
1 Improved energy efficiency of farmers' cooperative litchi drying operation in northern Thailand*

1.1 Abstract

In 2007, Hmong farmers growing litchi in the mountainous region of northern Thailand started to dry the fruit in response to its declining market price. However, the locally available dryer, although affordable and of a size appropriate for smallholder farmers' cooperatives, showed excessive gas consumption, and this, along with rising fuel costs, posed a threat to the drying operation. The objective of this study was to test low-cost, easy-to-implement modifications to a locally available convection dryer, to improve its energy efficiency. Experiments were conducted in cooperation with a Hmong farmers' cooperative in northern Thailand. Insulation of the air ducts and control of the air recirculation rate led to energy cost savings of US\$2.45 per dryer-load. With the modifications required being simple, the investment needed was recovered after only approximately 20 loads, while the energy efficiency of the dryer increased from 33% to 39%.

1.2 Introduction

The mountainous region of northern Thailand is inhabited by a large number of ethnic minorities, and over the last four decades, the population in this area has risen dramatically, with land use shifting from largely subsistence slash-and-burn-based agriculture to the growing of cash crops (Valentin *et al.*, 2008; Tipraqsa & Schreinemachers, 2009). Deforestation, erosion and water contamination have accompanied this change (Thapinta & Hudak, 2000; Kruawal *et al.*, 2005), and so to mitigate the impacts, the cultivation of perennial fruit crops – mainly litchi (*Litchi chinensis* Sonn.) – has been promoted in the region. Litchi belongs to the Sapindaceae family and is native to South-East Asia (Tindall, 1994). The fruit has proved to be suitable to the region's climatic and topographic conditions, and as a consequence, litchi orchards have recently proliferated, meaning that in just a short period of time, the north of Thailand has become the main litchi growing area in the country (Anupunt & Sukhvibul, 2005; Mitra & Pathak, 2010), with Thailand as a whole evolving into one of the world's largest

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producers and exporters of the fruit (Mitra & Pathak, 2010). However, about fifteen years ago, the domestic litchi market started to become saturated and as a result, the fruit price declined, with the low price leading to the conversion of litchi orchards into seasonal crop fields. This change worsened the level of erosion and water contamination in the region, because the introduced seasonal crops require intensive tillage and the greater use of agrochemicals (Sidle *et al.*, 2006).

Nowadays, only 40% of Thailand's litchi production reaches the international market (Mitra & Pathak, 2010), and while litchi exports could be expanded, this is hindered by the extremely short shelf life of the fruit (Revathy & Narasimham, 1997; Reichel *et al.*, 2010), as within 2 days after being harvested, the red colour of the pericarp turns brown, reducing the fruit's commercial value (Holcroft & Mitcham, 1996; Jiang *et al.*, 2006). A cool-chain system could be used to expand the export market, but in Thailand, this system is not well established (Mitra & Pathak, 2010).

Domestic market saturation, with a subsequent decrease in price of the fruit, was not the only reason why farmers converted their orchards. The following features, intrinsic to litchi production, proved to be challenging for smallholders: (i) the need to sell the fruits immediately after harvest, limiting the farmers' bargaining power, (ii) the irregular bearing of the fruit trees, resulting in a significant variation in yields, and (iii) the fact that litchi is non-climacteric and the harvest season is short, creating a farm-labour bottleneck from mid-May to mid-June.

In 2007, with the aim of making litchi growing more attractive and profitable, scientists from an international team working on sustainable agricultural practices and rural development issues encouraged Hmong farmers growing litchi in the Mae Sa watershed in northern Thailand to initiate on-farm fruit processing. Drying was chosen as the preferred processing technique, because it adds value to the product and reduces the need to sell it quickly (Schreinemachers *et al.*, 2010). Litchi drying was originally developed in China and is the oldest processing method known in terms of litchi fruit conservation (Chen & Huang, 2001). Dried litchis are popular in Asia (Kuhn, 1962) and are well known in Thailand (Subhadrabandhu & Yapwattanaphun, 2001); however, affordable dryers and of a size appropriate to smallholder farmer cooperatives are still at the early stages of development, and even though a variety of convection hot-air dryers are available (Precoppe *et al.*, 2008), the equipment is generally poor in terms of energy efficiency and

