad (2)$$

E_{st} was used as a substitute for the latent heat of vaporization (λ); to account for the water bonding forces, as suggested by Kudra (2009). The multiplication of E_{st} and m_w produced the heat used for moisture evaporation (Q_w). Energy efficiency (η) was defined as the ratio of the heat used to evaporate moisture to the heat supplied to the dryer (Q_{in}):

$$\eta = \frac{m_w \cdot \lambda}{Q_{\text{in}}} = \frac{m_w \cdot E_{\text{st}}}{Q_{\text{in}}} = \frac{Q_w}{Q_{\text{in}}} \quad (3)$$

Statistical analysis

Statistical analysis was performed using the SAS program (Ver. 9.3; SAS Institute Inc., Cary, USA) and using the general linear model (GLM). Data was subjected to an analysis of variance (ANOVA), and least significant difference (LSD) was calculated to detect significant differences among mean values, at a probability level of 5 %. The results of mean comparison were reported using a letter, with common letters indicating no significant differences.

Results and discussion

The drying time of the different dryer design were similar. After 15.52 ± 1.35 h, the load cells indicated a mass reduction of 120.00 kg and the dryers were switched-off. Kuhn (1962) observed longer drying time, but at his experiment lower air temperature was applied. The 144.5 kg of fresh litchi loaded to the dryer was reduced to 24.5 ± 0.1 kg of dried product. At the

Table 1 Average values and uniformity indexes for air velocity, air temperature and final moisture content in the double-slit dryer and in the single-slit prototype

Dryer type	Average			Uniformity index		
	Air velocity at the trays (m s^{-1})	Air temperature at the trays ($^{\circ}\text{C}$)	Dried litchi moisture content (% wet basis)	Air velocity at the trays	Air temperature at the trays	Dried litchi moisture content
Double-slit	0.99 ^a	58.7 ^a	23.5 ^a	0.76 ^a	0.97 ^a	0.75 ^a
Single-slit	0.92 ^b	58.7 ^a	23.5 ^a	0.91 ^b	0.99 ^b	0.93 ^b

Different letters in the same column indicate significant differences at a probability level of 5 %

beginning of the drying process, after pre-treatments, fruits were placed on the trays with average moisture content (wet basis) of 87.02 ± 1.15 %. The final product average moisture content was 23.46 ± 0.46 % wet basis. During the trials, average ambient relative humidity was 68.11 ± 5.27 % and the average temperature was 26.39 ± 1.05 $^{\circ}\text{C}$.

Impacts on batch uniformity

The average air velocity across the trays (v_{tray}) in the single-slit prototype was significantly lower than in the double-slit dryer, as shown in Table 1. Both dryers had averages that were below 2.5 m s^{-1} , the value suggested by Sokhansanj and Jayas (2007) to achieve a more uniform batch within cabinet dryers. Figure 4 shows that v_{tray} in the double-slit dryer was not uniform and so a vertical gradient is visible: air velocity was lowest at the top-tray and highest at the bottom-tray. Similar problem were observed by Nagle et al. (2008) at a fixed-bed dryer and by Tippayawong et al. (2009) at barn type dryer, both convection dryers used for small-scale fruit processing in Thailand.

In the single-slit prototype the uniformity index shown in Table 1 indicates that the modification resulted in a more uniform air velocity distribution. Maximum air velocity disparity for the double-slit dryer was $1.33 \pm 0.15 \text{ m s}^{-1}$, while the maximum disparity in the single-slit prototype was $0.60 \pm 0.05 \text{ m s}^{-1}$, which is significantly less. Nevertheless, Fig. 4 also reveals that there were still significant air velocity disparities between trays in the single-slit prototype.

