ANALYSIS OF FLUIDIZED BED AND INCLINED BED DRYING OF PADDY FOR MALAYSIAN CONDITIONS

By

MD. SAZZAT HOSSAIN SARKER

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in fulfillment of the requirements for the degree of Doctor of Philosophy

June 2014

DEDICATION

WITH ALL MY LOVE I DEDICATE THIS THESIS

TO

MY RESPECTED TEACHERS

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in partial fulfilment of the requirement for the degree of Doctor of Philosophy

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June 2014

Chairman: Associate Professor Mohd Nordin Bin Ibrahim, PhD
Faculty: Engineering

Industrial paddy drying is very important in Malaysia in terms of rice milling quality and energy consumption. This demands that drying conditions must be used that ensure the best quality rice and consume minimum energy. Less satisfactory operation of fluidized bed drying scheme imported from Thailand for the selected drying complexes of Padiberas Nasional Berhad (BERNAS) warranted further investigation. Besides, alternative industrial drying methods practiced in the complexes of BERNAS produce different quality milled rice that needed to be assessed to promote efficient operation. Computer simulation of industrial fluidized bed paddy drying and field investigation on industrial operation of existing single stage paddy drying using inclined bed dryer (IBD) and two stage paddy drying using fluidized bed dryer follwed by IBD were carried out to evaluate the present performances and to find out the possible ways of improving of the drying operations. Systematic and simplified approaches have been developed for evaluating the comparative performances of the industrial paddy drying systems in terms of drying behavior, quality of rice and energy consumption. The effect of drying methods on mechanical properties of rice dried with industrial methods was also investigated. In addition, energy and exergy analysis of industrial fluidized bed paddy drying was undertaken to determine the type and magnitude of exergy losses during high temperature (>100 ºC) drying process. Simulation results indicated that the dryer gives better performance in terms of increased throughput capacity for drying of low initial moisture content (<30%db) paddy than drying of high moisture content paddy; the dryer could be operated up to almost double than its existing operating capacity (8.5 t/h), while high mc (>35 % db) hindered the capacity to be at or below 7.75 t/h even if higher temperature of 160 ºC was used for reducing paddy moisture to desired outlet moisture of 24-25% (db). Based on field investigation, the FBDs dryers were found to be operated at lower throughput capacity (less than 50% of their design capacity) that caused higher specific energy consumption. The FBD of the complex of Simpang Empat, Perlis and Bukit Besar, Kedah were found to be operated at 7.75 to 9.5 t/h and 8.5 to 10.36 t/h throughput capacities, respectively where the maximum design capacities of these dryers were 25 t/h and 22 t/h, respectively. The comparative results of overall analysis between two stage and single stage paddy drying revealed that two-stage drying was still more suitable than single stage drying as it could reduce total process time up to 24.5% which ultimately led to raise the daily capacity of the drying complex while head rice yield (HRY) was found to be maintained between 44.5 to 52.5 % depending on seasons. In terms of specific energy consumption, the single and two stage drying consumed 5.07 to 6.38 MJ/kg of water evaporation and 5.95 to 8.02 MJ/kg of water evaporation, respectively. On the other hand, the single stage paddy drying using comparatively lower temperature of 35-39^{o}C and two stage drying with FBD at 120 ^{o}C as first stage and followed by IBD at 35-39 ^{o}C as second stage yielded 2-3.6% higher HRY than paddy dried by single stage with IBD using comparatively higher temperature of 40-44 ^{o}C while the whiteness and milling recovery were comparable. The specific electrical energy consumption in kWh to dry each ton of fresh paddy ranged from 16.19 to 22.07 and 21.37 to 30.69 by single stage and two stage, respectively. The specific thermal energy consumption varied between 787.22 to 1015.32 MJ/t and 666.81 to 1083.42 MJ/t, respectively. The energy analysis also showed that the electrical energy up to 47% and thermal energy up to 27% could be saved, if paddy is dried by single stage drying with IBD at 40-44 ^{o}C but quality could not be maintained. The results on comparative analysis on product quality of rice dried by IBDs of two complexes indicated that HRY was significantly different at $P \leq 0.05$ from one complex to another. In reducing paddy moisture from 22-23% wb down to around 12.5 % wb, the comparative milling results indicated that IBDs of Bukit Besar complex yielded 1-4% higher HRY for paddy dried at 38-39 ^{o}C than that of Simpang Empat complex where paddy was dried using 41-42 ^{o}C in the meantime milling recovery and whiteness were comparable at acceptable milling degree and transparency. The energy and exergy analysis results have shown that energy utilization ratio (EUR) increased and exergy efficiency decreased with increased drying air temperature and paddy initial moisture content. Meanwhile, EUR and exergy efficiency were found to be varied between 5.24 to 13.38 % and 41.30 to 58.14%, respectively. Exergy efficiency can be increased through providing sufficient insulation on dryer body and recycling the exhaust air which might need to further confirm for its economic viability. Overall investigation revealed that improper selection of drying air temperature for variable moist and impurity paddy lowered the performances of FBD. Simulation results and drying operation conducted at industry site revealed that the performance of the dryer in terms of increased drying capacity can be improved by altering the operating temperature based on simulation values**.** Paddy should be dried with IBD using temperature of 35-39 ^{o}C both in single stage drying and second stage drying after fluidized bed drying to obtain 1-4 % higher HRY.

