



THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Master of Science (Food Science)

DEGREE

Food Science

Food Science and Technology

FIELD

DEPARTMENT

TITLE: Drying Kinetics and Optimization for Instant Brown Rice Process

NAME: Mr. Tuan Quoc Le

THIS THESIS HAS BEEN ACCEPTED BY

THESIS ADVISOR

(Mr. Weracheet Jittanit, Ph.D.)

THESIS CO-ADVISOR

(Associate Professor Prisana Suwannaporn, Ph.D.)

DEPARTMENT HEAD

(Assistant Professor Wannee Jirapakkul, Ph.D.)

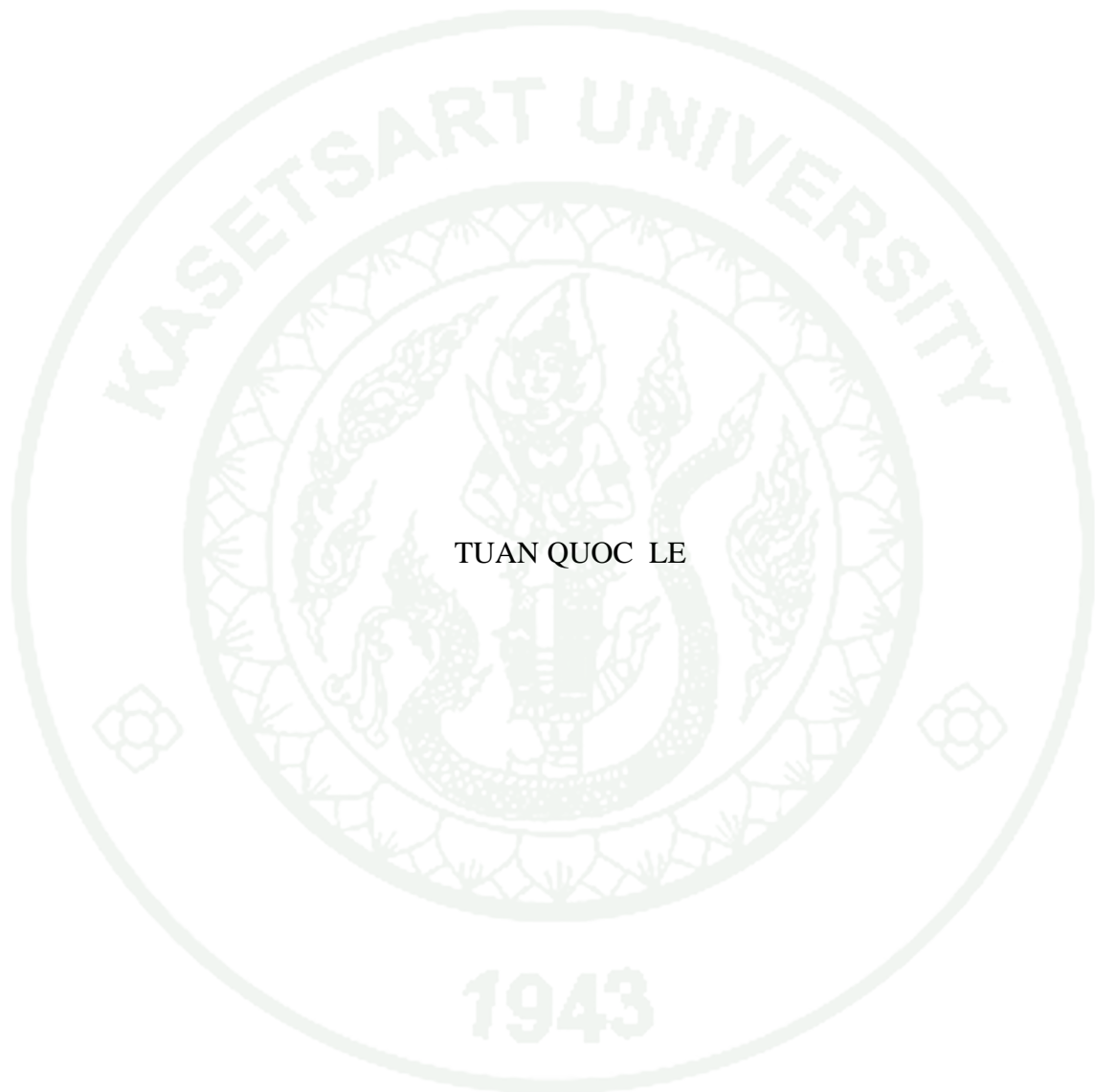
APPROVED BY THE GRADUATE SCHOOL ON

DEAN

(Associate Professor Gunjana Theeragool, D.Agr.)

THESIS

DRYING KINETICS AND OPTIMIZATION FOR INSTANT BROWN
RICE PROCESS



TUAN QUOC LE

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Master Science (Food Science)
Graduate School, Kasetsart University
2012

Tuan Quoc Le 2012: Drying Kinetics and Optimization for Instant Brown Rice Process.
Master of Science (Food Science), Major Field: Food Science, Department of Food
Science and Technology. Thesis Advisor: Mr. Weerachet Jittanit, Ph.D. 153 pages.

Two major parts conducted in this study were drying kinetics and optimization of operating process parameters for instant brown rice production. The single-stage drying in hot air oven (HAO) and microwave oven (MWO) and second-stage drying in MWO, fluidized bed dryer (FBD) and HAO were carried out to dry the cooked brown rice samples. The MWO appeared to be a suitable dryer for producing instant brown rice due to very fast drying rate, higher moisture diffusion possibly creating the porous structure and less shrinkage of dried-cooked brown rice whilst a dense structure and collapse was found at single stage drying in HAO. The less effect of drying was found at second-stage drying in FBD for temperature range of 160-200°C. Hii et al.'s model and Verma's model fitted well with the experimental data of conventional drying in HAO (single-stage and second-stage) and FBD (second-stage) whereas for MWO (single-stage and second-stage), Verma and Milikucut's model was the best fit model. Two modified models, modified Page and two-compartment, provided a wide range application for both convective drying and microwave drying as well as a reasonable goodness of fit.

Box-Benken design, with three factors involving water-rice ratio, microwave power level, and hot air temperature was applied to optimize the operating process parameters for color, rehydration ratio, and texture of instant brown rice. The microwave power showed the most effect on rehydration ratio whilst the ratio of water to rice affected on hardness and stickiness of rehydrated instant brown rice. All of 3 factors influenced on colour intensity of rehydrated cooked brown rice whereas microwave power level and hot air temperature showed the interaction effect on lightness. The higher operating parameters provided the higher rehydration ratio, higher lightness and lower colour intensity value. Hardness reduced as increase of water-rice ratio, microwave power and hot air temperature. Lower water-rice ratio, higher hot air temperature and higher microwave power levels resulted in less energy consumption due to the required shorter processing time. The operating parameters for optimal response were 1.58237, 595 W, 90 °C for water-rice ratio, microwave power level and hot air temperature respectively. This optimum condition provided the overall desirability of 82.3%.

Student's signature

Thesis Advisor's signature

ACKNOWLEDGEMENTS

I would like to sincerely express my appreciation and gratitude to Dr. Weerachet Jitanit, my thesis advisor for his advice, encouragement, and valuable suggestions, throughout the study. I would like to send my gratefulness to my committee, Assoc. Prof. Dr. Prisana Suwannaporn, my co-advisor and Dr. Savitree Thammathongchat for their comments and suggestions.

I would like to gratefully thank to the Dean of Faculty of Agro-Industry, the Head of Department for their valuable advices and their kindly providing scholarship for 2 years tuition fee.

I also would like to thank to all faculty members and staffs in the Department of Food Science and Technology, Faculty of Agro-Industry, Kasetsart University for their helpful assistance during my study. I would like to thank for the warm welcome and kindness of all friends both in Thailand and in Vietnam helping me for the period of 2 years.

I am especially appreciated my parents for their endless heartfelt support, love and care.

Tuan Quoc Le
April 2012

TABLE OF CONTENTS

	Page
TABLE OF CONTENTS	i
LIST OF TABLES	ii
LIST OF FIGURES	iv
LIST OF ABBREVIATIONS	viii
INTRODUCTION	1
OBJECTIVES	3
LITERATURE RIVIEW	4
METERIALS AND METHODS	35
Materials	35
Methods	37
RESULTS AND DISCUSSION	55
CONCLUSION AND RECOMMENDATIONS	101
Conclusion	101
Recommendations	102
LITERATURE CITED	104
APPENDICES	120
Appendix A Pre-treatment and drying preliminary test	121
Appendix B Texture determination and microscopy image capture	125
Appendix C Response surface methodology	129
Appendix D Experimental data	139
CURRICULUM VITAE	153

LIST OF TABLES

Table	Page
1 Thin layer drying models	42
2 The moisture diffusivity values determined by regular regime method and the parameters for Arrhenius relationship.	64
3 Regression coefficients and Analysis of Variance for responses and coefficients of determination.	80
4 Optimal parameters corresponding with each responses.	82
5 Mean values and standard deviation of dried cooked brown rice and rehydrated cooked brown rice color	91
6 Correlation coefficients between texture and physical properties of instant brown rice.	96
7 Specific energy consumption by different experimental runs.	97
8 Predicted response values at optimum by desirability function	98
9 Factor Settings at Optimum for multi-responses	99
 Appendix Table	
C1 Experimental runs (code values) of 3 factors for Box-Behnken design.	135
D1 Results of the fitting experimental data into various thin-layer drying models for single-stage drying in HAO at 50, 70 and 90°C	140
D2 Results of the fitting experimental data into various thin layer models for single-stage drying in MWO at power level of 425 W, 595 W and 850 W.	141
D3 Results of the fitting experimental data into various thin-layer drying models for the second-stage drying in HAO at 50, 70 and 90°C.	143

LIST OF TABLES (Continued)

Table		Page
D4	Results of the fitting experimental data into various thin-layer drying models for second-stage drying in FDB at 160, 180 and 200°C.	144
D5	Results of the fitting experimental data into various thin layer models for second-stage drying in MWO at power level of 425 W, 595 W and 850 W.	145
D6	Results of fitting the experimental data into various models for predicting the moisture diffusivity as a function of moisture content.	147
D7	Results of fitting the experimental data for empirical model of instant brown rice drying.	149
D8	Controlled values and optimization goals for texture and physical properties of instant brown rice	151
D9	Texture and physical properties of optimal operating process conditions and freshly cooked brown rice	151
D10	Correlation coefficients between textural and physical properties of instant brown rice.	152