delivers heterogeneous product quality (Nagle *et al.*, 2010; Precoppe *et al.*, 2011). Litchi drying is particularly an energy-intensive operation, first, because it involves having to substantially reduce moisture content, and second, because the litchi fruit's flesh performs strong water-bonding forces that impair water movement (Janjai *et al.*, 2010). Precoppe *et al.* (2011) observed that as the litchi drying process progresses, so energy efficiency decreases and heat losses rise – mainly via the exhaust air. Low efficiency levels are common among convective food dryers due to the complex relationship between food, water and air (Kemp, 2005; Mujumdar, 2007), and also due to the significant heat losses that occur with unsaturated exhaust air (Kudra, 2009). The latter can be minimised by adjusting the outlet air conditions; making them close to saturation (Baker & McKenzie, 2005), and one way to tackle this is to recirculate a proportion of the exhaust air (Baker, 2005; Strumiłło *et al.*, 2007). However, this method must be used carefully and with restraint, so as not to reduce the drying forces delivered and as a consequence increase drying times (Kudra, 2009), although the litchi drying rate is not strongly affected by relative humidity (Janjai *et al.*, 2011). In a previous study, Tippayawong *et al.* (2008) successfully improved the efficiency of a convection dryer for peeled longan (*Dimocarpus longan*) by recirculating a proportion of the exhaust air. Longan also belongs to the Sapindaceae family, and its drying behaviour is similar to litchi (Janjai *et al.*, 2009).

Rising energy prices, and particularly the price of liquefied petroleum gas (LPG), are a major concern for drying operations in Thailand (Román *et al.*, 2009). Since 1999, the price of LPG has no longer been set by the government, and so although it is still heavily subsidised, its rise has become a major threat to the economic viability of smallholder farmers' cooperative drying businesses. Given the high energy demands of the litchi drying process and the low efficiency of the convection dryers available in Thailand, LPG price rises can seriously inhibit the expansion of on-farm drying activities within the mountainous areas of northern Thailand, and; thus, impede rural development. The objective of this pilot-scale experiment was to develop low-cost modifications for a locally available dryer – to improve the energy performance of the equipment. Modifications were designed to be simple and easy to implement on dryers already in use, and also within the dryer assembly process.

1.3 Material and methods

1.3.1 Drying procedure

Experiments were conducted in the Mae Sa watershed (30 km north-west of Chiang Mai, in northern Thailand), where Hmong litchi growers have run a smallholder litchi drying cooperative since 2007. The cooperative uses a convection dryer that is a low-cost and simple-to-use cabinet dryer fuelled by LPG. The walls are constructed with 1.4-mm-thick steel sheets, but with no insulation materials. The dryer is 1.22 m wide, 1.19 m deep and 1.70 m high, and encloses 17 square-shaped trays, each with an area of 0.64 m². The trays are stacked on a rack at 70-mm intervals, and the rack is mounted on a carousel, allowing it to revolve around a central, vertical axis. At the top of the dryer unit, a 0.99-kW electric engine is connected to a gearbox, which engages the system, making the tray rotate at six revolutions per minute. Also, at the top of the unit, an air duct connects the rear left-hand side of the dryer to the front right-hand side. A radial air blower, powered by another 0.99-kW electric motor, induces the air. The dryer uses direct heat, with a gas burner positioned to the rear of the unit, just after the air inlet on the left, and with the burner controlled by a thermostat – with the temperature sensor located on the upper left-hand side of the dryer. The heated air, including combustion gases, travels from the burner through the duct and enters the drying chamber from the front right-hand side, after which a proportion of the air passes through outlets located in the rear right-hand corner of the unit before leaving the dryer. The remaining air passes through orifices in the rear left-hand corner, is mixed with the air already passing the gas burner and is then recirculated into the chamber (Fig 1-1). The chamber's air inlet is made of two slits 5 mm wide and 1700 mm long, and has 33 circular orifices of 5 mm radius distributed vertically at 50-mm intervals.