Abstrak tesis yang dikemukakan kepada Senate Universiti Putra Malaysia sebagai memenuhi syarat untuk ijazah Doktor Falsafah

ANALYSIS PENGERINGAN PADI DENGAN PENGERING FLUIDIZED BED DAN INCLINED BED BAGI KEADAAN DI MALAYSIA

Oleh

MD. SAZZAT HOSSAIN SARKER

Jun 2014

Pengerusi: Profesor Madya Mohd Nordin Ibrahim, PhD

Fakulti: Kejuruteraan

Pengeringan padi industri adalah penting di Malaysia berdasarkan kualiti beras terproses dan kegunaan tenaga. Ini menuntut kegunaan keadaan pengeringan yang mempastikan kualiti beras terbaik dan penggunaan tenaga minima. Penggunaan skim pengeringan *fluidized bed* dari Thailand di kompleks pengeringan Padiberas Nasional Berhad (BERNAS) Malaysia terpilih yang kurang memuaskan perlu kajian lanjut. Selain itu, kepelbagaian kaedah pengeringan diamalkan di komplek BERNAS menghasilkan kualiti beras terproses berbeza perlu diberi perhatian untuk meningkatkan kecekapan operasi. Simulasi berkomputer pengeringan olih pengering *fluidized bed* industri dan kajian lapangan operasi diindustri tersedia, dengan teknik pengeringan padi peringkat tunggal mengguna pengering jenis *inclined bed* (IBD) dan pengeringan padi dua peringkat mengguna pengering *fluidized bed* diikuti olih IBD, telah dijalankan untuk menilai prestasi semasa dan untuk mencari kaedah bagi meningkatkan operasi pengeringan. Pendekatan sistematik dan dipermudah telah dibangunkan untuk menilai perbandingan prestasi sistem pengeringan berdasarkan tingkah laku pengeringan, dan kualiti beras dan penggunaan tenaga. Kesan kaedah pengeringan ke atas sifat mekanik beras yang dikeringkan dengan kaedah industri juga dikaji. Di samping itu, analisis tenaga dan exergy untuk pengeringan *fluidized bed* industri juga dilakukan untuk menentukan jenis dan magnitud kehilangan exergy semasa proses pengeringan bersuhu tinggi (> 100 ºC). Keputusan simulasi menunjukkan prestasi pengering adalah lebih baik dari segi peningkatan kapasiti pengeringan untuk mengering padi berkelembapan permulaan rendah (< 30% db) berbanding padi berkelembapan tinggi; pengering boleh dikendalikan sehingga hampir dua kali ganda kapasiti operasi tersedia (8.5 t/h), manakala kelembapan tinggi (> 35% db) menghalang kemampuan untuk mencapai hanya dibawah atau pada 7.75 t/h walaupun suhu tinggi melebihi 160 ºC diguna untuk kurangkan kelembapan padi kepada kelembapan akhir diingini iaitu 24 - 25% (db). Berdasarkan kajian lapangan, pengering FBD didapati beroperasi pada kapasiti pemprosesan yang rendah (kurang daripada 50% kapasiti reka bentuk asal) menyebabkan penggunaan tenaga spesifik yang lebih tinggi. Pengering FBD terdapat di komplek Simpang Empat, Perlis dan Bukit Besar, Kedah dikesan