LIST OF FIGURES

Figure		Page
1	Experimental plan 1	38
2	Experimental drying plan 1	39
3	The procedures of fitting the thin layer drying models	43
4	Experimental plan 2: Instant brown rice production	50
5	Drying characteristics of cooked brown rice during single-stage drying in HAO (◆ = 50°C; ▲ = 70°C; ■ = 90°C)	56
6	Drying characteristics of cooked brown rice during single-stage drying in MWO (◆ = 425 W; ▲ = 595 W; ■ = 850 W).	57
7	Drying rate curves of cooked brown rice during single-stage drying in HAO (◆ = 50°C; ■ = 70°C; ▲ = 90°C) and MWO (× = 425 W; + = 595 W; ● = 850 W)	58
8	Drying characteristics of cooked brown rice during second-stage drying in HAO (◆ = 50°C; ▲ = 70°C; ■ = 90°C)	59
9	Drying characteristics of cooked brown rice during second-stage drying in FDB (◆ = 160°C; ▲ = 180°C; ■ = 200°C)	59
10	Drying characteristics of cooked brown rice during second-stage drying in MWO (◆ = 425 W; ▲ = 595 W; ■ = 850 W)	60
11	Drying rate curves of cooked brown rice during second-stage drying in HAO (◆ = 50°C; ■ = 70°C; ▲ = 90°C), FDB (× = 160°C; ■ = 180°C; ● = 200°C) and MWO (+ = 425 W; ▲ = 595 W; — = 850 W).	60
12	Effective moisture diffusivities determined by slope method for single-stage drying in HAO (◆ = 50°C; ■ = 70°C; ▲ = 90°C) and MWO (— = 425 W; + = 595 W; ● = 850 W).	66

LIST OF FIGURES (Continued)

Figure		Page
13	Effective moisture diffusivities determined by slope method for second-stage drying in HAO (◆ = 50°C; ■ = 70°C; ▲ = 90°C), FDB (× = 160°C; ▲ = 180°C; ● = 200°C) and MWO (+ = 425 W; ◆ = 595 W; - = 850 W).	67
14	Porosity curves of cooked brown rice during single-stage drying in HAO (◆ = experimental 50°C; ▲ = experimental 70°C; ■ = experimental 90°C; - - - = predicted 50°C; — = predicted 70°C; = predicted 90°C).	69
15	Porosity curves of cooked brown rice during single-stage drying in MWO (◆ = experimental 425 W; ▲ = experimental 595 W; ■ = experimental 850 W; - - - = predicted 425 W; — = predicted 595 W; = predicted 895 W).	69
16	Porosity curves of cooked brown rice during second-stage drying in HAO (◆ = experimental 50°C; ▲ = experimental 70°C; ■ = experimental 90°C; - - - = predicted 50°C; — = predicted 70°C; = predicted 90°C).	70
17	Porosity curves of cooked brown rice during single-stage drying in FBD (◆ = experimental 160°C; ▲ = experimental 180°C; ■ = experimental 200°C; - - - = predicted 160°C; — = predicted 180°C; = predicted 200°C).	70
18	Porosity curves of cooked brown rice during second-stage drying in MWO (◆ = experimental 425 W; ▲ = experimental 595 W; ■ = experimental 850 W; - - - = predicted 425 W; — = predicted 595 W; = predicted 850 W).	71

LIST OF FIGURES (Continued)

Figure		Page
19	True density of cooked brown rice after drying by (a) Single-stage drying in HAO (◆ = 50 °C; ▲ = 70 °C; ■ = 90 °C); (b) Single-stage drying in MWO (◆ = 425 W; ▲ = 595 W; ■ = 850 W); (c) Second-stage drying in HAO (◆ = 50 °C; ▲ = 70 °C; ■ = 90 °C); (d) Second-stage drying in FBD (◆ = 160 °C; ▲ = 180 °C; ■ = 200 °C); (e) Second-stage drying in MWO (◆ = 425 W; ▲ = 595 W; ■ = 850 W).	75
20	Images of samples captured from stereo microscope at 16x magnification (Freshly cooked 1 = Freshly cooked brown rice sample no.1; Freshly cooked 2 = Freshly cooked brown rice sample no.2; Pretreated = Cooked brown rice after freezing and thawing pretreatment; HAO = Sample after single-stage drying in HAO; MWO = Sample after single-stage drying in MWO; MWO-HAO = Sample after two-stage drying in MWO and HAO; MWO-FBO = Sample after two-stage drying in MWO and FBO; MWO-MWO = Sample after two-stage drying in MWO and MWO).	76
21	Interaction plot of WRr (A) with MWI (B) and HAt (C) for rehydration ratio	84
22	Surface - contour plot for rehydration ratio of dried cooked brown rice as a function of different processing conditions.	84
23	Surface - contour plot for rehydration ratio of dried cooked brown rice as a function of different processing conditions.	85
24	Interaction plot of MWI (B) with WRr (A) and HAt (C) for lightness	86
25	Surface - contour for lightness of rehydrated cooked brown rice as a function of different processing conditions.	86
26	Surface - contour for lightness of rehydrated cooked brown rice as a function of different processing conditions.	87

LIST OF FIGURES (Continued)

Figure		Page
27	Interaction plot between MWI (B) and HAt (C) for color intensity	88
28	Surface - contour for color intensity of rehydrated cooked brown rice as a function of different processing conditions.	89
29	Surface - contour for color intensity of rehydrated cooked brown rice as a function of different processing conditions	90
30	Surface - contour for stickiness of rehydrated cooked brown rice as a function of different processing conditions.	93
31	Surface - contour for stickiness of rehydrated cooked brown rice as a function of different processing conditions.	94
32	Desirability plot for multi-optimization of dried cooked brown rice as a function of different processing conditions.	99
 Appendix Figure		
B1	Force vs. time plot from measuring the texture of instant brown rice.	127
C1	Design points are at the midpoints of edges of the design space and at the center.	130
C2	Response surface methodology	132

LIST OF ABBREVIATIONS

ε	=	Porosity
A, A ₁ , B, N	=	Constants
a, b, c, d	=	Constants.
a ₀ , a ₁ , a ₂ , a ₃ , a ₄	=	Constants.
D _{eff}	=	Effective moisture diffusivity (m ² /s)
D ₀	=	Pre-exponential factor of the Arrhenius equation (m ² /s)
E _a	=	Activation energy (kJ/mol).
FDB	=	Fluidized bed dryer
HAO	=	Hot air oven
K, K ₁ , K ₂	=	Drying rate constants (1/min)
M _e	=	Equilibrium moisture content (% dry basis)
M _i	=	Initial moisture content (% dry basis)
mc	=	Moisture content (% dry basis)
MR	=	Moisture ratio
MR _{exp}	=	Experimental moisture ratio
MR _{pre}	=	Predicted moisture ratio
M _t	=	Moisture content at specified time (% dry basis)
MWO	=	Microwave oven
n	=	Constant, positive integer
PE	=	Mean relative percent error (%)
R ²	=	Determination of coefficient
R _c	=	Universal gas constant (kJ/mol K)
RMSE	=	Root mean square error
T _K	=	Drying temperature (K)
ρ _b	=	Bulk density (Kg/l)
ρ _p	=	True density (Kg/l)

DRYING KINETICS AND OPTIMIZATION FOR INSTANT BROWN RICE PROCESS

INTRODUCTION

It is widely known that rice is one of the most popular food grains in the world. More than a half of the world's population consume rice as a main food, especially for Asian people. In accordance with the traditional cooking practice, the rice, however, has to be boiled or steamed for a long period prior to eating which is considered as an inconvenience practice. Furthermore, it would be more inconvenient even impossible to cook rice if people are off from home cooker.

The majority of people have often eaten white rice, which is polished and almost removed the velamen of rice after de-husking. Many components of nutrition such as essential vitamins presenting at this layer were removed. It would be a healthy and convenient practice if people turn to consume brown rice instead of white rice due to its wealthiness of nutrition, especially vitamin B.

As a tendency changes in modern lifestyle with industrial development, the processed convenience food products-instant foods have been interested. Instant food means simple, fast, and convenient food, which is easy and instant to prepare besides being hygienic, free from microbial contamination, and also convenient to eat. In the modern days where the life is at fast pace with the time, the instant foods play an important role in people's day-to-day life especially for rice product. It is apparent that rice products with the short time in cooking before serving and the nutritional assurance have been expected. Therefore, the instant brown rice product would be considered as a solution for this expectation.

So far, the current knowledge has been very limited and still insufficient to produce high quality instant brown rice that requires only short time rehydration and comparable quality with the normally cooked brown rice. The thermal process and drying technology including pre-treatments are usually applied in instant rice

production. Although there are some instant brown rice products appearing in the market, some drawbacks remain for such products in terms of cooking time and eating quality.

Deriving from above reasons, in order to be suitable and healthy for the modern lifestyle, the improved instant brown rice product in terms of rehydration properties and eating quality was therefore desirable and developed in this study. The proper process for instant brown rice production was investigated with the purpose of fulfilling the knowledge gap in this area. The rice variety used in this study was Jasmine Rice (KDML 105) because of its popularity, pleasant aroma and soft texture. The outcome of this work will help food industry improving their products and gaining more benefits from their operations.

OBJECTIVES

To determine the suitable manufacturing process for producing the instant brown rice that is able to rehydrate quickly with comparable quality to the normal cooked brown rice.

Specific objectives

1. To study the effects of drying conditions and methods involving various temperatures and microwave power levels for single-stage and two-stage drying in fluidized bed dryer, hot air oven, and microwave oven on drying characteristics and physical properties of cooked brown rice.
2. To develop the mathematical models for estimating the moisture content changes, effective moisture diffusivity and empirical physical properties of cooked brown rice during drying process.
3. To optimize the operating process parameters for the instant brown rice production by considering the responses on the physical properties and eating qualities of instant brown rice.
4. To determine the energy consumption of instant brown rice production for drying processes in order to provide the useful data for the food industry.