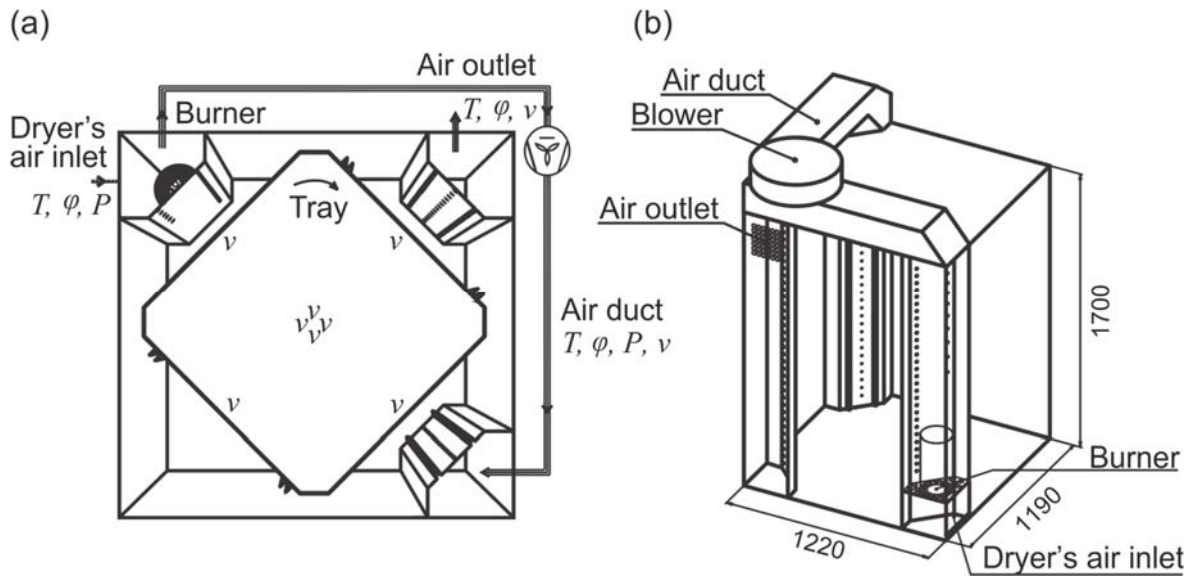


Fig 1-1. (a) Top, cross-sectional view of the dryer used to process litchi in northern Thailand, showing where measurements were performed (T , temperature; ϕ , relative humidity; P , pressure; v , air velocity), and (b) trimetric view of the rear of the equipment (dimensions in mm).

The cooperative's current drying procedure was applied in the study, so for each drying batch, 350 kg of fresh litchi was purchased from local orchards, with only ripe, high-grade litchi of the 'hong-huay' variety used. The fruits were hand-peeled, deseeded and then immersed in citric acid solution (0.03% w/v) for 7 minutes, after which they were immersed in a potassium metabisulphite solution (0.05% w/v) for another 7 minutes at room temperature. After chemical pretreatment, the fruits were drained and placed on the dryer's trays, with the tray loadings controlled using a digital balance (T23P; Ohaus, Pine Brook, NJ, USA). Each tray was loaded with 8.5 kg of litchis, making a total initial drying mass of 144.5 kg. The cooperative employs a stepwise temperature regime with no preheating phase. During the first stage of the experiment, the thermostat was set to 70 °C and the drying process lasted for 3 h. After that, during the second stage, the thermostat was set to 65 °C and the drying process lasted for 6 h, whilst for the third and final stage, the thermostat was set to 60 °C and the drying process continued until a total reduction of 130 kg of mass could be observed. For the experiments, the weight of the dryer itself was recorded by mounting it on three load cells (LCM501-100; Omega Engineering, Stamford, CT, USA).

1.3.2 Experiment design

Modifications to the locally available convection dryer aimed to improve the equipment's energy efficiency by reducing heat losses. The air duct and blower located at the top of the dryer were covered with 30-mm-thick mineral wool and then shielded by a 0.8-mm-thick steel sheet. At the outlet, a 0.22 m × 0.22 m metal sheet was installed as a sliding-door, allowing the operator to adjust the size of the outlet. By reducing the outlet size, the proportion of air recirculating increases. For the modified dryer (MDF), during the first stage of the drying process, the outlet was 100% open, but when the thermostat was adjusted for the second stage, the outlet was partially closed, reducing the outlet area by 50%. During the third stage, the outlet was closed further, leaving only 15% of the outlet area open. The MDF dryer was compared against the unmodified equipment (UMD) – for which no insulation or adjustment in terms of air recirculation was present. Six drying events were conducted in total, three replications for each dryer type.