beroperasi pada kapasiti pemperosesan masing-masing 7.75 - 9.5 t/jam dan 8.5 - 10.36 t/jam, dimana kapasiti reka bentuk maksimum pengering tersebut adalah masing-masing 25 t/jam dan 22 t/jam. Keputusan analisis perbandingan keseluruhan antara pengeringan dua peringkat dan pengeringan tunggal mendedahkan bahawa pengeringan dua peringkat adalah lebih sesuai berbanding pengeringan tunggal kerana ia boleh mengurangkan jumlah masa pemprosesan sehingga 24.5% yang akhirnya menjurus kepada peningkatan kapasiti pengeringan harian kompleks, manakala keluaran kepala beras (HRY) dapat dikekalkan di antara 44.5 -52.5% bergantung kepada musim. Dari segi penggunaan tenaga spesifik, pengeringan tunggal dan dua peringkat mengguna masing-masing 5.07 - 6.38 MJ/kg dan 5.95 - 8.02 MJ/kg air tersejat. Walaubagaimanapun, pengeringan tunggal mengguna suhu agak rendah pada 35 – 39 ^{o}C manakala pengeringan dua peringkat dengan FBD pada suhu 120 ^{o}C sebagai peringkat pertama dan diikuti dengan IBD pada 35 - 39 ^{o}C untuk peringkat kedua dapat menghasilkan HRY pada 2 - 3.6 % lebih tinggi berbanding pengering tunggal dengan IBD pada suhu operasi yang tinggi sedikit pada 40 - 44 ^{o}C, sementara keputihan dan perolihan kisaran adalah setanding. Penggunaan tenaga elektrik spesifik dalam kWh oleh pengeringan tunggal dan dua peringkat untuk mengeringkan setiap tan padi segar adalah masing-masing antara 16.19 hingga 22.07 dan 21.37 ke 30.69. Penggunaan tenaga haba spesifik masing-masing berbeza di antara 787.22 - 1.015.32 MJ/t dan 666.81 - 1.083.42 MJ/t. Analisis tenaga juga menunjukkan bahawa penjimatan tenaga elektrik sehingga 47% dan tenaga haba sehingga 27% boleh dicapai jika padi dikeringkan secara pengeringan tunggal dengan IBD pada 40 - 44 ^{o}C tetapi kualiti tidak dapat dikekalkan. Keputusan analisis perbandingan kualiti beras yang dikeringkan oleh IBD di kedua-dua komplek menunjukkan bahawa HRY berbeza dengan ketara pada $P \leq 0.05$ dari satu komplek ke komplek yang lain. Dalam mengurangkan kelembapan padi daripada 22 - 23% wb kepada kira-kira 12.5% wb, keputusan perbandingan pengilangan menunjukkan bahawa IBD di komplek Bukit Besar memberikan bacaan HRY antara 1 - 4% lebih tinggi untuk padi yang dikeringkan pada 38 - 39 ^{o}C berbanding dengan komplek Simpang Empat di mana padi dikeringkan dengan suhu 41 - 42 ^{o}C sementara perolehan pengilangan dan keputihan adalah setanding pada darjah pengilangan dan ketelusan yang boleh diterima. Akhir sekali, kesimpulan boleh dibuat bahawa padi perlu dikeringkan dengan IBD pada suhu 35 - 39 ^{o}C dalam kedua-dua pengeringan tunggal dan pengeringan peringkat kedua selepas pengeringan *fluidized bed* untuk memperolehi nilai HRY dengan 1-4 % lebih tinggi. Keputusan analisis tenaga dan *exergy* menunjukkan bahawa nisbah penggunaan tenaga (EUR) meningkat dan kecekapan *exergy* menurun dengan peningkatan suhu udara pengeringan dan kandungan kelembapan awal padi. Sementara itu, EUR dan kecekapan *exergy* didapati berubah masing-masing antara 5.24 hingga 13.38 % dan 41.30 hingga 58.14 %. Kecekapan *exergy* boleh ditingkatkan dengan melakukan penebatan yang mencukupi pada badan pengering dan mengitar semula udara ekzos dimana prestasi economi mungkin perlu dipastikan. Pemilihan suhu udara pengering yang tidak sesuai dengan kelembapan padi dan kandungan bendasing akan merendahkan prestasi. Keputusan simulasi dan hasil operasi pengeringan di tapak industri mendedahkan bahawa prestasi pengering dari segi kapasiti pengeringan boleh ditingkatkan dengan mengubah suhu operasi berasaskan hasil simulasi. Akhir sekali, kesimpulan boleh dibuat bahawa padi perlu dikeringkan dengan IBD pada suhu 35 - 39 ^{o}C dalam kedua-dua pengeringan tunggal dan pengeringan peringkat kedua selepas pengeringan dengan *fluidized bed* untuk memperolehi nilai HRY dengan 1-4 % lebih tinggi.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Nordin Bin Ibrahim, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Salleh Punan, PhD
Deputy Director
Food Technology Research Centre,
MARDI
(Member)