LITERATURE RIVIEW

1. The concept of instant rice and quick cooking rice products

At present, there are some interestingly commercial rice products namely instant rice, minute rice and quick cooking rice. In order to clarify the meaning of each commercial name, the following descriptions must be presented.

Quick cooking rice is referred to the product that requires the use of cooker such as electric cooker or microwave oven. Such rice has to be boiled but the cooking time is shorter than that of conventional rice. Dissimilarly, minute rice and instant rice are referred to the products that need hot water to rehydrate but using very short time to be ready to eat. In Japan, the cooking times for these products can be divided into two groups, 3-10 minutes for instant or minute rice, over 10 minutes for quick cooking rice.

According to some references, the instant rice products are defined as the product that requires only about five minutes for swelling in hot water, not necessarily boiling and still retains most of nutritional value in rice (Weibye, 1983). As stated by Sturgeon (1984), the so-called “quick-cooking” rice products are typically prepared by precooking to the pre-determined moisture content and subsequently drying to a stable condition prior to sale. Then, such products can be rehydrated rapidly by hot water. Such rice products can be prepared from white rice, brown rice, or wild rice. Normally, the white rice is more popular raw material in such instant rice products.

2. The benefits of instant brown rice

Brown rice is a whole grain, which only remove the hull without polishing. Retaining this brown layer is very beneficial for health while white rice is not because it is polished to remove this brown layer. This does not mean that the white rice is not healthy; it just does not have some benefits of a whole grain. Brown rice still contains the whole grain - the bran, germ, and endosperm. That means it retains most of its

original nutrients such as fiber, which are lost when the grain is processed into white rice. The other useful components include the vitamins especially vitamins B (thiamin, riboflavin, niacin and folic acid) and minerals which related to many diseases because of their deficiency. According to the U.S. Department of Agriculture, brown rice contains 15 vitamins and minerals, including potassium, magnesium and selenium (Filipic, 2010).

During the last decade, the consumption of brown rice has been obviously increasing due to the health concern of people. It is well-known that brown rice is a health food that is rich in dietary fibre, mineral oils, and various vitamins which may be able to prevent various cancers (Jaisut *et al.*, 2009).

3. Brown rice, instant rice, and instant brown rice quality problem

The brown layer of brown rice brings many benefits for human health as well as preventing some diseases (Filipic, 2010). Nevertheless, the brown layer affects on eating quality; it causes rice to be harder in chewing. The other drawbacks of brown layer for processing are that it acts as heat and mass transfer barrier. (Bardet *et al.*, 1961; Hirokawa *et al.*, 1986). Moreover, although the brown rice is well known about its nutritional superiority, in many countries, it is not enjoyed a wide spread sale as the ordinary white rice. One reason directly causes such rice unpopular is that it is more difficult to cook properly than ordinary white rice. It normally requires a cooking time of about forty-five minutes and tends to become gummy (Bardet *et al.*, 1961). Furthermore, some chemical substances inside brown layer cause undesirable odors, which can call “bran rice odor or old rice odor”- an unpleasant-feeling in eating especially when brown rice is stored for long period (Yamamoto *et al.*, 2005).

There are several processes to produce instant rice but most processes are commonly derived from the home cooking process consisting of pre-treating, cooking, and then drying. The degrees of cooking, gelatinization, expansion, or puffing of the dried-rice product are influential to final cooking time for instant rice. The advantage of instant rice process is well known. That is when the rice is cooked

again by the consumer, the water can migrate faster through the kernel since the starch has been priorly gelatinized causing many cracks and fissures in the kernel.

In accordance with customers' demand, a desirable instant rice product should be able to rehydrate in short time whilst their qualities must be similar to the usual cooked rice. However, the manufacturing processes normally affect on the quality of rice and sometimes resulting in a long time spending for rehydration and a poor eating quality.

The degree of incomplete gelatinization leads to hard texture. Controlling degree of gelatinization is also a challenge. The surface of rice grains is normally gelatinized and gradually forward to the center of rice grains. The surface might be gelatinized while it is still not completely gelatinized at the interior area of kernel, which leads to non-homogeneous gelatinization and subsequent firmness of texture. On the other hand, if continuing the process to complete the degree of gelatinization at the center of rice kernel, the final product will have extensive losses, puffing paste or broken up which affect product's homogeneity (Campbell and Hollis, 1954; Ozai-Durrani, 1965).

To obtain the homogeneous gelatinization and improve process for instant rice, some previous researchers applied a number of pretreatments. For instance, the heating treatment before cooking was introduced by Campbell and Hollis (1954). This treatment encourages starch gelatinization and shortens the whole process since the formation of cracks or fissures facilitates the subsequent processes. High-pressure treatment was studied for reducing the percentage of broken rice and increasing the degree of gelatinization (Smith *et al.*, 1985; Yamamoto *et al.*, 2005). Baz *et al.* (1992) applied two-stage cooking to improve the uniformity and texture of instant rice products. It can be seen that most of researches used heat or thermal treatments that might cause some undesirable consequences such as a loss of natural rice flavor, a lighter in taste or a browner in cooked rice color.

The challenges for instant rice production are that two most important properties of instant food, rehydration time and eating quality, could not be perfectly obtained altogether. Some processes can produce more porous or more cracks in rice kernel structure that is considered as a condition for faster rehydration time. However, those processes lead to the poorer eating quality. Luh and Mikus (1980) found that the instant rice that cooks in 5 minutes has a much poorer texture than that of normally cooked rice while instant rice that cooks in 10 minutes, the texture is very close to that of normally cooked rice.

4. Concepts of cooking method and their effects

The process of instant rice might not provide a high eating quality if excluding cooking step. Ghamsemi *et al.* (2009) showed that one of the most important processing steps to provide desirable texture in rice grains is cooking. It involves heat and mass (water) transfer. The starch of rice absorbs moisture and swells during cooking due to its gelatinization (Campbell and Hollis, 1954). Cooking caused gelatinized the rice starch and increases the moisture content to the range of 60 - 80% (w.b.). The volume and size of such rice were increased whereas the texture was softer and palatable.

Several cooking methods have been applied for producing instant rice. Cooking was conducted by single-stage cooking at normal pressure (Campbell and Hollis, 1954; Ramesh, 2003; Langmalawat *et al.*, 2008), by two-stages cooking at normal pressure (Baz *et al.*, 1992; Rewthong *et al.*, 2011), and by single-stage cooking at high pressure (Smith *et al.*, 1985; Yamamoto *et al.*, 2005; Prasert and Suwannaporn, 2009). The cooking process with a single-stage is normally convenient because of needed short time in cooking. However, it is the fact that the cooked rice is limited in degree of gelatinization especially cooking at normal pressure. The degree of gelatinization could be improved by combining with high pressure for cooking. The single-stage cooking at high pressure provides well-gelatinized cooked rice although the instrument is not widely used since high level of pressure might cause dangerous practices. The instrument has to be special design. The two-stage cooking at normal pressure provides better-gelatinized rice than that of single-stage cooking at

normal pressure; however, cooking time is quite long. Applying two-stage cooking and combining with appropriately high pressure would improve the cooked rice quality in terms of gelatinization aspect and cooking time.

Parallel with pre/post-cooking and controlled pressure cooking, the ratio of water to rice is specially regarded. Based on the ratio of water to rice in cooking, the cooking method can be classified into two methods, boiling and pilaf method (Bett - Garber *et al.*, 2007). The rice is normally cooked by traditional cooking which may be conducted by boiling rice in excess water for a period of time (boiling method) or in limited water - pilaf method (Bett -Garber *et al.*, 2007). Each of method provides different advantages and disadvantages. Boiling method takes longer time than that of pilaf method. Using too much water in cooking leads to long time cooking and the leaching of solid when draining excess water. The pilaf method use limited water when cooking meaning that there is no draining step applied during cooking process. The pilaf method is now applied by many kinds of commercial rice cooker. This method appears to be interested by consumer because of acceptable flavor retained after cooking period in comparison with cooking with excess water and convenient practice in terms of no draining step required during cooking (Crowhurt and Creed, 2001; Bett -Garber *et al.*, 2007).

In aspects of flavor and aroma of cooked rice, it was found that the adjustment of water to rice ratio within a certain range might not influence on the flavor. Bett-Garber *et al.* (2007) found that the water to rice ratio affected textural quality of rice but had an insignificant effect on flavor especially if using the pilaf cooking method. The suitable amount of water in cooking or the ratio of water to rice might depend on the rice variety and process. For instance, Rewthong *et al.* (2011) used 1.5:1 for the ratio of water to rice in cooking Jasmine rice.

As mentioned earlier, the cooking process is normally applied for gelatinization process, swelling, and achieving the desirable moisture content. The steps of draining all of excess water (boiling method) and post-cooking are conducted to gain desirable moisture content. These steps are conducted to ensure that the cooked rice obtains desired moisture content when cooking finished.

When using two-stage cooking, pre-cook and post-cook (Rewthong *et al.*, 2011) at the high pressure level and suitable temperature (Prasert and Suwannaporn, 2009) together with the suitable water-rice ratio in cooking for instant rice production, the quality of final product would be improved. Moreover, if brown rice is used as raw material, it is encouraged to combine cooking with high pressure to improve the degree of gelatinization as well as losing the rice bran layer. The rice bran layer retained for brown rice is the cause of rough texture or undesirable feeling (mentioned above). For this practice, the commercial pressurized cooker operating at a certain high-pressure level, an acceptable temperature and a controlled cooking time would respond the demands of instant brown rice production in comparison to normal rice cooker (normal pressure).

5. The process conditions and their effects on instant brown rice quality

5.1 Soaking and its effects

For instant rice, soaking might bring both benefits and drawbacks. Campbell and Hollis (1954) stated that soaking the raw rice before cooking resulted in facilitating cooking step, uniformity, completed-gelatinization degree, and promoting the formation voids in the dried products. Afterward, Ahromrit *et al.* (2006) found that soaking resulted in the increase of the dimensions of rice grains and swelling of starch granules and subsequently widening the cracks in the rice grains by water diffusion. On the other hand, some researchers found that soaking cause the leaching of solid, the splitting of the kernels especially when soaking at high temperature. Han and Lim (2009) soaked brown rice at low (25°C) and higher (50°C) temperature and found that starch leaching at high temperature was higher than that of lower temperature soaking. Luh and Mikus (1980) also agreed that the soaking temperatures could be the cause of splitting of the kernels and leaching of solid. These levels are higher if soaked temperature is higher than the gelatinization temperature of rice starch.

