DIC-Assisted Hot Air Drying of Post-harvest Paddy Rice

Sabah Mounir and Karim Allaf

Nomenclature

A_i and q_i	Coefficients of Crank solution according to the geometry of the sample
D_{eff}	Effective diffusivity of water within husks ($m^2\ s^{-1}$)
d_{eq}	Equivalent thickness of rice grain husks
k	Slope of $\ln((W_\infty - W)/(W_\infty - W_o))$ versus time (s^{-1})
P	DIC steam pressure (MPa)
t	Time (s)
t_d	DIC thermal treatment time (s)
t_D	Time taken to dry paddy rice from 32 to 12.5 % dry basis (min)
v_m	Absolute velocity of solid porous medium ($m\ s^{-1}$)
v_w	Absolute velocity of water flow within husks ($m\ s^{-1}$)
W_∞	Final water content, dry basis, in solid matrix $t \to \infty$
W	Water content, dry basis, in solid matrix at time t
W_i	Initial water content, dry basis, in solid matrix
W_o	Theoretical value of water content, dry basis, in solid matrix at starting time (% dry basis)
ρ_m	Apparent density of dry material ($kg\ m^{-3}$)
ρ_w	Apparent concentration of water in material ($kg\ m^{-3}$)
τ	Corresponds to Fick's number: $\tau = D_{eff}\left(\frac{t}{d_p^2}\right)$

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1 Introduction

Rice is one of the major cereals in the world economy. Paddy rice production stands at more than 730 million tons or 487 million tons of milled rice (FAO 2012). The moisture content of paddy rice at harvest can be as high as 28–35 % dry basis (db), especially when harvested during the rainy season. Paddy rice should be dried to typically 12–15 % db moisture content, which is known to be adequate for safe storage, milling, hulling, and whitening, and then stored as milled rice in order to prevent the production of mycotoxins (Hall 1970).

Standard drying usually involves moisture and temperature gradients within a kernel, inducing the development of a strong tensile stress gradient between the surface and the core of the kernel (Sharma and Kunze 1982). Different drying operations result in extensive kernel fissuring with a significant broken ratio during subsequent husking and milling. Hot air drying often results in over-dried grains, which become brittle and predisposed to cracking.

Drying and storage conditions (temperature, air moisture) affect all functional and structural properties (Pearce et al. 2001; Cogburn 1985). In an attempt to prevent kernels becoming more vulnerable to fissuring, researchers and the food industry have preferentially adopted low-temperature drying. Hence, the drying time is relatively long (from 8 to 12 or even 24 h) and involves a few tempering periods. Sarker et al. (1996) reported that a high initial moisture content or a high air temperature for drying resulted in a large number of fissured kernels. A related investigation indicated that the broken ratio could be related to the drying rate constant and the duration of drying (Chen et al. 1997). Others suggested the air temperature for drying should be kept below 53 °C to minimize the effect of thermal expansion on rice fissuring. Sharma and Kunze (1982) showed that only a small number of kernels fissured during drying and that most kernel fissuring occurred within 48 h after drying. After the drying stage, a milling/polishing process is carried out. Milling of the dried, cleaned paddy rice is to enable the following treatments:

- Hulling: to remove the external envelopes of the grain (hulls) to obtain brown rice
- Whitening: to eliminate the outer layers (pericarp) and the germ of the kernel by milling the brown rice to produce “white rice”

After sorting, white rice can be polished or glazed with a mixture of talc and glucose to enhance the product’s commercial value and prolong its shelf life.

Paddy is the most suitable form for the storage of rice. Usually the storage life of unmilled paddy rice and brown rice is rather short, not exceeding a few months, and is limited by the presence of insects and larvae. Fundamentally, rice is subject to the same storage requirements as any other cereal: it should be kept in cool, dry, dark conditions. Milling, which is performed to make white rice, removes the outside silver skin (aleurone layer) and the rich-in-nutrients grain germ. This increases the shelf life of rice, but at the cost of losing a large proportion of its nutrients. Furthermore, since rice is likely to absorb odors very quickly, it should be kept well away from sources of strong smells. Depending on the variety, when stored in a dry, tightly sealed container, white rice can be stored for up to 3 years.

Despite taking precautions and using low drying kinetics, the broken rice ratio is still too high and results in a relatively low yield of head rice. After industrial milling, 100 kg of paddy rice yields about 60 kg of white rice, 10 kg of broken grains, 10 kg of bran and flour, and 20 kg of hulls (FAO 2012).