1.3.3 Measurements

Fig 1-1a shows a top cross-section view of the dryer and the location of the sensors used to measure the air properties during the drying process, while Table 1-1 contains details of the instruments used, with the device placements and specifications according to ISO (1997). Temperature (T), relative humidity (ϕ) and pressure (P) were recorded at the inlet and in the duct. Air velocity (v) in the duct was also recorded after the blower. At the outlet T , ϕ and v were recorded. To calculate the air flow volumes, a 1-metre-long tube with a diameter of 0.12 m was installed at the outlet, and v was recorded at nine different positions in the cross-section of the tube. Gas consumption was measured with a gas flow meter, and electricity consumption was recorded using a digital kilowatt-hour meter placed at the AC socket. All the sensors were connected to a computer for data recording.

Table 1-1. Locations and measuring intervals of the sensors used during the six experiments

Sensor location	Measuring device	Measurement interval (s)	Model	Manufacturer
Inlet	Hygrometer-thermometer	30	HC2-S	Rotronic (Bassersdorf, Switzerland)
Inlet	Pressure transducers	30	PAB41X-C-800-1200	Omega Engineering
Duct	Hygrometer-thermometer	30	HC2-IC1	Rotronic
Duct	Pressure transducers	30	PAA35X-V-3	Omega Engineering
Duct	Hot-wire anemometer	30	FMA-905	Omega Engineering
Outlet	Hygrometer-thermometer	30	SC05	Rotronic
Outlet	Hot-wire anemometer	30	TVS-1008 FMA-904	Omega Engineering
Bellow dryer	Load cell	30	LCM501-100	Omega Engineering
Gas cylinder	Gas flow meter	30	FMA-1600A	Omega Engineering
AC socket	Kilowatt-hour meter	60	Energy Logger 4000	Voltcraft (Hirschau, Germany)
Trays	Hot-wire anemometer	1	TVS-1008	Omega Engineering

Air velocity at the trays was measured while there were no fruits inside the dryer, with the gas burner turned-off and with the trays stationary. Eight hot-wire anemometers were placed on the surface of the trays, four in the centre and four around the edges as shown in Fig 1-1a. Air velocity at the trays was measured at every other tray starting from the top tray, with measurements taken for 2 min. Three replications of the measurements were performed and for the MDF dryer, measurements were made separately with the outlet 100%, 50% and 15% open.

A thermal camera (FLIR, InfraCAM, Stockholm, Sweden) was used to assess the surface temperature of the dryer. Images were corrected for the temperature and relative humidity of the ambient air, for emissivity and distance from the dryer.

1.3.4 Product sampling and analysis

Fresh pretreated products were sampled just before being placed on the trays. The dried products were sampled when the trays were removed from the dryer at the end of the drying process, with samples collected from every other tray, starting from the top tray. Products were sealed in polyethylene film bags and refrigerated until transported to a laboratory for moisture content analysis. Moisture content was determined by the gravimetric method (ASABE, 2008) using a convection oven (UFE 400; Memmert, Schwabach, Germany), drying the samples for 24 h at 103 °C. Two measurements were performed per sample bag, and the moisture content (X) then calculated on a dry basis (db).

1.3.5 Energy performance evaluation

Instantaneous evaporation rate (\dot{w}) was obtained based on the reduction in dryer weight over time, monitored with the load cells placed under the dryer. The instantaneous drying rate (\dot{n}_w) was calculated dividing \dot{w} by the litchi dry matter content in the dryer (m_{dm}): $\dot{n}_w = \dot{w}/m_{dm}$ (Toledo, 2007).

Liquefied petroleum gas (LPG) consumption over time was obtained from the gas flow meter and converted to instantaneous thermal power input (\dot{Q}_{in}) by multiplying it by the LPG heating value, which was entered as 50.1 MJ kg⁻¹ (NSRDS, 1971). The sum of \dot{Q}_{in} delivered the total amount of heat supplied to the dryer (Q_{in}). LPG composition in Thailand is 70% propane and 30% butane.

Specific heat consumption (q_c) was obtained from the ratio of the heat supplied to the dryer (Q_{in}), to the amount of water evaporated (m_w): $q_c = Q_{in}/m_w$ (Baker, 2005). The m_w value was obtained from the load cells by subtracting the initial weight of the dryer from the final weight.