Norashikin Abdul Aziz, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

Declaration by the student

I hereby confirm that:

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Symbol	Meanings	Unit
A	Area	m^2
A_d	Dryer surface area	m^2
Av.	Average	-
c_a	Specific heat of dry air	kJ/kg.°C
c_p	Specific heat of dry grain	kJ/kg.°C
c_v	Specific heat water vapor	kJ/kg.°C
c_w	Specific heat of liquid water	kJ/kg.°C
C.O.P	Coefficient of performance	-
Cond.	Conditioner	
D	Inside pipe diameter	m
Df	Degree of freedom	-
D	Solid fraction in paddy	-
E	Apparent modulus of elasticity	MPa
E	Relative error	-
E_{ff}	Combustion efficiency	%
E.H.E	Effective heat efficiency	%
EMC	Equilibrium moisture content	%
E_r	Ratio of energy required	-
E_s	Energy supplied	kJ/s
ERH	Equilibrium relative humidity	-
F	Feed rate/Peak bending force	Kg/s or t/h / N
FBD	Fluidized bed dryer	-
FMC	Final moisture content	%
G	Fracture energy and airflow rate	J/m^2
H	Humidity ratio or absolute humidity	Kg moisture /kg dry air
HT	High temperature	
Ha	Convective heat transfer coefficient	$w/m^2.K$
H	Bed thickness/hour/Specific enthalpy	M or kJ/kg
Heap.	Heaped/heaping	
HR	Head rice	-
HRY	Head rice yield	%
H.U.F.	Heat utilization factor	-
I	Impurity	-
L	Length of dryer	M
LT	Low temperature	
LSU	LoussianaStae University	
IBD	Inclined bed dryer	-
IRRI	International rice research institute	-
M	Moisture content of grain	% or fraction
KBB	KilangBeras BERNAS	
M_i	Initial moisture content	% or fraction
M_f	Final moisture content	% or fraction

M_e	Equilibrium moisture content	% or fraction
MR	Average moisture ratio	-
MRD	Mean relative deviation	Fraction or %
N	Number of data points/Layers	
P	Amount of dry product	Kg
RH	Relative humidity	%
PVS	Saturation vapor pressure	Pa
P_v	Vapor pressure	Pa
P_{atm}	Atmospheric pressure	Pa
P_{swb}	Saturation vapor pressure at T_{wb}	Pa
R^2	Coefficient of determination	
T_i	Initial air temperature	^oC
T	Air temperature	^oC
t	Time	Second/Minute/hour
delt	Time step	^oC
T_m1	Initial paddy temperature	^oC
T_m2	Paddy temperature after drying	^oC
T_{wb}	Wet bulb temperature	^oC
T_d	Drying air temp., ^oC	^oC
T_o	Outlet air temperature, ^oC	^oC
TAW	Residence time	min
U	Overall heat transfer coefficient	$W/m^2.K$
V	Air velocity / Amount of vapour	m/s or kg
W	Width of dryer	m
WKP	Whole kernel percentage	
Δp_f	Pressure drop	kPa
ρ_p	Grain density	kg/m^3
ρ	Air density	kg/m^3
μ	Coefficient of viscosity	Pa.s
δ	Deformation	mm
σ	Bending strength	MPa

Subscripts

am	Ambient
da	Drying air
di	Dryer inlet
do	Dryer outlet
e	Environment
f	Final
i	Initial
o	Outlet
1	Initial
2	Outlet