The cooking time for both brown and white rice is long, close to 50 and 17 min, respectively, and only 4 min later it is overcooked.

With paddy rice, the instant controlled pressure drop (DIC) process is employed as a post-harvesting treatment to reduce drying time, improve yield, and produce higher quality brown and white rice (short cooking time, etc.).

Indeed, in numerous new unit operations, DIC technology has greatly intensified the limiting transfer phenomenon, reduced energy consumption, and can be considered an environmentally friendly process (Al Haddad 2007). DIC treatment is followed by hot air drying and shade polishing.

An optimized DIC treatment can improve the multidimensional qualities of the product in terms of its nutritional, hygienic, organoleptic, and convenience attributes. DIC treatment has many advantages in terms of processing time (not exceeding 30 s whatever the variety) and drying kinetics (about 2–3 h instead of 1 day under standard 45–50 °C hot airflow conditions). Shade polishing yields up to 67–70 % of high-quality whole-grain rice rather than the usual 52–60 %. A tasting evaluation was carried out by an international panel and the rice was found to be perfect after cooking for 6 min, and overcooked after 18 min, compared to 17 and 20 min, respectively, for the same variety of standard products. The shaded shelf life of the final product far exceeds 2 years.

2 Materials and Methods

2.1 Raw Material

A large panel of Vietnamese paddy rice was selected for investigation, with different initial moisture contents measured just after harvesting (from 28 to 35 % db), and diverse sizes and forms; with 15–25 % amylase. The samples of raw paddy rice were sorted in order to completely eliminate extraneous bodies as well as green grains and empty husks.

2.2 Treatment

In the present study a simple sorting operation was performed just after harvesting to remove waste from the paddy rice. DIC treatment is normally included as a post-harvesting stage, followed by hot air drying. The treatment design is illustrated in Fig. 1, which is a flow diagram of the main operations carried out on the paddy rice just after or 6–8 h after harvesting.