Energy efficiency (η) was defined in accordance with Strumiłło *et al.* (2007) – as the ratio of the heat used to evaporate moisture (Q_w), to the heat supplied to the dryer (Q_{in}), where Q_w was calculated using the amount of evaporated water and the latent heat of vaporisation (λ):

$$\eta = \frac{m_w \cdot \lambda}{Q_{in}} = \frac{Q_w}{Q_{in}} \quad (0-1)$$

Litchi isosteric heat of sorption (E_{st}) was used to estimate the latent heat of vaporisation, as suggested by Kudra (2009); therefore, λ was calculated as a function of X in dry basis, as modelled by Janjai *et al.* (2010):

$$\lambda \approx E_{st} = (50.892e^{-0.023X})55.5087 \quad (0-2)$$

The course of product moisture content X throughout the drying process was estimated from the product's final moisture content and the reduction in the dryer's weight due to water evaporation.

Heat losses via exhaust air ($Q_{L,out}$) were calculated in line with Kemp (2012) – based on the saturation deficit of the air at the outlet. $Q_{L,out}$ was obtained by subtracting the exhaust's heat (Q_{out}) from the heat of the saturated exhaust air (Q_{out}^*), as shown in Eq. 0-3. Q_{out} was calculated from the enthalpy of the exhaust air (h_{out}), the mass flow at the outlet (\dot{m}_{out}) and Δt , while Q_{out}^* was calculated using the mass flow that would be just enough to hold the \dot{w} and produce saturated exhaust air (\dot{m}_{out}^*).

$$Q_{L,out} = Q_{out} - Q_{out}^* = (h_{out} \cdot \dot{m}_{out} \cdot \Delta t) - (h_{out} \cdot \dot{m}_{out}^* \cdot \Delta t) \quad (0-3)$$

To calculate \dot{m}_{out}^* , \dot{w} was divided by the absolute humidity of the saturated exhaust air (Y_{out}^*), reduced by the absolute humidity of the ambient air (Y_{amb}), where psychrometric conversions were made in accordance with WMO (2008).

$$\dot{m}_{out}^* = \frac{\dot{w}}{Y_{out}^* - Y_{amb}} \quad (0-4)$$

The recirculation rate (r) was obtained by dividing the mass flow of the recirculated air \dot{m}_r by the mass flow in the duct (\dot{m}_{duct}). The mass flow of the recirculated air was calculated from the difference between the mass flow in the air duct (\dot{m}_{duct}) and the mass flow at the outlet (\dot{m}_{out}), as shown in Eq. 0-5. A maximum recirculation rate (r^*), one that would produce a saturated exhaust air, was calculated from \dot{m}_{out}^* , assuming that an increase on relative humidity of the air inside the drying chamber would not jeopardise \dot{w} .

$$r = \frac{\dot{m}_r}{\dot{m}_{\text{duct}}} = \frac{\dot{m}_{\text{duct}} - \dot{m}_{\text{out}}}{\dot{m}_{\text{duct}}} \quad (0-5)$$

The mass flow in the air duct (\dot{m}_{duct}) and the mass flow at the outlet (\dot{m}_{out}) were calculated from, air velocities, cross-section area and air density. Air density was obtained using the CIPM-2007 formula (Picard *et al.*, 2008), entering the values for air temperature, relative humidity and pressure measured at the duct and at the outlet.

1.3.6 Statistical analyses

Before performing the analysis of variance (ANOVA), data normality was evaluated by comparing the residual distribution against the normal distribution, with the aid of a Quantile–Quantile plot. The data were then submitted to a one-way ANOVA and also to a comparison procedure using a *t*-test with a 5% probability level. As suggested by Piepho (2004), the results were subsequently displayed as a list, using lowercase superscript letters to show whether or not the comparisons were statistically significant. In the results, means sharing a common letter indicate that no significant differences were found, while means followed by different letters indicate that significant differences were obtained. The analyses were performed using SAS 9.3 (SAS Institute Inc., Cary, USA).

1.4 Results and discussion

During the experiments, the average ambient temperature was 28.3 ± 1.5 °C, and the average relative humidity was $68.7 \pm 3.5\%$. After pretreatment, the *X* of the fresh litchi was 9.7 ± 0.2 kg kg⁻¹, and for the dried product, *X* was 0.15 ± 0.01 kg kg⁻¹. The initial mass of 144.5 kg of fresh litchi yielded 14.87 ± 0.81 kg of dried product, containing an average of 13.54 ± 0.19 kg dry matter. Even though the same temperature regime for both dryer types was used, on average, the MDF target moisture content was reached 2.45 h earlier, consuming, on average, 2.61 kg less LPG and using 1.97 kW h (7.09 MJ) less electricity. The reduction in LPG consumption represented a saving of THB 65.00 (USD 2.12) per batch and the reduction in electricity consumption represented a saving of THB 10.00 (USD 0.33) per batch. Taking into consideration that the modifications to the MDF dryer cost THB 1500.00 (USD 48.96), the investment was recovered after approximately 20 loads. Even though the electricity consumed by the two electrical motors represented only $4.3 \pm 0.1\%$ of the total energy input, the obtained saving was important, as, in Thailand,

energy obtained from electricity is about three times more expensive than energy obtained from LPG.