Additionally, soaking step also affects on the percentage of broken rice. According to Horigane *et al.* (1999) and Ahromrit *et al.* (2006), cracked rice grains occurred during drying and milling. Many cracks were also found in grains during soaking which can cause rice grains to be broken during cooking. It might increase an amount of broken rice if high pressure and high temperature are applied altogether in cooking process after soaking. Therefore, some recent researches did not apply the soaking step in the instant rice process such as Luangmalawat *et al.* (2008) and Rewthong *et al.* (2011).

5.2 High-pressure and high temperature in cooking process and their effects

The desirable characteristics of quick-cooking rice are whole grain shape and similar appearance after cooking to the conventional cooked rice grains as well as the comparable taste, palatability, texture, and stickiness (Kohlwey, 1987). Both high temperature and high-pressure (HP) cooking are considered to be potential method for producing desired instant brown rice. Using HP in cooking promotes the water penetration and higher degree of swelling in rice grains, which might result in a higher degree of gelatinization and higher digestibility. HP treatment also resulted in denaturation of water soluble protein and an increase in some free amino acids. HP processing was proved to be one of the advantageous processing methods for preparing cooked rice with better palatability (Yamakura *et al.*, 2005; Prasert and Suwannaporn, 2009).

According to Prasert and Suwannaporn (2009), pressure levels and moisture content in cooking process affected on the physical and physicochemical properties of instant rice. The hardness and chewiness of rehydrated rice were decreased as moisture content and pressure increased. Pressure and moisture content affected on the density, rehydration ratio, and volume expansion. Moreover, it appeared that the pressure was the main factor influencing the pasting properties of instant rice. Therefore, controlling the cooking step in instant rice production process would assist managing the moisture content, volume of cooked rice and eating quality for the final product.

Degree of gelatinization is one of the most important factors for instant brown rice. Gelatinization is the process that takes place when starch is heated in the presence of water, resulting in the irreversible disruption of molecular order with a starch granule. Evidence of this loss of order can be seen by irreversible granule swelling, loss of birefringence, loss of crystallinity and leaching of amylose from starch granules (Whistler and BeMiller, 1999). For being full degree of gelatinization after cooking, the cooked brown rice should obtain the moisture content between 60 and 75% (w.b.).

Many people object to the taste and texture of brown rice (Bardet *et al.*, 1961) due to their outer layer (bran layer) causing the roughness. This problem could be improved by cooking in high pressure cooker. This practice is related to the cooking conditions, water-rice ratio, cooking time, cooking temperature, and cooking pressure.

The hermetic pressure cooker helps cooking process faster because the process or mass and heat transfer are facilitated. However, a very long cooking time at high pressure may result in the pastier and stickier rice surface, starch granules burst and the leakage of pasty liquid from rice. Moreover, the long cooking time tends to reduce the vitamin B₁ content in cooked rice. Despite the high initial vitamin B₁ content, a portion of the vitamin B₁ content of ordinary brown rice is lost during cooking. Normally, at the atmospheric conditions of 90°C and 100°C cooking, the cooking times of 30 and 15 minutes are viewed appropriate for better quality of the cooked rice (Islam *et al.*, 2002). For brown rice, cooking time is approximately longer than 40-45 minutes (Bardet *et al.*, 1961), nonetheless it would be shorter in pressure-cooking. The brown rice can be cooked for about 15-20 minutes at high pressure and temperature while the texture is not gummy, even if over cooked. After this processing, the cooked brown rice may still be rich in vitamins since the cooking time is shorter (Bardet *et al.*, 1961).

Generally, for instant rice product, the intact of rice grain is one of the desirable characteristics for final products that are directly affected by cooking temperature and cooking period. A number of broken cooked rice may appear during

cooking. Cooking temperature should be concerned because rice cooking at higher temperature produces softer and stickier grain texture, however, it results in more off-white color grains ((Baz *et al.*, 1992; Leelayuthsoontorn and Thipayarat, 2006). Moreover, the temperature of cooking above 100°C caused dextrinization resulting in a mushy texture (Baz *et al.*, 1992).

5.3 Cooling, freezing, thawing and their effects

After cooking, the rice should be cooled under low temperature to avoid over cooking which make the cooked rice sticky and mushy (Ozai-Durrani, 1948; Campbell and Hollis, 1954; Yamamoto *et al.*, 2005). Cooling may be operated at room temperature that is controlled by the air conditioner.

A process proposed by Ozai-Durrani (1965) was that the rice grains was pretreated to get 60-80% moisture content (soaking, cooking or steaming) and conducted the freezing treatment (freezing temperature from -5 to -30°C) prior to thawing. The freezing rate is not important; cooked rice could be frozen by slow freezing or quick freezing rate. The researcher believed that as a result of the freezing treatment, the rice become bleached and has a glistening, snow-white, frosty, and completely-opaque appearance. The rice grain after thawing was plump and increased in volume by about 10% of the volume of the rice prior to the freezing treatment.

In addition, Ozai-Durrani (1965) emphasized that the frozen rice grains must be controlled for their thawing step so that the water in rice is thawed at a rate slow enough to allow the rice reabsorbing all of melted water. Slow increase of temperature of rice until melting point of the frozen moisture can be reached by raising the temperature to only about 0.1°C above the freezing point and maintaining the rice at this temperature. It was assumed that if the thawing rate was not controlled and more rapid than the ability of rice to absorb, the rice grains would shrink, lose their volume, collapse into flat grains and have chalky white spots with checks and cracks on the surface which are undesirable characteristics.

Related to starch retrogradation, cooling and thawing steps described above are treatments that could cause starch retrogradation (Yu *et al.*, 2010a and b). The retrogradation of starch component affects on the eating quality of cooked rice, increasing hardness, and decreasing the adhesiveness. The impact of cooling rates on starch retrogradation and textural properties of cooked rice was evaluated by Yu *et al.* (2010b).

The retrogradation describes the process when a heat starch paste is cooled below the melting temperature of starch crystallites; meanwhile the amylase and amylopectin reassociate and unite with the swollen starch grains in an ordered structure that results in viscosity increase, gel firming, and textural staling of predominantly starch-containing systems. This phenomenon is generally regarded as a recrystallization (formation and subsequent aggregation of double helices) process of amylose and amylopectin. The rapid initial rate of retrogradation related to the loss of networked amylose, the development of amylose aggregated, and binding of granule remnants into assemblies by amylose and amylose aggregates. Thus, amylose is responsible for short-term (less than one day) changes during retrogradation (Zhou *et al.*, 2002). Amylopectin forms shorter double helices, which can be attributed to restrictions imposed by the branching structure of the amylopectin molecules and the chain lengths of the branches. Thus, amylopectin retrogradation proceeds slowly over several weeks of storage and contributes to the long-term rheological and structural changes of starch systems. Lai *et al.* (2000) reported the retrogradation kinetics of pure amylopectin from 13 rice cultivars. Generally, the amylopectin system showed two stages of retrogradation behavior during early (≤ 7 days) and late (> 7 days) storage.

In view of that, for the process of instant rice applying the freezing as Rewthong *et al.* (2011), and then a short period of cooling during thawing process (0.1-25°C), might cause rice starch retrograded in term of amylose retrogradation. It is noted that starch retrogradation can occur if the starch is stored at a suitable temperature, which is approximately 4°C (Lu *et al.*, 1998; Mohamed *et al.*, 2006; Rewthong *et al.*, 2011). While the retrograded starch might lead to hard texture product, which is not desirable (Kadan *et al.*, 2001; Yu *et al.*, 2010a and b), this

process might, however, bring some advantages if the cooked rice is too waxy. The slight retrogradation of amylose could maintain the firmness in texture. Nevertheless, it should be conducted in research to detect this effect.

Generally, combining freezing and thawing steps would bring instant rice production to many benefits, separating cooked rice into individual kernel (reduce the adhesiveness) facilitating for drying process and would affect on the shape and raise the volume size of sample.

5.4 Drying conditions, methods and their effects

5.4.1 Convective drying in single stage

The drying operation is the most critical step in the manufacturing of quick-cooking rice or instant rice. The characteristics of dried-cooked rice depend mainly on the drying schemes. The instant rice quality would be different for various drying conditions and drying methods. The shape distortion or shrinkage, breakage and poor rehydration and texture would occur due to improper drying procedure.

Hot air drying is an effective method for preserving perishable agricultural products (Min *et al.*, 2005). A high moist product dried by hot airflow generally experiences a warming-up period, a constant drying rate period, and one or several falling rate periods. Drying with only hot airflow takes a long time and has low energy efficiency, especially during the falling rate periods. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced moisture transfer and, sometimes, reduced heat transfer. Prolonged exposure to elevated drying temperature may result in substantial degradation of quality attributes, such as color, nutrients, and flavor (Zhang *et al.*, 2003 and 2005) and severe shrinkage that reduces bulk density and rehydration capacity.

During last decades, many researchers studied instant rice drying using various conditions. Carlson *et al.* (1979) dried hot cooked rice immediately after cooking in a centrifugal fluidized bed dryer down to moisture content between 8-10%

using the temperature of about 140-150°C and an air velocity of 610 to 915 meters per minute for 3 to 5 minutes. With this process, the researcher believed that the rehydration time of dried product was about 15 minutes by pouring with about 2.5 parts of boiling water per part of rice. It can see that drying temperature and air velocity applied in this research are relatively high.

The single-stage drying under agitated conditions can be carried out by fluidized bed dryer; however, the bed thickness, velocity, and agitation condition should be concerned during drying process. Groesbeck *et al.* (1990) advised that the thickness of the layer of cooked rice should be between 5 and 12 mm on a belt of the dryer. Using a high hot air velocity can reduce the stickiness of the cooked rice. The velocity of the hot air generally ranges from 20 to 200 meters/min (lower than that of the method of Carlson *et al.*, 1979).