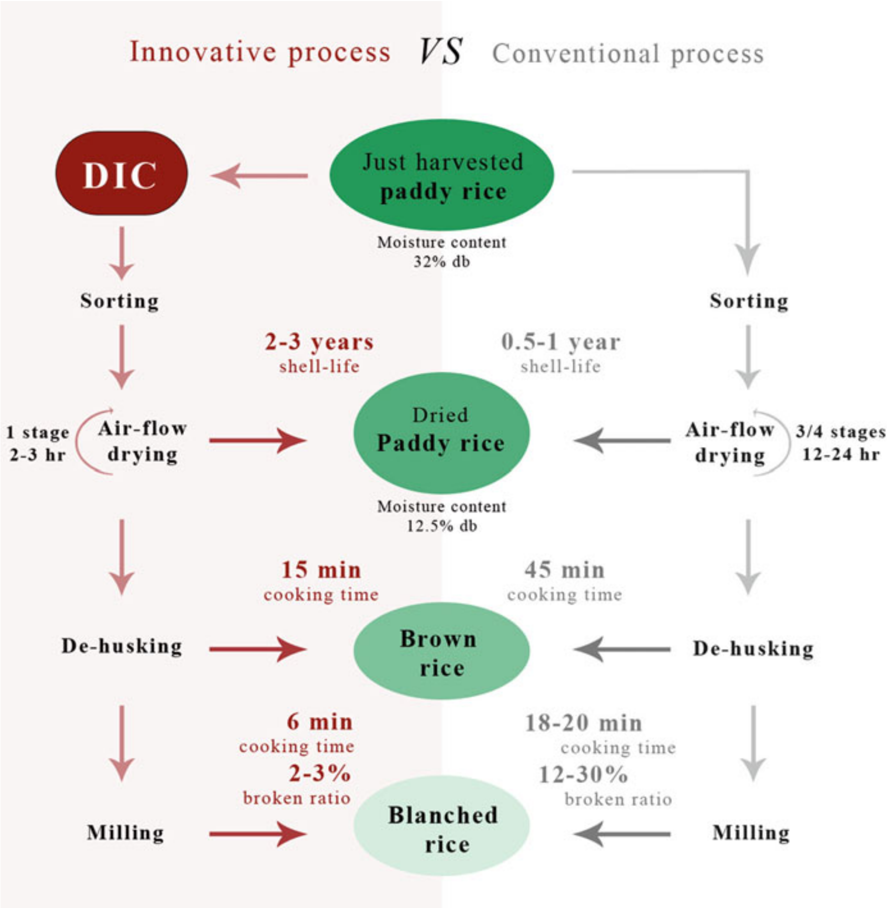

Fig. 1 Rice treatment protocol of post-harvest DIC-assisted drying

2.2.1 The Instant Controlled Pressure Drop (DIC) Process

The DIC process has been defined as two main stages of: (1) thermal treatment carried out under a high saturated steam pressure of 0.1–0.6 MPa, which allows the temperature of the product to attain between 100 and 160 °C, for a short duration of 5–60 s followed by: (2) an abrupt pressure drop towards a vacuum (4–5 kPa) with a very high decompression rate (higher than 0.5 MPa s^{-1}) which is generally maintained for 5–20 s. During the first stage, steam condensation on the surface of the grain helps to heat the paddy rice. This superficial moisture requires time to diffuse down to the core and reach homogeneous moisture and temperature levels before the pressure drops.

2.2.2 Drying Process

As soon as the paddy rice is recovered from the DIC reactor it is dried. The purpose of the drying stage is to reach a water content close to 12–14 % db. A static bed drier is used with a 2 cm thin layer of DIC-treated or -untreated paddy rice which is placed under an airflow at a constant input temperature of 50 °C. The speed of the airflow should be higher than 1.25 m s^{-1}.

Pilatowski et al. (2010) assumed the transfer mechanisms to be external and internal heat and mass transfers in this type of thermal drying process. Heat is generally transferred from air to the surface of the grain by convection and from the surface towards the grain core by conduction. There is mass transfer within the product, which, in the present case, is assumed to occur only through the liquid. Different phenomena (capillary flow, diffusion, etc.) may occur; however, the moisture gradient remains the driving force.

Duong Thai (2003) proved that mass transfer was the limiting transfer process within a paddy rice husk since it had the highest resistance to moisture diffusion (Duong Thai et al. 2008). Indeed, heat transfer and the homogenization of temperature distribution within the grain must be conducted more quickly because of the higher diffusivity of heat compared to moisture. Thus, the entire process of heating by condensation of saturated steam is controlled by the transfer of moisture within the grain; numerous studies and experiments have already confirmed that the mass diffusivity D_{eff} of moisture in a porous material is much lower than the thermal conduction diffusivity α:

$$D_{eff} \ll \alpha \tag{1}$$

Thus, by assuming drying *kinetics* is controlled by the mass transfer of water within the husks, Mounir and Allaf (2009) proposed and adopted the air-washing/diffusion model. This model is used to obtain an initial airflow that washes the surface, followed by a Fick-type diffusion process.

Experimental values can be used in the actual diffusion model to identify the effective diffusivity D_{eff}. It should be noted that the experimental data relative to the starting period should not concern the diffusion process. Furthermore, values related to the final paradoxical stage of drying (Mounir and Allaf 2008) must not be included in the model. The theoretical value W_o, calculated by extrapolating the diffusion model at $t = 0$, should be distinct from the real value of the initial water content W_i. The difference ($\delta W_s = W_i - W_o$) between this theoretical value, W_o, and the real one W_i is the starting accessibility (δW_s), with corresponds to the amount of water extracted at the beginning through the rapid interaction between the airflow and the surface, independently of any diffusion process. By modifying the matrix structure, the values of D_{eff}, W_∞, and δW_s vary and may be considered as the main response parameters characterizing the functional impact of DIC treatment.

2.3 Assessment Protocol

Paddy rice grains with a water content close to 12.5 % dry basis were dehusked and polished. The resulting white rice was separated into two categories: unbroken grains (more than nine-tenths the length of normal head rice) and broken grains. The yield and the broken ratio were consequently determined according to the following equations:

$$\text{Yield of unbroken grain} = \frac{\text{Mass of unbroken grain}}{\text{Total mass of white rice}} \tag{2}$$

$$\text{Broken ratio} = \frac{\text{Mass of broken grain}}{\text{Total mass of white rice}} \tag{3}$$

Cooking time can be determined using sensorial or instrumental methods. The first method was defined by Habba (1997). The second tasting method was conducted by a six-person international panel (one Malaysia, one Middle East, one North Africa, two France, and one Mexico). The two responses selected were the time required to reach a good level of cooking and the time required just to reach the overcooked state.

3 Results and Discussion

3.1 Drying Kinetics

Pilatowski et al. (2010) studied the kinetics of airflow drying at 50 °C with DIC-treated Mexican paddy rice just after harvesting (Morelos-A98). Here, too, the drying time t_D needed to reach 12.5 % dry basis from an initial moisture content of 32 %, was determined. DIC treatment significantly reduced the drying time of Paddy rice t_D by a factor of 5.5, down from 1,110 to 205 min.