The thermo-image of the UMD dryer (Fig 1-2) shows elevated temperature at the dryer's walls, indicating high heat loss levels. Dryers of a small capacity usually show significant heat losses from the dryer body due to the high surface-to-volume ratio (Kemp, 2012). These kinds of losses were particularly high in the studied dryer, not only due the surface-to-volume ratio, but also because the walls were not insulated. However, the relatively low price of LPG in Thailand makes insulating the entire dryer not economically advantageous. Insulating only the ducts – where the temperature of the air is higher – was seen as a compromise given the current price of the fuel.

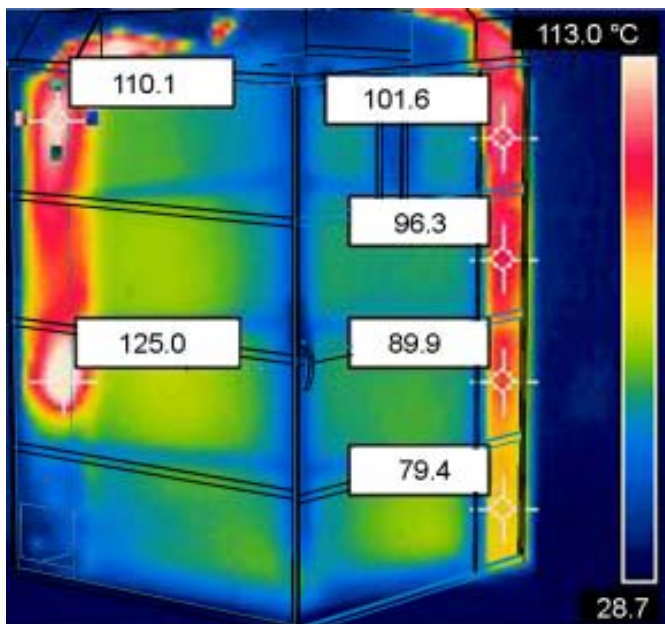


Fig 1-2. Thermal image of the unmodified dryer, values shows surface temperature in degree Celsius.

For the UMD dryer, the heat input provided by the LPG was 1009.2 ± 30.2 MJ in total, from which 336.0 ± 15.3 MJ was actually used for moisture evaporation. For the MDF dryer, the heat input provided by LPG was 878.4 ± 9.5 MJ, from which 343.1 ± 4.3 MJ was used for evaporation. The value used for the specific heat of water vaporisation, as calculated from the litchi isosteric heat of sorption, was 2.62 MJ kg^{-1} . To produce 1 kg of dried litchi, 1.42 kg of LPG was used by the UMD dryer, while 1.24 kg was used by the MDF dryer. Table 1-2 shows that the modifications made to the dryer were effective at improving the energy performance of the MDF dryer; q_c was significantly lower and η was significantly higher.

Table 1-2. Energy performance indices for the unmodified dryer (UMD) and the dryer modified to achieve an improved energy performance (MDF)

Dryer type	Drying time (h)	Total LPG consumption (kg)	Average thermal power input (kW)	Electricity consumption (kW h)	Drying rate ($\text{g kg}^{-1} \text{s}^{-1}$)	Specific heat consumption (MJ kg^{-1})	Energy efficiency (%)	Heat losses via exhaust air (MJ)
UMD	15.88 ^a	20.14 ^a	17.64 ^a	12.72 ^a	0.17 ^a	7.82 ^a	33.30 ^a	245.87 ^a
MDF	13.43 ^b	17.53 ^b	18.16 ^a	10.75 ^b	0.20 ^b	6.75 ^b	39.06 ^b	138.47 ^b