CHAPTER 1

INTRODUCTION

1.1 Overview

Paddy drying is a solemn issue in all paddy-producing countries. It sometimes becomes a crucial problem in humid tropical climates like Malaysia. Because, it is the most critical operation after harvesting rice crop. Efficient management of the influx of freshly harvested paddy is an important factor to the millers for maintaining quality of rice. Freshly harvested paddy with high moisture content (mc) of 25–35% has to be rapidly dried down to 18–20% for temporary storage (it is noted that the moisture content is expressed on the percentage wet basis throughout this chapter unless stated otherwise). Delay in drying, incomplete or ineffective drying will reduce grain quality and enhance postharvest losses. In tropical countries, paddy is usually harvested at high moisture content between 20 and 25% (Inprasit and Noomhorm, 2001 and Igathinathane *et al.*, 2008). Further drying down to 12–14% mc is important for prolong storage prior to milling. Drying methods have a direct effect on energy consumption and quality of rice. Numerous drying options have been investigated for quality rice. Besides single stage, two stage paddy drying are being practiced at industry level in many countries like Thailand, the Philippines, Indonesia, Taiwan and Malaysia. Both single stage drying with inclined bed dryer (IBD) and two stage drying with fluidized bed dryer (FBD) followed by conditioner (for tempering and cooling) and IBD are being used in commercial paddy drying complexes of Padiberas Nasional Berhad (BERNAS) in Malaysia. The schematic diagrams of two basic types of industrial FBD have been shown in Figure 1.1a and Figure 1.1b.

During two-stage drying system, firstly the high moisture grain would be dried by air at high temperature and high velocity to medium moisture level between 18-19%. Subsequently, in the second stage of drying, ambient air temperature and low airflow would be used to reduce the grain moisture to the safe level usually at 13-15%. Two stage grain drying strategy has been suggested by many researchers (Bhattacharya *et al*., 1971; Sutherland and Ghaly, 1990; Soponronnarit , 1997 and Thakur and Gupta, 2006). Jittanit *et al*. (2010a) reported the feasibility of two stage drying for high moisture seeds of corn, wheat and rice to achieve higher germination rate (more than 90%).

Even though use of fluidized bed dryer for grain drying has been reported earlier by Abid *et al*., 1990; Sutherland and Ghaly, 1990; Tumambing and Driscoll, 1991 but research and development works on fluidized bed paddy drying technique beginning with an experimental batch dryer and climaxing with a commercial continuous flow dryer were carried out by Soponronnarit research group (Soponronnarit and Prachayawarakorn, 1994; Soponronnarit *et al*., 1995; Soponronnarit *et al*., 1996a; Soponronnarit *et al*., 2001).