The second main objective was to estimate the effective diffusivity D_{eff} of moisture within the grain husks. The results were systematically in agreement with the surface airflow washing/diffusion model with R^2 between 0.912 and 0.995. From a scanning electron microscope (SEM) image (Fig. 2), it was possible to calculate the equivalent thickness d_{eq} of husks from ten repeated measurements; the mean value was 79.4 ± 0.5 μm.

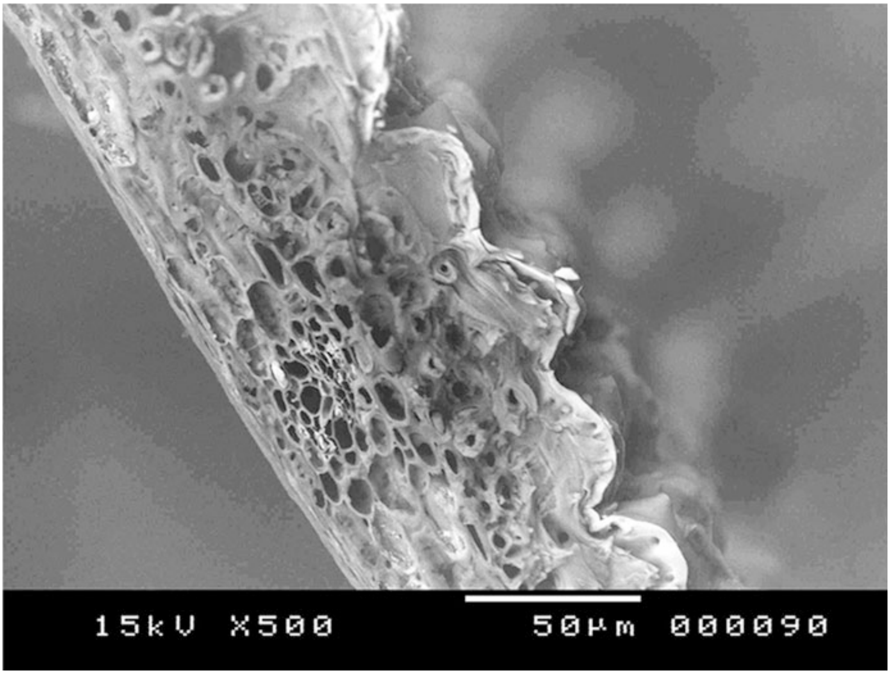

Fig. 2 SEM of husk of Mexican paddy rice (Morelos-A98)

The optimum response in terms of maximizing the effective diffusivity D_{eff} was calculated to be $D_{\mathrm{eff}} = 1.18 \pm 0.06$ E$-$13 m^2 s^{-1} for DIC treatment at a steam pressure of 0.54 MPa and a processing time of 16 s; experimental trials confirmed this value compared with $D_{\mathrm{eff}} = 0.22 \times 10^{-13}$ m^2 s^{-1} for untreated paddy rice.

3.2 Hulling, Polishing, and Yields

Breaking mainly occurs during the drying process as a result of the humidity gradient, causing mechanical strains within the grain. In standard processes, in spite of tempering periods during drying to minimize the amount of breakage, rice has a high broken ratio, exceeding 21 % of the blanched rice. Conversely, DIC treatment achieved before hot air drying, dehusking, and subsequently polishing in order to obtain white rice; resulted in a great amount of head rice. The yield that was attained in this study was around 69.5 % of the initial total amount of paddy rice. Thus, DIC treatment considerably reduces the percentage of broken grain ratio to between 1.5 and 3 %.

3.3 Cooking Time

With an international panel formed specifically for the purpose of carrying out a tasting test, the minimum cooking time and the starting point for overcooking were determined to be 5 and 18 min, respectively, for DIC-treated samples compared to 16 and 21 min, respectively, for untreated samples.

Another aspect of "cooking" time was calculated by immersing rice in cold water (20 °C). In less than 2–3 h, white rice was perfectly cooked with completely gelatinized starch.

4 Energy Consumption, Environmental Impact, and Cost

Shade experiments were used to calculate the total energy consumption of DIC treatment, which was about 250 kWh/ton of paddy rice. On a pilot plant scale, drying paddy rice from 30.5 to 12.5 % dry basis required 215 kWh/ton after DIC treatment compared with 750 kWh/ton with untreated paddy rice (Qinghua et al. 2002). From these results we concluded that the energy demand for both DIC treatment and final hot air drying was lower (415 kWh/ton instead of 750 kWh/ton) in relation to standard hot air drying, independently of operational handling.