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

The dryer's air blower produced a mass flow of 275.4 g s^{-1} . In the UMD, the recirculation rate was 72.5% throughout the drying process, while for the MDF, this rate was only during the first 3 hours. Thereafter, during the second drying stage, the exhaust outlet was partially closed and the recirculation rate increased to 76.6%. During the third stage, the outlet was further closed and the recirculation rate increased to 89.0%. The optimum recirculation rate, one needed to minimise exhaust heat losses, starts at 79.1% and increases in an almost exponential manner to 99.9%, as shown on Fig 1-3. Likewise, the optimum exhaust mass flow would be 63.2 g s^{-1} at the beginning of the drying process, decreasing on a quadratic decay manner, and reaching a minimum of 2.0 g s^{-1} at the end of the drying process. Fig 1-3 also shows that the closing of the MDF dryer outlet reduced the exhaust mass flow from 78.1 g s^{-1} during the first drying stage, to 70.7 g s^{-1} during the second drying stage, and to 35.9 g s^{-1} during the third drying stage. Regarding the relative humidity of the exhaust air, for the UMD dryer, it decreased steadily with drying time, similar to the findings made by Tippayawong *et al.* (2009) when drying peeled longan. For the MDF dryer, the relative humidity of the exhaust air increased with the increase in recirculation rate. In addition, Fig 1-3 shows that closing the dryer's air outlet represented a simple and low-cost modification to the dryer, one that effectively reduced exhaust heat losses. It shows that, while for the UMD dryer, $Q_{L,x}$ increased with drying time, for the MDF dryer, the increase in the recirculation rate and subsequent increase in exhaust air relative humidity counteracted the growing heat losses at the outlet. In total, 107.4 MJ was saved with the closing of the outlet, representing 2.1 kg of LPG worth THB 53.39 (USD 1.74). For the UMD dryer, 24.4% of the heat input was lost via unsaturated exhaust air, while for the MDF dryer, this value was 15.8%. Finally, drying curves show that the increase in the recirculation rate did not jeopardise driving forces (Fig 1-3, bottom).

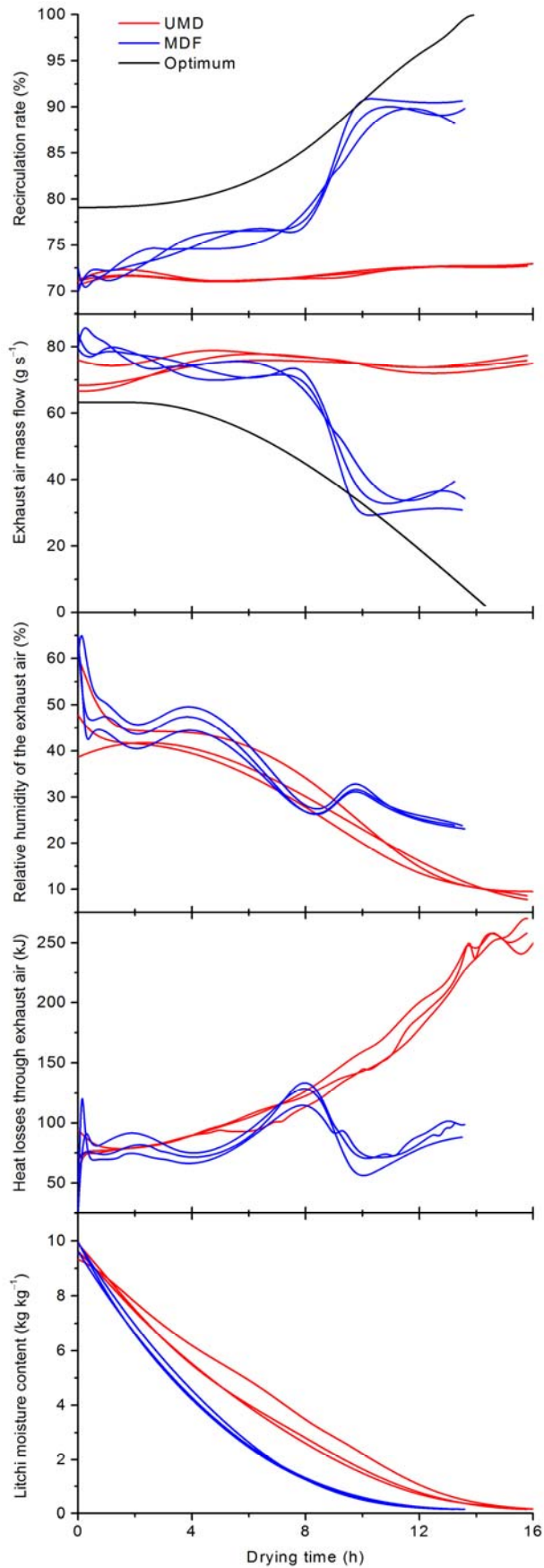


Fig 1-3. Recirculation rate, exhaust air mass flow, relative humidity and heat losses, plus drying curves for the unmodified dryer (UMD), and for the dryer with controlled air recirculation and insulation of the ducts (MDF) – modified to reduce heat losses.