In convective drying, the relatively high drying temperature is better for rehydration of instant rice product in case of requiring puffing phenomenon. Roberts (1952) and Baz *et al.* (1992) used high temperatures for drying cooked rice (140-230°C) and believed that the instant product would be better in rehydration properties due to puffing phenomenon. The puffing phenomenon could be explained by the fact that during drying process, the moisture is removed from the surface of the rice grains faster than the internal moisture diffusion causing the harder surface. The case hardening formation can coat the moisture inside rice grain; meanwhile the moisture inside gain absorbs heat and tends to move out the rice grain because of reaching evaporated state. This process creates the difference moisture pressure between inside and outside of kernel that leads to explosion or puffing phenomenon. The puffed size and shape of rice kernel are increased; the kernel has a bigger hollow inside that easily allows water penetrating during rehydration. Ramesh and Srinivasa Rao (1996) also stated similarly that once the external layer of cooked rice dehydrated, a hard surface was formed and further water removal from internal layers became more difficult and internal stress built up. Prasert and Suwannaporn (2009) achieved the similar results of puffing phenomenon for instant white rice.

In support of single-stage convective drying temperature, Ramesh and Srinivasa Rao (1996) pointed out that the drying temperature for cooked rice should be between 160 and 240°C. The drying of cooked rice at temperature of 160 to 240°C could remove moisture content rapidly in thin layer drying operation. As the temperature was below 160°C, drying took the longer time, leading to poor rehydration. At higher temperature of more than 240°C, the dehydrated cooked rice became brown and unacceptable.

It appeared that single-stage drying in convective schemes at high temperature is selected by most of researchers. At low air temperature (less than 70°C) drying with single-stage, the drying period takes place for a long time that induce the dense structure of rice grains (Robert, 1972) resulting in poor rehydration properties. However, Rewthong *et al.* (2011) were interested in hot air drying at low temperature (80°C) for cooked white rice to produce the instant rice.

5.4.2 Microwave drying

5.4.2.1 Microwave drying and food material properties

Microwave was developed during World War II. Microwave heating is now found as a very convenient home application. Microwave heating takes place due to the polarization effect of electromagnetic radiation at frequencies between 300 MHz and 300 GHz (Decareau, 1985). The polarization effect of electrical energy is a function of the electromagnetic frequency, the dielectric, and electric properties of the materials, the viscosity of the medium, and the size of the polar molecules.

Food materials are, in general, poor electric conductors but can store and dissipate electric energy when subjected to an electromagnetic field. The electrical basis of interaction is described in terms of dielectric properties: dielectric constant (ϵ') and dielectric loss factor (ϵ''). These represent for the proportion of energy that can penetrate the material and the amount of energy that can

absorb by the material, respectively. The loss tangent ($\tan \delta$) is the ratio of (ϵ' / ϵ'') which is combination of the ability of material that can be penetrated by electric field and dissipate that energy as heat. The dielectric properties of materials are the most important factors in consideration frequency or MW power application for biological materials.

In general, 915 MHz microwaves have deeper penetration depth in foods than 2450 MHz, and the penetration depth of microwaves varies with temperature and shape of material. The limited penetration depth of microwaves in foods often causes non-uniform heating. Because of the refraction, microwaves entering spherical and cylindrical foods are directed towards the center of materials. For relatively small-sized foods, e.g. when the sphere diameter is less than 2.5 to three times the microwave penetration depth, this would cause central heating (Lu *et al.*, 1998). When microwaves propagate through a lossy material, a fraction of microwave energy is converted into heat and the remaining power decreases with the distance from the surface.

The dielectric properties play a critical role in determining the interaction between the electric field and the foods (Buffler, 1993). The dielectric properties of food materials are affected by many factors, including frequency of the microwaves, food temperature, moisture content, salt content, and other constituents. In a food system, the change of dielectric properties with respect to temperature depends upon frequency, bound water to free water ratio, ionic conductivity, and composition of the material. For example, at microwave frequencies used by the food industry, both the dielectric constants and dielectric loss factor due to polarization of bound water in foods would increase with temperature. On the other hand, these two properties of free water would decrease when temperature increases (Calay *et al.*, 1995).

5.4.2.2 Mechanisms of microwave heating

The absorption of microwaves by a dielectric material results in the microwave giving up their energy to the material, with a consequential

rise in temperature. Two important mechanisms that explain heat generation in a material placed in a microwave field are ionic polarization and dipole rotation.

Water molecules or moist of food are polar and are the most important constituent that contribute to the dielectric properties of moist foods. In general, the higher the moisture content, the larger the dielectric constant and loss factor of material so that the better heating. At temperatures above freezing, moisture exists in foods in one of the two forms- free water and bound water. The free water components have dielectric properties similar to those of liquid water, while the bound water exhibits ice-like dielectric properties. Dielectric properties of foods, in general, decrease rapidly with decreasing moisture content to a critical moisture level. Below this moisture level, the reduction in loss factor is less significant due to the bound water. During microwave drying, the wetter parts of foods absorb more microwave energy and tend to level off the uneven moisture distribution. The moisture leveling effect is less pronounced when the moisture content is below the critical moisture, as the reduction of loss factor with reducing moisture content is not significant.

5.4.2.3 Microwave drying in food material and cooked rice

The frequency of 2450MHz is the most commonly used in domestic MW oven with the reflecting cavity wall that can produce several modes of MW, maximizing the efficiency of heating for variety of food materials.

The common characteristic of drying in MW is that the heat is generated within the material, mass transfer occurs from the pressure gradient created by vapor generation inside the material, rapidly forcing water vapor to the sample's surface which create the pumping action (Sun, 2008). This pushes the water out of sample greatly fast, thus, resulting in the very short time in drying. However, the too rapid generation of heat in product can cause the generation of great internal steam pressure resulting in material expansion or explosion or 'puffing' (Nijhuis *et al.*, 1998). However, this may or may not be a limitation, depends upon the desired quality attributes of the final products. For cooked rice, Campbell Hollis (1954)

explained that the rapid drying is a result of preliminary cracking and fissuring which help the drying procedure to be quicker. Their research advised that the swollen rice grains should be dried rapidly in order to set them in their enlarged size and to produce a porous structure so that the rehydration of the dried products can take place rapidly during final cooking by customer. Microwave drying could specially create porous structure for products by its high drying rate (Krokida & Maroulis, 1999).

Microwave drying at high power level provides some advantages over conventional hot air drying in term of fast drying rate, minimizing the heating at the less water location, thus reducing the overheating at the location where heating is not required (Krokida & Maroulis, 1999; Sharma and Prasad, 2004). Microwave drying has a major advantage in speeding up the final drying in the falling rate region in which conventional drying becomes less effective and take a long time due to reduced heat and moisture transfer. The unique characteristic of microwave is that it interacts directly with moisture in the core area of sample. Microwave heating provides a positive gradient for moisture to migrate from inner toward the surface, thus significantly reducing drying time (Tang *et al.*, 2011).

Nevertheless, there are several limitations of MW drying method. It is generally not economical to use microwave to replace conventional drying method for completing drying process in large-scale production. Only 50-70% of the line power is converted into MW radiation by magnetrons; only a part of this field is absorbed by the drying material, depending on its loss factor, physical size, and moisture content (Feng & Tang, 1998). The sample might be burnt color if the high initial moisture product exposes to the microwave drying for a long period (Chou and Chua, 2001). Since only a limited amount of water is available during the final stages of drying processes, the material temperature can easily rise to a level that causes scorching. The final product temperature in MW drying is difficult to control, compared to that in hot-air drying in which product temperature never rises beyond air temperature. According to Clark (1996) and Nijhuis *et al.* (1998), excessive temperatures along the edges and corners of products may lead to overheating and irreversible drying-out resulting in possible scorching and development of off-favors. Although MW heating can readily deliver energy to generate heat in the moist portion

within foods, one of its major drawbacks is the inherent non-uniformity of the electromagnetic field within an MW cavity. However, this problem can be partially offset by using wave-guides and a rotating tray (Cohen & Yang, 1995).

On the other hand, when using microwave to finish the product drying could avoid the case-hardening formation so that the harder in texture of sample that relates to case-hardening formation could be rejected in terms of drying by MW (Prabhanjan *et al.*, 1995). The most successful drying application is the finishing drying of pasta products down to moisture content of 13 %. When hot air is applied, a case hardening forms after the pasta loses surface moisture, resulting in reduced moisture diffusion rate and slow drying process. This problem can be alleviated by using a slow drying process at a low temperature and relatively high humidity. This process, however, may take over eight hours. (Tang *et al.*, 2011). This result should be referred for instant brown rice production since case-hardening can cause longer in rehydration time and lessen eating quality.

Microwave drying in food processing applications have been conducting but successful exploitation of microwave heating applications relies on understanding of the interaction between microwave and food. Microwave heating in foods is a complicated physical process, which depends upon the propagation of microwaves governed by Maxwell's equations for electromagnetic waves, on the interactions between microwave and foods determined by dielectric properties, and on heat dissipation governed by basic heat and mass transfer theories. Thus, it is vital to provide a suitable range of microwave power level applications for specific foods such as instant cooked brown rice.

5.4.3 Advanced drying process and instant rice drying

The heat and mass transfer through conduction, convection, and radiation have their own advantages and disadvantages. Applying two-stage or multi-drying processes for instant rice production have not yet been widely applied. However, there have been a number of biomaterials that applied the multi-stage

drying with the evidence of improved product quality and energy efficiency (Prabhanjan *et al.*, 1995; Varith *et al.*, 2007; Alibas, 2007; and Gowen *et al.*, 2008).