Figure 4 shows that where v_{tray} was lower, the temperature at the tray (T_{tray}) was also lower. Likewise, where v_{tray} was higher, T_{tray} was higher. In convection dryers, air velocity is fundamental, because it influences the drying temperature and so affects product quality (Chua et al. 2000; Carrín and Crapiste 2008). Even though a significant difference in T_{tray} inside the single-slit prototype was observed, the uniformity index, as shown in Table 1, reveals that the temperature distribution was more uniform inside the single-slit prototype. The maximum temperature disparity between trays for the double-slit dryer was of 9.8 ± 1.4 $^{\circ}\text{C}$, while for the single-slit prototype the maximum disparity was significantly smaller: 5.0 ± 1.4 $^{\circ}\text{C}$.

Fig. 4 Air velocity, air temperature and moisture content of dried litchis on trays 1, 5, 9, 13 and 17 for both double-slit dryer and single-slit prototype. The error bars indicate standard deviation, and different letters in the same chart indicate significant differences at a probability level of 5 %

The uniformity index in Table 1 shows that for the single-slit prototype, the more uniform v_{tray} and T_{tray} conditions produced a more uniform dried product, because air velocity and temperature are the main factors which influence drying rates (Holdsworth 1971) and as a result, the moisture content of the final product (Martinov et al. 2007). Figure 4 clearly reveals the impact of v_{tray} and T_{tray} on the moisture content of the final product. On the top trays of the double-slit dryer (where v_{tray} was inferior and T_{tray} was lower), the final moisture content was highest, being above 30 % and; thus, unsuitable for storage purposes (Kuhn 1962). On the bottom trays, where v_{tray} and T_{tray} values were higher, the product became over-dry, and so unsuitable for the commercial market. In the single-slit prototype, the moisture content disparity between trays was significantly lower; for the double-slit dryer the maximum disparity was 40.7 ± 1.7 % wet basis, and for the single-slit prototype it was only 11.1 ± 2.2 % wet basis. Although those improvements were achieved, still, significant differences in terms of product moisture content between trays were observed at the single-slit prototype. Nagle et al. (2010) observed that adding insulation to a dryer's walls improved batch uniformity and this should be a strategy to be considered on further research. Despite the differences in X , at the single-slit prototype all the fruits reached the recommended 30 % moisture content, even the ones at tray 9, where v_{tray} and T_{tray} values were at their lowest.

Figure 5 shows how the single-slit design at the chamber's inlet improved vertical air velocity distribution. Heated air reaches the dryer's corners from the top, creating a vertical differential pressure gradient, with higher pressures at the bottom and lower pressures at the top. This pressure gradient

produced the v_{tray} non-uniformity in the double-slit dryer, while in the single-slit prototype, the new design increased the average differential pressure significantly, to 2.34 hPa, while for the double-slit dryer, the average was 1.88 hPa. This higher pressure reduced the vertical gradient and improved uniformity. Regarding pressure uniformity, the γ value for the double-slit dryer was 0.93 ± 0.01 , and for the single-slit prototype, 0.98 ± 0.01 , and so was significantly different at a probability level of 5 %

The design modification improved batch uniformity, and final product moisture content for the single-slit prototype was significantly more uniform than for the double-slit dryer. The reduction to a single slit increased the pressure difference, so helping to reduce the vertical gradient at the corner of the dryer. The more uniform pressure resulted in a more uniform v_{tray} value. The smaller air velocity difference between the trays made the T_{tray} more uniform, and this combination of a more uniform v_{tray} and T_{tray} made the difference between trays in terms of product moisture content smaller, so improving batch uniformity. This improvement is of critical importance because there is a growing demand for dried fruits (Carrin and Crapiste 2008), but the market requests uniformity (Bena and Fuller 2002) and when it is not achieved great financial loss occur (Xiao 2009), what is particularly challenging for the smallholder farmers.