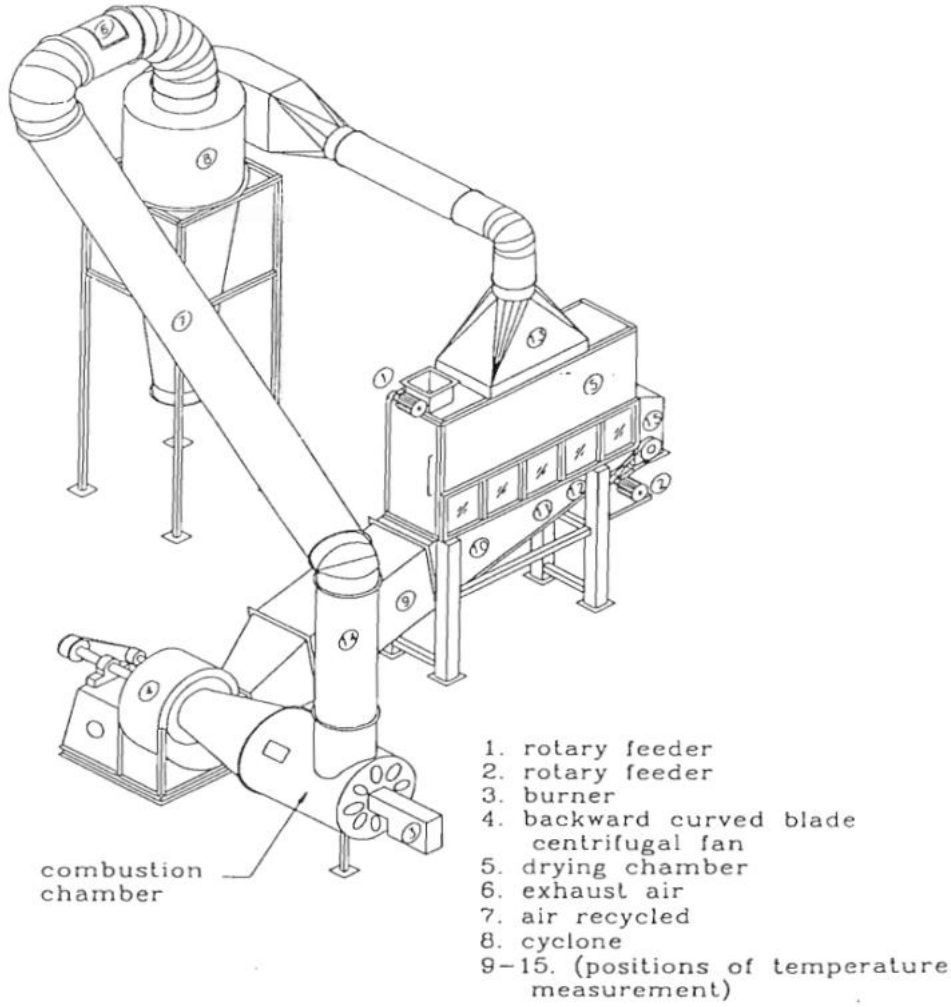

Figure 1.1a. Commercial fluidized bed paddy dryer (diesel or oil fuel operated)
(Source: Soponrannarit *et al*. 1996b).

Two-stage drying by a FBD with tempering and ventilation as elements of each stage yielded a higher rice quality and thermal efficiency compared with single-stage drying (Prachayawarakorn *et al*., 2005a). Fluidized bed drying as first stage or pre-drying of moist paddy has been suggested by Sutherland and Ghaly (1990). Soponronnarit (1997) and Poomsa-ad *et al.* (2001a) recommended that in order to save energy and obtain a high head-rice yield, damp paddy should be dried in a fluidized bed dryer (FBD) for the first stage to 18-19% moisture content (mc) followed by tempering and then be dried by ambient air ventilation to 12-14% mc. Meanwhile, in-store dryer or deep bed dryer, ambient air ventilation or sun drying methods are widely used for further or complete moisture reduction for safe storage of paddy. The most common dryer for paddy drying in Asia is fixed deep bed dryer either in the form of rectangular bins such as flat bed and inclined bed or circular bins IRRI.www.knowledgebank.irri.org at @EbookBrowse).