The two-stage or multi-stages in drying is a strategy which some researchers have applied for their high moisture content products or sensitive products due to many benefits such as high product quality and saving energy consumption (Weibye, 1983; Baz *et al.*, 1992; Thakur and Gupta, 2006). These strategies exploit the advantages of each drying method and reduce their disadvantages. For instance, to produce quick-cooking rice, Groesbeck *et al.* (1990) dried cooked rice with 55-75% moisture content (w.b) at temperature from 140 to 185°C in two separated stages. Firstly the sample was dried under stationary conditions to moisture content of 20-35% (w.b) and secondly under agitated conditions to moisture content of 3-15% (w.b.). This method provided dried-cooked rice with a bulk density between 37g/100cc and 42g/100cc and rehydration time was about 10 minutes when putting into hot water. Before that, Roberts (1952) and Weibye (1983) pointed out that the first stage of drying should be conducted at a relatively high temperature (should be from about 170 to 250°C, preferably around 200°C) to cause rapid moisture removal resulting in the sponge-like grains. From the second stage drying, the temperature should be reduced to avoid browning of the rice grains. These researches concerned the effect of temperature impacting on quality of dried cooked rice. After the grains were porous during the first stage drying by high drying rate, the drying temperature is then reduced to complete the product drying. These practices can reduce browning of the rice grains and economize the energy consumption. Consequently, after the proper degree of porosity is reached, the drying is finished at conventional temperature levels.

Similarly, Weibye (1983) reduced the drying temperature (50-70°C) but lower than that (120-150°C) of Roberts (1952) to avoid case hardening formed during drying and to improve the energy effectiveness. The case hardening of final product causes the undesirable characteristics when eating as well as causing the rough chewiness (Roberts, 1952; Weibye, 1983) although the case hardening might be good for puffing process (Prasert and Suwannaporn, 2009). Reducing the hardness of

outer layer can facilitate moistures removal. Therefore, using the period of drying that forms case-hardening and appropriate drying temperature can improve product quality. As mentioned earlier, the second-stage drying at low temperature helps the product getting the safe moisture content for storage so the hot air dryer would be normally useful for the second stage drying.

Fluidized bed dryers is also an attractive technique; a number of researchers found that fluidized bed dryer facilitates an excellent rate of heat and mass transfer between the food and the surrounding air which results in shorter time of drying (Sturgeon, 1984; Giner and Calvelo, 1987; Ramesh and Srinivasa Rao, 1996; Poomsa-ad *et al.*, 2002). Ramesh and Srinivasa Rao (1996) pointed out that the fluidized-bed dryer can produce the product with the uniform moisture. However, the limitation for this equipment is the agglomeration if the samples have high initial moisture content such as pre-germinated brown rice (Sootjarit *et al.*, 2011). Deriving from this limitation, this dryer would be only applicable for the second stage drying of instant brown rice process after the sample is dried to the certain level to avoid clumping. Moreover, the operating condition for fluidized-bed drying must be carefully determined because of not only their disadvantages mentioned above but also the fluidized bed dryer requires high-energy consumption by using high air flow velocity to fluidize the material during drying process. Furthermore, sometimes it causes undesirable effects on the product qualities such as burn, dark color and collapse of kernels as drying at high temperature and over drying occurs (Hess, 1984).

Normally two stages of drying are intermittently interfered by tempering period. Baz *et al.* (1992) and Thakur and Gupta (2006) stated that two-stage drying with the tempering period in between brought advantages in reducing the breakage of grain. Reducing broken grains leads to a uniform product and increase sensory value of final products. These results are the positive effects of intervening rest periods between the two stages of drying on drying rate, the energy consumption and product quality. During the period of the rest stage, the grain released moisture as an effect of the residual temperature and the grain moisture become uniformly distributed within the kernels (Thakur and Gupta, 2006).

In addition, the rest period between two-stage drying is needed to uniformly spread the moist inside the grain and between grains. During drying time, the rice grains will absorb the heat from the drying agents via various ways such as convection, conduction, or radiation. The moisture content inside grain is hardly uniform especially if the product is thick. During the first period of drying procedure, the moisture can be removed rapidly but the drying rate can decrease at the later drying period due to lower moisture content of sample. On the other hand, if the sample is kept stable during drying process, at some positions, drying agents cannot contact with the sample; as a result, the non-uniformity of dried sample would appear. Therefore, the tempering or agitation step should be deemed during drying. Groesbeck *et al.* (1990) showed that agitating helped shortening the drying time with fast moisture removal and caused the reduction of stress crack and fissure in dried precooked rice. It is apparent that applying agitating or having the period of resting between two stages of drying could resolve the problems about stickiness and agglomeration that cause difficulties for drying process and raise the uniformity in final product.

Microwave-drying method has been preferred in terms of its unique characteristic of very fast drying rate, which can create the porous structure in product. However, it might not be appropriate for product at all of microwave power levels.

6. Quality attributes of instant rice and process condition effects

A freshly cooked brown rice should be a control sample for comparing the qualities with the instant brown rice product. The desired quality of final instant rice product is that after rehydration, the volume of instant rice should increase to 1.5-3 times of dry grains; its color, flavor, and texture should be similar to cooked rice without hard core or un-gelatinized center (Luh and Mikus, 1980; Smith *et al.*, 1985).

Many physical properties and physicochemical properties of instant rice such as hardness, chewiness, color, shrinkage, structure, and rehydration were mentioned by prior researchers (Luangmalawat *et al.*, 2008; Ghamsemi *et al.*, 2009; Prasert and Suwannaporn, 2009).

6.1 Texture

The properties of starch are deeply related to the palatability of rice. Rice proteins in pattern of amino acid compositions are also important components for palatability of cooked rice. Lipid-starch complexity affect on texture properties. These compositions are usually affected during production process of instant rice; the hydrothermal treatments, cooking, or drying process have strong impact to these components and the qualities of cooked rice (Yamakura *et al.*, 2005).

The process of instant brown rice production is quite similar to rice parboiling process. Rice starch granules are gelatinized during instant rice production process involving cooking and drying. Some of gelatinized starch then can re-associate or form the complexity with lipid causing the firmness in texture. The re-association or retrogradation of starch depends on moisture content and storage temperature. Retrogradation will be maximum at moisture content of 25% w.b and room temperature (Ali and Bhattachara, 1976). Protein bodies in rice are ruptured and the solubility of the protein can reduce after instant rice production process. The effect of this change relates to eating quality of instant brown rice.

6.2 Color

A number of researchers pointed out that the most important quality attributes of instant rice product are color and rehydration capability. In practical viewpoint, the consumers require the product that has whiter color and fast rehydration rate. These attributes are affected by the process conditions especially cooking, drying conditions, and drying methods (Luangmalawat *et al.*, 2008; Prasert and Suwannaporn, 2009; Rewthong *et al.*, 2011).

A common problem of the drying of cooked rice is the change of product color from whiteness to yellowness, which is easy to observe for white rice. The suitable color of finished product should not have much burnt color or yellowness although change of color is unavoidable. The various drying temperatures and initial moisture contents of rice normally result in different product color. This appears because of non-enzymatic browning namely Maillard reaction occurring by the reducing sugar, amino acid in rice and high temperature heating. For cooked rice drying at air temperature between 50 and 120°C, the color of dried cooked white rice were not significantly different (Luangmalawat *et al.*, 2008). It was also observed that the air temperatures of 160–240°C are the suitable range for drying cooked rice for the single stage drying by fluidized bed dryer. At higher temperature than 240°C, the dehydrated cooked rice became brown and was unacceptable (Ramesh and Srinivasa Rao, 1996).

The color of cooked rice is also affected by the conditions of pretreatments, soaking, boiling, and steaming process. Bhattacharya and Subba Rao (1966) found that the colors of raw rice and parboiled rice are different by varying the conditions of soaking and steaming because a large part of the sugar is leached out into the soaking medium while a small drop occurs during heating causing the change in color. The boiling process significantly altered the color and exterior integrity (Luangmalawat *et al.*, 2008). Likewise, high-pressure cooking also caused cooked rice to be more yellow (Leelayuthsoontorn and Thipayarat, 2006). Steaming at high pressure also caused severe discoloration (brown-yellow). However, it is noted that for the cooked brown rice, the browning or yellowness of dried product should not be too worried since brown rice itself has natural brown-yellow color. The color changes of dried product should be analyzed by intensity of color like a research of Roy *et al.* (2008).

6.3 Shrinkage and collapse

The important consequence of shrinkage is the decrease of the rehydration capability of the dried product (Mayor and Sereno, 2004). Shrinkage and collapse of

biological materials during drying takes place simultaneously with moisture diffusion and thus may affect on the moisture removal rate. The shrinkage also represents for quality of final products. The shrinkage also affects on the other physical properties of materials, such as the density and porosity (Wang and Brennan, 1993). Hence, the studies of the shrinkage phenomena, volume change, density, or porosity are important for the better understanding of the impact of drying process on the final product quality.

Wang and Brennan (1993) pointed out that two factors that affect on the shrinkage of dried potato are drying temperature and moisture content. For two-stage drying, in the first stage of drying at high drying temperature, the shrinkage of cooked rice occurred (Ramesh and Srinivasa Rao, 1996). The shrinkage sometimes leads to some disadvantages.

According to Luangmalawat *et al.* (2008), for the single-stage drying in hot air dryer, the shrinkage of cooked rice after drying was found to be insignificantly different between drying temperatures of 50 and 120°C. It must be noted that this is invalid for all of temperatures and moisture ranges and drying methods.

6.4 Microstructure

The image of microstructure can show the internal changes of cooked rice after drying. Image processing and image analysis provide the needed qualitative data for enhancing the quality of products (Aguilera, 2005). A number of researches applied this method and got the well-understandable supporting evidence for their statements.

Microstructure is one of the cooked rice quality characteristics that can be affected by processing conditions. The morphology of dried cooked rice is contributed by all the processes from cooking (Leelayuthsoontorn and Thipayarat, 2006) to drying (Rewthong *et al.*, 2011). The result of Luangmalawat *et al.* (2008) indicated that the dried-cooked rice after rehydration was more porous than freshly cooked rice, but morphologies were not different among the samples obtained from low (50, 80) and

relatively high temperature drying (120°C). The microstructure exhibited that the soft texture at high cooking temperature corresponded to the increase of pore size and thickness of sponge-like texture of inner layer endosperm (Leelayuthsoontorn and Thipayarat, 2006). Moreover, Bello *et al.* (2004) stated that the heating time significantly affected on the rupture force and translucence index of cooked rice. However, the researchers showed that the most important factor that affected on the rupture and translucence index of cooked rice was the heating temperature. Rewthong *et al.* (2011) found that freeze drying could create some voids in the microstructure of dried cooked white rice. Such formation of large pores in the freeze-dried cooked rice might be caused by growing ice crystals. This morphological feature is typical for a freeze-dried product. Lewicki and Pawlak (2003) also found larger pores inside a freeze-dried apple sample.