Impact on energy performance

Table 2 shows that the drying time was not affected by the modification to the chamber's air inlet, so there was no significant difference in terms of electricity consumption. The

Fig. 5 Differential pressure for the double-slit dryer and single-slit prototype; at the corner formed by the dryer wall and the chamber inlet. The error bars indicate standard deviation, and the letters within the same dryer indicate significant differences at a probability level of 5 %

Table 2 Energy performance indices for the double-slit dryer and the single-slit prototype

Dryer type	Drying time (h)	Electric energy consumption (kW h)	LPG consumption (kg)	Thermal power input (kW)	Air mass flow rate (kg s ⁻¹)	Drying rate (g kg ⁻¹ s ⁻¹)	Energy efficiency (%)
Double-slit	15.49 ^a	12.71 ^a	19.05 ^a	17.23 ^a	0.27 ^a	0.12 ^a	32.97 ^a
Single-slit	15.55 ^a	12.66 ^a	14.30 ^b	12.81 ^b	0.11 ^b	0.12 ^a	42.41 ^b

Different letters in the same column indicate significant differences at a probability level of 5 %

average electrical power input, as consumed by the two electric motors that run the blower and the tray rotation mechanism, was 817.3 W.

Table 2 shows that the amount of LPG consumed (m_{LPG}) by the single-slit prototype was significantly lower, even though same temperature regime was applied. The smaller m_{LPG} of the single-slit prototype can be attributed to a significant reduction in the dryer's air mass flow rate ($\dot{m}_{\text{air}}$). At the duct of the double-slit dryer, $\dot{m}_{\text{air}}$ was on average 0.27 ± 0.01 kg s⁻¹, while for the single-slit prototype it was $0.11 \pm$

0.02 kg s⁻¹. The air mass flow at the outlet was, in turn, also significantly reduced; for the double-slit dryer it was 0.073 ± 0.003 kg s⁻¹ while for the single-slit prototype it was 0.061 ± 0.002 kg s⁻¹. At the duct, no significant differences in relative humidity (φ_{duct}) and temperature (T_{duct}) were observed between the two dryers, the average being 4.89 ± 0.85 % and 101.34 ± 7.40 °C. In contrast, at the outlet, air left the single-slit prototype significantly moister and cooler, as the average φ_{out} for the double-slit dryer was 29.58 ± 2.87 %, while for the single-slit prototype it was 61.72 ± 1.93 %. According to

Fig. 6 Drying rate and relative humidity of the exhaust air for the double-slit dryer and single-slit prototype

Baker and McKenzie (2005) heat losses via unsaturated exhaust air are greatly reduced by adjusting the relative humidity of the exhaust air closer to saturation.

The average T_{out} for the double-slit dryer was 56.04 ± 2.38 °C and for the single-slit prototype it was 47.12 ± 0.31 °C. The average absolute humidity of the exhaust air (Y_{out}) at the outlet of the double-slit dryer was 34.09 g kg^{-1} , while for the single-slit prototype it was 51.99 g kg^{-1} , a significant difference at a probability level of 5 %. The higher Y_{out} value of the single-slit prototype can be explained by the fact that the drying rate ($\dot{n}_w$) was not affected by the reduction in $\dot{m}_{\text{air}}$, as shown in Table 2. The lower $\dot{m}_{\text{air}}$ of the single-slit prototype associated with the maintenance of $\dot{n}_w$ allowed it to save 4.75 ± 0.87 kg of LPG per batch. Given the low-cost of the modifications made, it is estimated that an investment made in the new dryer could be recovered within 8 batches.

Figure 6 shows the variation in $\dot{n}_w$ and φ_{out} values over the drying period. No constant-drying rate period was observed, as the drying rate progressively decreased over time. Janjai et al. (2010) and Zhao et al. (1999) have observed that water movement in litchis is controlled by diffusion, and that the fruit dries over the falling-rate period (Rizvi 2005; Carrin and Crapiste 2008). The maximum drying rate was observed at the beginning of the drying process, then decreased over time. For the double-slit dryer, the maximum $\dot{n}_w$ was $0.19 \pm 0.01 \text{ g kg}^{-1} \text{ s}^{-1}$, while for the single-slit prototype it was $0.20 \pm 0.00 \text{ g kg}^{-1} \text{ s}^{-1}$. At the end of the drying process, $\dot{n}_w$ was $0.03 \pm 0.02 \text{ g kg}^{-1} \text{ s}^{-1}$ for the double-slit dryer and $0.02 \pm 0.02 \text{ g kg}^{-1} \text{ s}^{-1}$ for the single-slit prototype. Exhaust air relative humidity reached a maximum at the beginning of the drying process; for the double-slit dryer, the maximum φ_{out} reached 46.04 ± 5.50 %, while for the single-slit prototype it was 76.09 ± 0.71 %. As drying proceeded, φ_{out} decreased as a result of the decreasing moisture content of the product. At the end of the drying process, φ_{out} reached its lowest values, which were 10.68 ± 0.99 % for the double-slit dryer and 31.29 ± 2.63 % for the single-slit prototype.