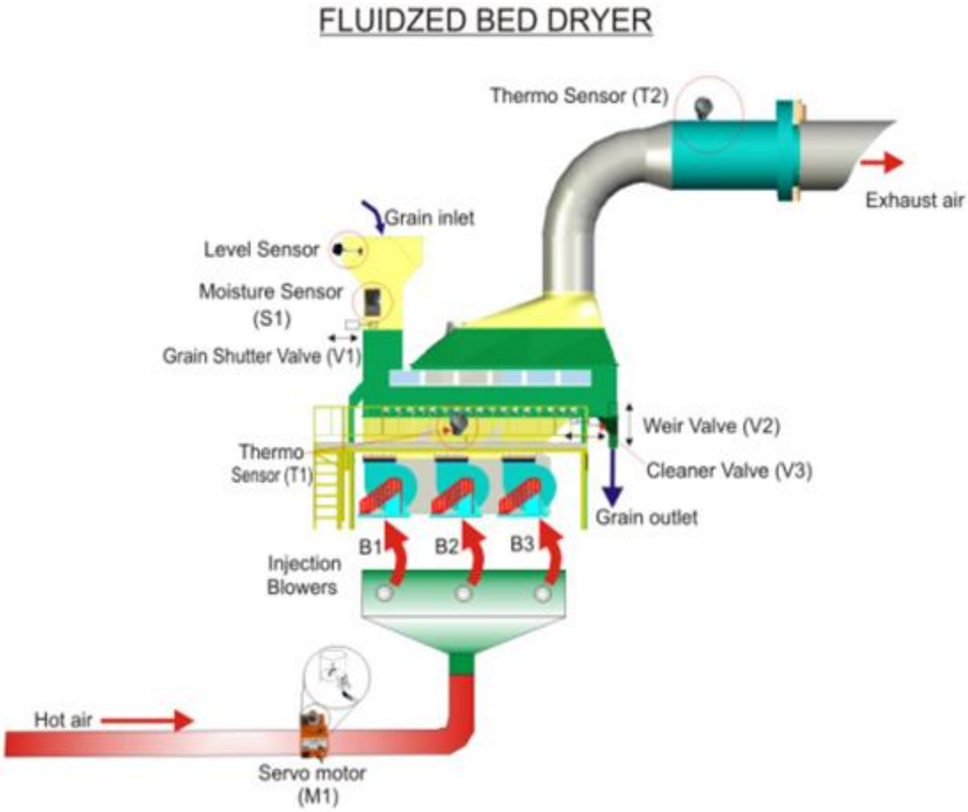

Figure 1.1b. Commercial fluidized bed paddy dryer (rice husk operated)
(Source: Int. Rice Engineering Co. Ltd, Thailand and BERNAS, Malaysia).

However, IBD is very popular as single stage dryer for complete drying of paddy in commercial rice mills of Malaysia. Recently, IBD is found to be used as second stage dryer after fluidized bed dryer (FBD) in very few drying complexes of BERNAS. IBD is a type of deep bed or fixed bed dryer in which the drying bed is inclined to get advantages for easy and faster discharge of paddy after drying as shown in Figure 1.2.

On the other hand, in terms of product quality, Bhattacharya *et al*. (1971) suggested that the breakage of rice during milling could be considerably reduced if a two-stage drying process was applied. Soponronnarit *et al*. (1998a) also reported that the yellowing rate of paddy was significantly affected by temperature, water activity and their interaction. Formation of fissures in grain and subsequent breakage denote mechanical failures of rice kernels. Hence, effects of drying methods or drying temperature on various mechanical properties need to be assessed that can ultimately affect milled rice quality.

Figure 1.2 Pictorial view of industrial inclined bed dryer

Previous researchers (Ban, 1971; Choudhury and Kunze, 1972; Kunze, 1979; Bonazzi *et al*., 1997; Cnossen and Siebenmorgen, 2000; Fan *et al.*, 2000) reported fissure formation phenomenon in rice kernels under different drying conditions. They added that fissures decline the structure and hardness of kernels and consequently reduce head rice yield. Among various mechanical properties, tensile strength was measured by Kunze and Choudhury (1972) while compression and bending tests were determined by many (Husain *et al*., 1971; Kunze and Choudhury, 1972; Prasad and Gupta, 1973; Chattopadhyay et al., 1979; Nguyen and Kunze, 1984; Bamrungwong *et al*., 1987, 1988; Wouters and Baerdemaeker, 1988; Chattopadhyay and Hamann, 1994; Kamst *et al.*, 1999). However, effect of industrial drying methods (where various drying temperature from higher temperature of 120 ºC to lower temperature of 35-45 ºC usually used) on bending strength, young's modulus of elastic and fracture energy) are seldom reported.

One of the most important challenges of the drying industry is to reduce the cost of energy for good quality dried products (Dincer, 1998). Soponronnarit (1998a) recommended that under hot and humid climates, paddy should be dried with low air flow rate and near-ambient air to minimize energy consumption and moisture gradient in grain bed and to obtain high percentage of head rice yield. Instead, two stage drying process was suggested by Bhattacharya et al. (1971) to reduce the breakage of rice during milling.

Despite the wide application of stage drying with the combination of different drying systems, such as the fluidized bed or spouted bed drying method with ambient air ventilation, deep bed drying or in-store drying and stationary bed for paddy or food grain drying, there are limited published studies relevant to single stage drying with the inclined bed dryer, and two stage drying with the fluidized bed dryer with or without the provision of tempering as the first stage followed by the inclined bed dryer as the second stage dryer. Generally, there are some discrepancies in drying practices regarding operating parameters and in drying performances based on energy consumption and quality of the final product between the industry and the laboratory. Hence, it is necessary to evaluate the performance of any dryer or drying system to check its operational status. Therefore, one of the objectives of this study was to assess the actual drying practices of the commercial paddy drying process and to suggest the suitable drying strategy based on drying kinetics, energy consumption and final quality of rice for the rice processing complex of BERNAS within the present physical facilities.