The increase in storage time to 18 months instead of the usual 9 months, together with yields from whole grains of 97–98 % of head rice compared to 79 % for untreated rice, would confer a significant economic advantage on DIC-assisted drying if it were used just after harvesting.

The potential energy of a husk is about 4,200 kWh/ton of husk, which means that 1 ton of paddy rice contains about 840 kWh husk energy. Indeed, during the milling of paddy rice, about 70 % of the weight is recovered as broken and unbroken white grain rice. Bran represents about 8 % of the weight while 22 % of paddy rice is recovered as husk. This husk can advantageously be used as fuel in the rice mills to generate steam as well as electricity for parboiling. Paddy husk contains about 75 % volatile organic matter, and 1 ton equivalent husk has an energy equivalent to 0.75 TEP (ton equivalent petrol). The final rice husk ash is about 25 % of the weight of the husk, with around 85–90 % of amorphous silica.

So 1,260 tons of just harvested paddy rice at 30 % wb (wet basis) water content can be dried using DIC post-harvest treatment to reach the required value of 12 % wb in less than 2–3 h, without any tempering period; 1,000 tons of adequately dried paddy rice can then be obtained. The energy needed for the total operation of DIC-assisted drying to remove about 260 tons of water would be around 465 MWh. 700 tons of unbroken white grain rice and about 220 tons (22 %) of husk would be produced. By burning this husk, about 140 TEP or about 1,500 MWh could be generated.

The USDA report says that Egypt's paddy rice production in the year May 2012 to April 2013 is expected to rise to 6.37 million tons of dried paddy rice, i.e., 4.5 million tons of dried unbroken white grain DIC rice. This would be equivalent to 1.4 million tons of husk, corresponding to about 0.5 million TEP or 2.5 million barrels of petrol. DIC-assisted drying would need less than 33 % of this energy to process paddy rice.

5 Conclusion

The technology using instant controlled pressure drop (DIC) as a post-harvesting treatment for paddy rice, followed by conventional airflow drying, is one of the most efficient drying processes. The most appropriate way to use this type of two-stage drying is to apply DIC treatment just after or 6–9 h post-harvest; standard airflow drying is then very efficient. This drying strategy enables the user to increase drying performance, reduce costs, and optimize product quality. The impact in terms of decreasing the drying time is impressive: 205 min compared with 1,110 min and no tempering period needed. DIC was subsequently optimized and carried out under a steam pressure of 0.5 MPa for 16–30 s. Minimizing the broken ratio is particularly important and it was reduced to around 3 % compared to 21 % for untreated rice. The big advantage of using DIC is that the rice preserves its aromatic properties for longer. Regarding cooking, DIC rice is characterized by a short cooking time compared with untreated rice (5 min versus 15 min) and a lengthy period before the overcooked point is reached (about 18 min as against 20 min). Finally, it is worth noting the impact of DIC treatment in terms of microbial decontamination and elimination of insects, which allows a long shelf life, in excess of 18 months.

According to many studies carried out in university laboratories and in industry, the main advantages of this two-stage DIC drying have been established for a large range of paddy rice varieties.

DIC treatment used just after harvesting/sorting and before any drying stage removes the weaknesses of "normal processing" by:

- Reducing drying time (2–3 h instead of 12–24 h)
- Increasing the whole DIC drying performance through more homogeneity and lower energy consumption
- Increasing industrial processing capacities
- Reducing the broken ratio (1–3 % instead of 10–30 %), thereby increasing yields (by about 10 %)
- Shortening cooking time (6 min instead of 17 min) with a longer time before overcooking (reached 16 min after cooking instead of 4 min)

(continued)

- Preserving organoleptic content and improving grain quality
- Maintaining aromatic content
- Improving intrinsic nutritional value
- Increasing shelf life (2–3 years instead of 6 months to 1 year)

The use of husks as an energy source would be very important. It could ensure about three times more than the total energy needed for DIC-assisted drying and processing of paddy rice. In the case of Egypt, the annual rice production is about 6.4 million tons of paddy rice. Using DIC-assisted drying, the annual production of unbroken white grain rice could reach 4.5 million tons (compared with of 3.6 million tons) and 1.4 million tons of husk. This corresponds to 2.5 million barrels of petrol; only 33 % of this energy would be used in the DIC drying process as such. It would be interesting to explore the use of the bran (0.5 million tons) and ash (0.3 million tons) end products for nutritional purposes and as high-quality soil fertilizer, respectively.

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