As a consequence of the reduced m_{LPG} with the single-slit prototype, the thermal power input ($\dot{Q}_{\text{in}}$) was significantly lower, as shown in Table 2. For both dryers, $\dot{Q}_{\text{in}}$ reached a maximum at the beginning of the drying process, this being 27.82 ± 1.86 kW for the double-slit dryer and 21.22 ± 0.45 kW for the single-slit prototype. As the drying process progressed, $\dot{Q}_{\text{in}}$ reduced as a result of the decreasing stepwise temperature regime and decreasing moisture content of the fruits. By the end of the drying process, $\dot{Q}_{\text{in}}$ had reached its lowest values: 7.32 ± 0.88 kW for the double-slit dryer and 6.42 ± 0.81 kW for the single-slit prototype.

The litchis' isosteric heat of sorption, used to calculate energy efficiency, was on average 2.65 MJ kg^{-1} , ranging from 2.40 MJ kg^{-1} at the beginning of the drying process, to 2.81 MJ kg^{-1} at the end. Table 2 shows that energy efficiency was significantly higher for the single-slit prototype. Energy

efficiency value obtained from the double-slit dryer was similar to the one reported by Tippayawong et al. (2009), who studied longan drying with an equipment suitable for small-scale production. Longan drying behaviour is comparable to litchi (Janjai et al. 2010). In general, the main reason for the low η in convection dryers is the inefficient air–material heat transfer and the high energy losses through the exhaust air (Kudra 2009). Particularly for small capacity dryers, losses from the dryer body are also significant due to the high surface-to-volume ratio (Kemp 2012). Nagle et al. (2010) and Tippayawong et al. (2008) have reported significant improve on energy efficiency by adding insulation to the dryer's walls, and this should be considered on further research.

Over the drying period a decrease in the value of η was observed. Precoppe et al. (2011) reported that as the litchi drying process progresses heat losses via unsaturated exhaust air rises, what explains the observed η decrease over time. For the double-slit dryer, the maximum value reached was 44.57 ± 5.40 %, while for the single-slit prototype it was 50.74 ± 2.37 %. The lowest η values reached, at the end of the drying process, were 18.88 ± 1.35 % for the double-slit dryer and 15.28 ± 1.45 % for the single-slit prototype.

Conclusions

In this research a dryer suitable to small-scale processing in rural area was improved. Modifications to the dryer's chamber air inlet, reducing the number of slits from two to one, resulted on a more uniform air velocity and more uniform temperature in the drying chamber, producing a more homogeneous batch. In addition, the constriction of the chamber inlet reduced the air mass flow, but did not decrease the drying rate, improving energy efficiency. Although the dryer can be further improved the results here represents a step forward in fulfilling the demand for equipment suitable for smallholder farmers engaged on small-scale drying at rural areas.

Acknowledgments This study was conducted as part of an international program named "Sustainable Land Use and Rural Development in the Mountainous Regions of Southeast Asia" (SFB 564). It was funded by the *Deutsche Forschungsgemeinschaft* (DFG) and co-funded by the National Research Council of Thailand (NRCT). We should express gratitude to the Hmong Mae Sa Valley Cooperative, and to Likhitchewan Co., Ltd, for taking part in this research study, and would also like to thank the Faculty of Agriculture at Chiang Mai University for hosting the SFB 564 office and supporting the project's laboratory work.

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