Although previous researchers have reported different efficient paddy drying techniques associated with energy consumption and product quality, yet, very few published research works have appeared on effect of drying method on overall energy consumption (i.e energy to process per ton of paddy) and rice quality especially for the case of industrial paddy drying with FBD and IBD in Malaysia. Moreover, a thorough engineering assessment might be required for industry to introduce the suitable drying option at their processing plant based on energy utilization and expected quality of milled rice.

1.2 Problem statement

Efficient management of high moisture and impurity freshly harvested paddy through two stage drying with fluidized bed dryer (FBD) followed by inclined bed dryer (IBD) is a challenging issue for BERNAS rice processing complexes. Because, this is newly introduced drying practice at selected commercial sites of BERNAS. Less satisfactory operation of fluidized bed drying scheme imported from Thailand warranted further investigation for Malaysian condition. The operating parameters of FBD such as drying air temperature, bed thickness, air velocity and feed rate are not selected based on weather and paddy conditions which really vary season to season, day to day even batch to batch. As experienced during field observation, the drying air temperatures were also not selected judicially to dry greatly variable moisture content paddy for the case of both FBD and IBD thus affecting the product quality and elevating processing cost. Therefore, it was necessary to evaluate the performance of the existing two stage and single stage industrial paddy drying system to check their operational status in terms of drying kinetics, rice quality and energy consumption for Malaysian paddy conditions. Besides, the rice industry communities are found less careful about the world concern of energy usage issues especially in using thermal energy as its source is rice husk which is obtained as by-products at mill site. So energy and exregy analysis are very important to evaluate very high temperature (>100ºC) fluidized bed paddy drying in order to determine the scopes of improvement of the available useful energy at industry site.

1.3 Goal of the study

These research works focused on improvement of industrial paddy drying in BERNAS, Malaysia. The main goal of this study was to evaluate and improve the industrial fluidized bed paddy drying. Besides, the activities were also aimed in evaluating the effect of different drying methods on the rice quality, mechanical properties and energy consumption during drying of paddy using industrial inclined and fluidized bed dryer that can be used in suggesting for further improvement of current drying practices at mill site. This study can be a guide for the rice industry to select suitable drying options and drying parameters as well for achieving better quality rice at reasonable energy usage.

1.4 Specific objectives

The specific objectives of the study were as follows:

1. To develop a computer simulation model in order to study industrial fluidized bed paddy drying behaviour and to select suitable operating parameters to ascertain possible maximum throughput capacity of the dryer at reasonable energy usage.
2. To evaluate the performances of industrial paddy drying operations with inclined bed dryer (IBD) and fluidized bed dryer (FBD) with or without tempering provision based on drying kinetics, quality of rice and energy consumption for determining the suitable drying options.
3. To investigate the effect of industrial drying methods on mechanical properties of rice.
4. To analyse energy and exergy efficiencies of industrial fluidized bed paddy drying.

1.5 Outline of the thesis

Next to the introductory chapter, the review of literature on paddy drying, modeling and simulation on fluidized bed paddy drying, industrial paddy dryers including fixed bed dryer & fluidized bed dryer with their quality and energy & exergy analysis are presented in Chapter 2. The overall approaches for the research with clarification of the reasons of splitting out the chapters are presented in Chapter 3. The concept for developing the mathematical model and systematic approach for simulation in reducing paddy moisture and calculating energy consumption by fluidized bed dryer and subsequently validating the model with the industrial drying data and research data are discussed in Chapter 4. In Chapter 5, Industrial paddy drying with inclined bed and fluidized bed dryer based on their usual practices and improved operational approach with subsequent outcomes of this study are explained. A critical assessment of current drying practices based on drying behaviour, milled rice quality and energy consumption and further guidelines for the industry are also offered in this chapter. In Chapter 6, the effect of industrial drying methods on mechanical properties of paddy is focused. In addition, energy and exergy analysis of industrial fluidized bed paddy drying are discussed in Chapter 7. Finally, the conclusions of this work and further recommendations are presented in Chapter 8.

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