Fig 1-4 shows the air velocity above the trays. To account for the rotation, measurements performed on the edge of the trays were averaged. The closing of the outlet had only a small effect on the air velocity above the tray and on air velocity distribution in the drying chamber (Fig 1-4). With the outlet completely open, average air velocity above the trays was 0.98 m s^{-1} and the coefficient of variation (CV) was 46.2%. With the outlet 50% open, the average air velocity was 0.94 m s^{-1} and the CV was 47.8%. With the outlet 15% open, average air velocity was 0.92 m s^{-1} and the CV was 49.8%. The high CVs are due to the non-uniform distribution of the air in the chamber. Fig 1-4 shows a centre-edge unequal air velocity and also a vertical gradient – with lower air velocities at the top and higher air velocities at the bottom.

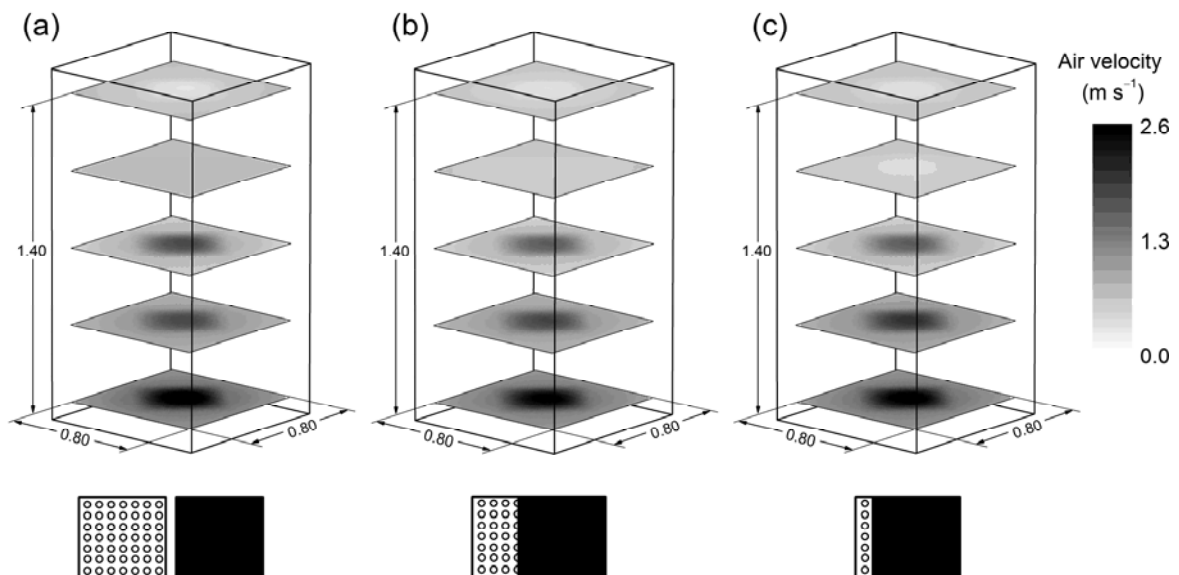


Fig 1-4. Air velocity for trays 1, 5, 9, 13 and 17, with (a) the dryer's air outlet 100% open, (b) the outlet 50% open and (c) the outlet 15% open.

1.5 Conclusions

In this study, modifications to the design of a dryer to be used by smallholder farmers and suitable for small-scale fruit processing industries were investigated. By insulating the air ducts and controlling the amount of air recirculating, a significant improvement to the energy performance of the dryer was obtained. The key findings of the study are that the design modifications made to the dryer reduced energy losses, resulted in lower energy costs and improved energy performance, without affecting air flow distribution uniformity inside the chamber. The modifications are simple enough to be incorporated into dryers already in use and into the assembly processes of companies producing such dryers in

Thailand. Further reduction in the energy requirements of litchi drying may be achieved by decreasing the fruit's initial moisture content using osmotic dehydration, and by improving the gas burner design to give better combustion.

1.6 Acknowledgments

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