The information about the porosity involving bulk and true densities of dried-cooked brown rice after drying for each time step is useful for analyzing the extent of porous or sponge-like structure of dried rice samples. These kinds of structures are directly related to the rehydration rate of dried products that is commonly required for the instant or quick-cooking rice. Porosity, true density, and microstructure of instant brown rice would be detected in this study.

6.5 Rehydration

An important quality of dried cooked rice is rehydration capability. The requirement of the customer is an instant rice product with short rehydration time. Rehydration capability and rehydration time depend on the food structure (Aguilera, 2005), and the porosity (Luangmalawat *et al.*, 2008). The porosity is an important physical property of instant rice. If the porosity of rice is uniform, dried cooked rice will be able to rehydrate in short time.

Besides, the effects of pretreatments prior to drying process, soaking, cooking, drying condition (temperature) and drying methods directly contribute to grain porosity. Carlson *et al.* (1979) showed that the drying temperatures of about 140-150°C provided rehydration time of quick-cooking rice about 15 minutes by

pouring about 2.5 parts of boiling water per part of rice. Groesbeck *et al.* (1990) stated that the drying temperatures of 140 to 185°C provided the rehydration time of dried precooked rice about 10 minutes by putting rice into hot water. Prasert and Suwannaporn (2009) indicated that high temperature of tray drying caused the puffing phenomenon and resulted in high rehydration ratio. In contrast, Luangmalawat *et al.* (2008) found that effect of lower drying temperature (50 to 120°C) is insignificant on the cooked rice rehydration ratio. Rewthong *et al.* (2011) found that freeze-drying could provide more voids in dried cooked rice structure because of crystal ice formation. The rehydrated rice from dried cooked rice should be almost similar to conventionally cooked rice in terms of texture, moisture, and swelling. The drying condition and method cause porous structure or hollow inside rice grain. However, finally, the authors seem to be interested in conventional drying method that includes the freeze treatment prior to drying for producing their dried cooked rice product.

To rehydrate instant rice product, recent researches still apply the cooking method for preparing the instant rice to be ready to serve. Luangmalawat *et al.* (2008) cooked instant white rice by immersing in hot water (95°C) for 10 minutes while Prasert and Suwannaporn (2009) cooked instant white rice by heating in microwave oven and draining excess water with spending total time of 11 minutes. Microwave application in cooking instant food has been become more popular now in home.

7. Thin-layer drying model development

7.1 Thin layer drying model

The thin layer drying models and their corresponding parameters in the equation can be used to predict the change of moisture ratio with time. There have been a number of mathematical models that have been constructed for predicting the drying curves (Roberts *et al.*, 2008; Hii *et al.*, 2009). Ramesh and Srinivasa Rao (1996) pointed out that drying characteristic of cooked rice in vibro-fluidized bed dryer can be explained by Page's equation. However, there has been no study of models for instant brown rice drying so far.

Generally, thin layer model is classified into three categories namely theoretical, semi-theoretical and empirical (Ozdemir and Onur Devres, 1999) as described below:

Ozdemir and Onur Devres (1999) stated that the theoretical model type only considers the internal resistance to moisture transfer whereas the others regard to external resistance to moisture transfer between the product and air (Henderson 1974; Parti 1993). Fick's second law of diffusion was the theoretical drying model. Nevertheless, the assumption of this model type is invalid in case of using this law to describe the falling rate drying period (Moss and Otten, 1989).

Semi-theoretical models are a solution of combination between theory knowledge and ease of use (Fortes and Okos, 1981). Semi-theoretical models are generally derived by simplifying general series solution of Fick's second law or modification of simplified models (Ozdemir and Onur Devres, 1999). However, this kind of model is only valid within the certain conditions that they were developed (temperature, relative humidity, air velocity and moisture content range). Moreover, this kind of model does not need assumption of food geometry, mass diffusivity and conductivity (Parry, 1985). Some examples of these models were Henderson and Pabis's model, two-term model, Lewis's model, Page's model and Verma *et al.*'s model and Hii *et al.*'s model.

It can be seen that the Henderson and Pabis's model is the first term of a general series solution of Fick's second law. This model was used to predict the drying of corn (Henderson and Pabis, 1961), wheat (Watson and Bhargava, 1974), rough rice (Wang and Singh, 1978), and peanut (Moss and Otten, 1989). However, during the first 1 or 2 hours of drying corn, Henderson and Pabis (1961) found the poor fit of this model due to the greater temperature difference between the kernel and air. The slope of the Henderson and Pabis model, coefficient k , is related to effective diffusivity as drying process is controlled by liquid diffusion in the falling rate period (Suarez *et al.*, 1980; Madamba *et al.*, 1996). Similarly, Two-term model is the first two terms of general series solution of Fick's second law. This model also disregards the particle geometry and is used to describe the drying of agricultural products such

as drying of corn (Henderson, 1974), white bean, and soybean (Hutchinson and Otten, 1983). Nevertheless, it requires constant product temperature and constant diffusivity assumption. Lewis's model, where its intercept is unity, is a special case of the Henderson and Pabis model. The Lewis's model was used to describe drying of barley (Bruce, 1985). The disadvantage of this model seems to be overestimated the early stage and underestimated the later stages of the drying curve (Bruce, 1985). The Verma *et al.*'s model that was found successfully applied to sun drying of green bean by DoyMaz (2005) is another form of the two-term model (Hii *et al.* 2009). Hii *et al.* (2009) developed the new semi-theoretical model that was a combination of the page and two-term drying models. This model described well for drying of cocoa beans for both of artificial and natural drying techniques.

In order to achieve a goodness of fit, some of models were modified. The Page's model was modified from the Lewis's model to overcome the shortcomings (Ozdemir and Onur Devres, 1999). This model has provided the good prediction for drying of short and medium rough rice (Wang and Singh, 1978). The modification of Page's model was also done by Diamante and Munro (1991) for mathematical modeling of sweet potato slices undergoing hot air drying. Recently, Jittanit (2007) modified Page's model in terms of widening its application by putting temperature parameter into model. Moreover, this research also modified two-compartment model by the similar manner. The results of two stages drying for paddy rice indicated that these types of models showed the well-fitted characteristic. Then, some researches was subsequently applied these types of models to predict moisture changes for various products such as pumpkin (Jittanit, 2011) and GABA rice (Sootjarit *et al.*, 2011).

Empirical models directly derived from the relationship between moisture ratio and drying time from experimental drying data. This type of model neglects the fundamentals of drying process and their parameters have no physical meaning. Therefore, this model cannot provide the clear view of the important phenomena occurring during drying process. However, Wang and Singh, (1978) applied this kind of model to describe the drying of rough rice.

In general, the drying characteristics of foods somewhat followed an exponential pattern with one or two terms in the model. It might also involve empirical parameters inside the model (Diamante and Munro, 1991). Generally, the semi-theoretical model types are widely interested by number of researches since they are at the balance between theoretical knowledge and ease of use (Fortes and Okos, 1981).

8. Effective moisture diffusivity

The effective moisture diffusivity is an overall mass transport property of water in the drying material involving liquid diffusion, vapor diffusion, hydrodynamic flow and other possible mass transfer mechanisms (Karathonos *et al.*, 1990). Generally there are several methods to determine the effective moisture diffusivity (Ramesh, 2003; Hii *et al.*, 2009), method of slope (Karathonos *et al.*, 1990; Rahman and Lamb, 1991; Ramesh, 2003; Langmalawat *et al.*, 2008); computer optimization method (Bakshi and Singh, 1982; Karathonos *et al.*, 1990) and regular regime method (Karathanos *et al.*, 1990; Jittanit, 2011; Sootjarit *et al.*, 2011). Fick's second law of diffusion is generally adapted to describe the diffusivity. Crank (1975) provided the analytical solutions to estimate the diffusivity of un-steady mass transfer case for most of standard geometries, slab, sphere and cylinder, in terms of finite and infinite. Generally, the solution assumes that the sample prior to drying process has uniform initial moisture distribution, unidimensional moisture movement, constant diffusivity, no volume change and negligible external resistance. With an appropriate initial and boundary conditions, the diffusivity of certain geometry could be estimated.

The regular regime method is simple, practical, and convenient in describing the moisture diffusion for drying process. However, this method just only shows the single diffusivity value of the entire process and for sufficiently long durations of drying (Ramesh, 2003; Hii *et al.*, 2009). The computer optimization method is not user friendly in comparison with regular regime due to its complicated solving solution; however, it provides the potential for diffusivity estimation. The slope method derives the same theoretical equation with regular regime method that may

be interested by scientist. Furthermore, this method has been successful in estimation of moisture diffusivity for various products (Thuwapanichayanan *et al.*, 2008) especially for drying of cooked rice (Ramesh, 2003; Luangmalawat *et al.*, 2008). The attention of scientists might be on the slope method which can show diffusivity changes during drying process and provides more useful information for understanding drying process.

Brown rice can be considered as a finite cylindrical shape. Mass transfer in a radial direction is similar to mass transfer for an infinite cylinder. For infinite cylindrical shape, the moisture diffusion is only through the radial direction whereas the ends of the cylinder are too far to have any measurable influence on moisture transfer. However, for the finite cylindrical shape, mass transfer from the two ends surface is similar to the mass transfer for an infinite slab. Considering the finite cylindrical shape to be an infinite slab will account for all the mass transfer from the two ends of the cylindrical shape. This approach allows us to include the mass transfer from both the radial direction and from the cylinder ends. The approach is quite similar to the heat transfer solution of Myers (1971).

8.1 Empirical effective moisture diffusivity model

The relationship between effective moisture diffusivity coefficient and moisture content has been expressed by empirical models in linear, polynomial, and exponential forms (Tong and Lund, 1990). Ramesh (2003) dried cooked white rice and found that the experimental data fitted well in the exponential model pattern. Luangmalawat *et al.* (2008) also conducted the cooked white rice drying research and found that with assumption of shape for cooked rice of spherical shape and water diffusion in radial direction, the suitable form of model was inverse third order polynomial form. It described well the relationship between D_{eff} and moisture content. Moisture diffusion for spherical geometry might consider in the radial direction but for cylindrical shape, the moisture diffusion direction in sample should not ignore the two edges of cylinder.

9. Physical properties and their empirical models

For instant brown rice, the porous structure within the grain determines rehydration capacity or time. Similar to thin layer drying model development, the model for estimating the porosity of instant rice should be developed. The porosity of rice represents for the changes of material physical properties including holes, voids, or spaces inside and outside of sample, relating to collapse or shrinkage, which are the consequences of drying process. The porosity can be expressed as a function of bulk and true densities. The porosity of grain is the ratio of the volume of holes inside kernel (air volume) and the open voids outside of kernel to the overall volume of grain in bulk.

Porosity is a function of drying process and moisture content. Various researches develop the models describing the relationship between porosity and moisture content. The model types vary from linear (Joshi *et al.*, 1993; Karababa, 2006; Vilche *et al.*, 2003) to non-linear function (Rahman, 2001). According to Sun (2008), referred by Rahman (2001), the porosity is a function of moisture content and temperature. The initial porosity and final moisture content of product is very important factors affecting on the model pattern. The empirical models of linear function are normally adequate to express the result of short time drying. It seemed to be user-friendly due to its simplicity. In the real practice, however, the porosity change corresponding with moisture content might not be a linear form because this process includes the complicated physical changes and depends many factors, especially the initial and final moisture contents. Some models have to put the critical moisture content parameter into model in order to be more adequate (Sun, 2008).

When the linear function is not good-fitted model, the non-linear and polynomial models might be a solution. These models usually present a good fitting to experimental data. Although there are several limitations existed for model development, a number of published works were successful in their model development.

10. Optimization by response surface methodology

Methodologies that help the researchers reaching the goal of optimization are referred as Response Surface Methods (RSM). A type of RSM was developed by Box and Behnken. For this RSM type, the researcher could run only three levels of the factors and yet desire a design that is close to rotatable. Rotatable design means that all factor-level combinations are at equal distance from the center of the factor space. Rotatability is a desirable property for response surface.

While the central composite design (CCD) with face-centered center points also has 3 levels, it places most of the design points at the corners of the experimental region. If that region is defined as the feasible conditions for the process, the face-centered central composite is a natural choice. However, if one is starting at a particular combination of factors and is simply searching for better conditions, a more spherical arrangement of design points will be more efficient.

For instant rice production, a number of researches showed that initial moisture content, degree of gelatinization and drying technique are the most important factors contributing to the quality and price aspect of the final product. The initial moisture content prior to drying process directly related to ratio of rice to water in cooking step and rice starch gelatinization. Drying technique is undoubtedly critical and crucial for quality of instant rice product.

Consequently, in order to apply the response surface method, three important factors should be the ratio of rice to water, the microwave power level for the first-stage drying in microwave and the temperature range for second-stage drying in hot air dryer. For three factors and three levels for each factor, it would be suitable for Box- Behnken design than CCD since Bex-Benhken design requires fewer tests than exact rotatable design of CCD. Moreover, it can avoid the point on one or more corner of the cube (design structure) representing factor-level combinations that are impossible to test such as very high level of microwave power level.

MATERIALS AND METHODS

Materials

1. Rice sample

The rice seeds (*Oryza sativa* L.) of the KDML105 variety (jasmine rice) were chosen for the present study because of their better market price and popularity. The seeds were produced by the Chonburi Rice Seed Center located in Chonburi province, Thailand.

2. Equipments and Instruments

- Digital amclamp Meter (Hioki 3282, HIOKI E. E. Corporation, Japan).
- Mini Lab colorimeter (Minolta Chroma Meter, model CR-300, Osaka 541, Japan).
- Texture analyzer (TA.XTPlus, Stable Micro System Ltd., UK).
- Leica stereomicroscope (S8APO, Leica Microsystems Imaging Solutions Ltd., Cambridge CB1 3XJ, UK).
 - Digital camera for microscope (Leica DFC280, Leica Microsystems Imaging Solutions Ltd., Cambridge CB1 3XJ, UK).
 - Fluidized bed dryer (230 V/50 Hz/3 kW, Sherwood Scientific, Cambridge, England).
 - Hot air oven (model T.308L, Memmert GmbH Co.Ltd., Schwabach, Germany).
 - Microwave oven (“SHARP” MWO 26 Lt model R-892P, SHARP Co.Ltd., Bangkok, Thailand)
 - Laboratory de-husker (motor 0.5 HP, 220V, 50Hz, Ngek Seng Huat Part., Ltd., Bangkok, Thailand).
 - Digital pressure cooker (model ZB-DEP2200, Satian Stainless Steel Public Company Limited, Bangkok, Thailand).

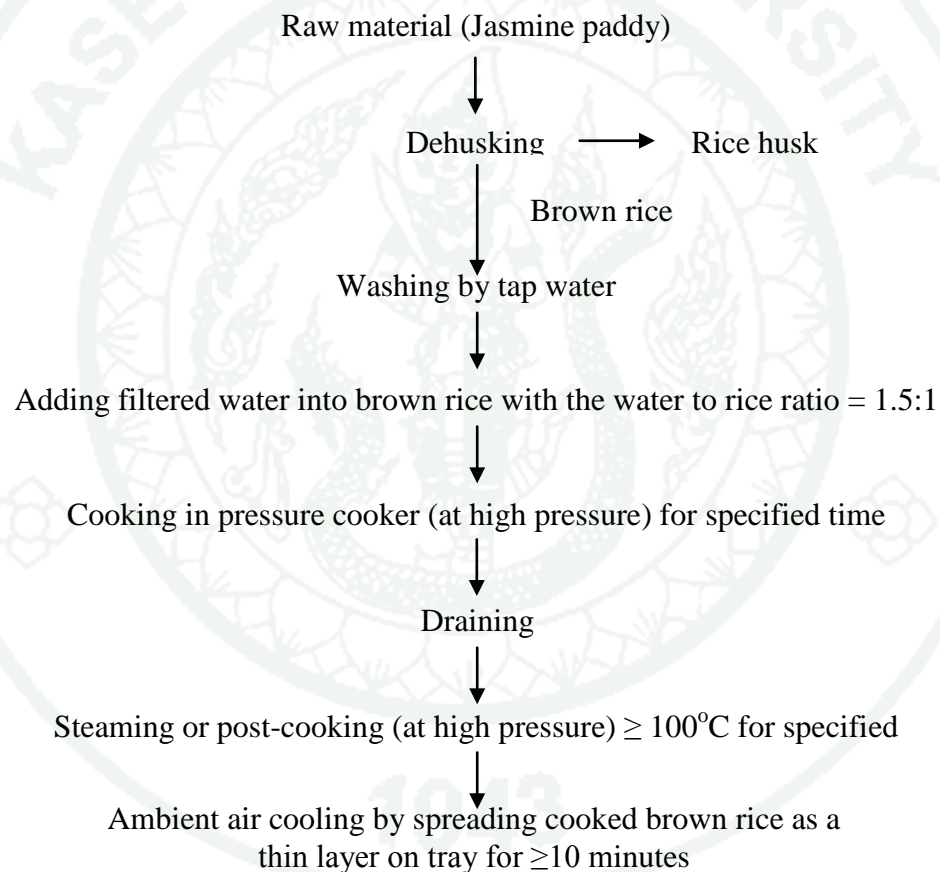
- STATGRAPHICS Centurion version XVI (StatPoint Technologies, Inc. Warrenton, VA 20186, USA).
- Statistical software package Statistica 5.5 (StatSoft, Inc. Tulsa, OK 74104 USA).



Methods

In order to investigate the appropriate process for producing the instant brown rice with high quality, the study was divided into two parts (experimental plans). The first part was conducted to study the drying kinetics, physical properties and modeling whereas a process of optimization was designed for second parts.

1. Drying curves and model development (Fig. 1)



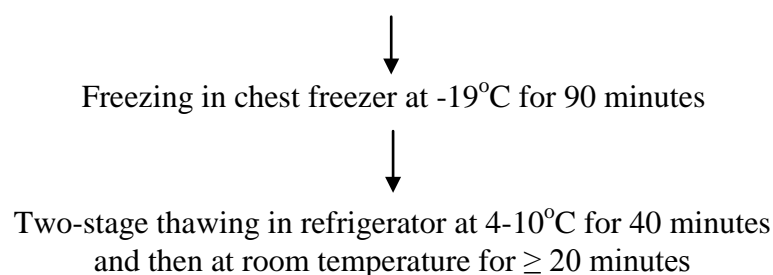


Figure 1 The experimental plan 1

1.1 Sample preparation

The rice seeds (*Oryza sativa* L.) of the KDML105 variety (jasmine rice) were dehusked to be brown rice using a laboratory dehusker. After separating the husk and broken rice out, 500 grams of jasmine brown rice was washed by tap water and then cooked in a “Zebra” digital pressure cooker. The cooking process was modified from Rewthong *et al.* (2011) that applied two-stages; first cooking period was roughly 18 minutes. After first cooking period, the lid of cooker was opened to release the pressure out and then started the second cooking stage for approximated period of 15 minutes. The cooker temperature range was $\geq 100^{\circ}\text{C}$ and the operating pressures were 40-70 kPa. The ratio of filtered water to rice was 1.5:1. The cooked brown rice was then exposed to pretreatments prior to drying. The pretreatments consisted of (1) freezing the cooked brown rice in the chest freezer at temperature -18 to -20°C for 90 min by spreading rice as a single layer on aluminum trays and (2) thawing the frozen cooked brown rice by two stages. The first stage of thawing was conducted in the refrigerator at temperature about $6 - 8^{\circ}\text{C}$ for 40 min and followed by the second stage at room temperature for 20 minutes. Prior to drying, the sample was sprayed with cold water at temperature of 8°C in order to easily separate the cooked rice that agglomerated. The moisture content of brown rice sample before drying was approximately 68-70% wet basis (w.b).

1.2 Drying experiments

The cooked brown rice prepared by the method previously described was dried by 4 drying schemes that have the potential for producing the instant brown rice. The diagram showing the sequence of steps of each experimental drying scheme is presented in Figure 2.

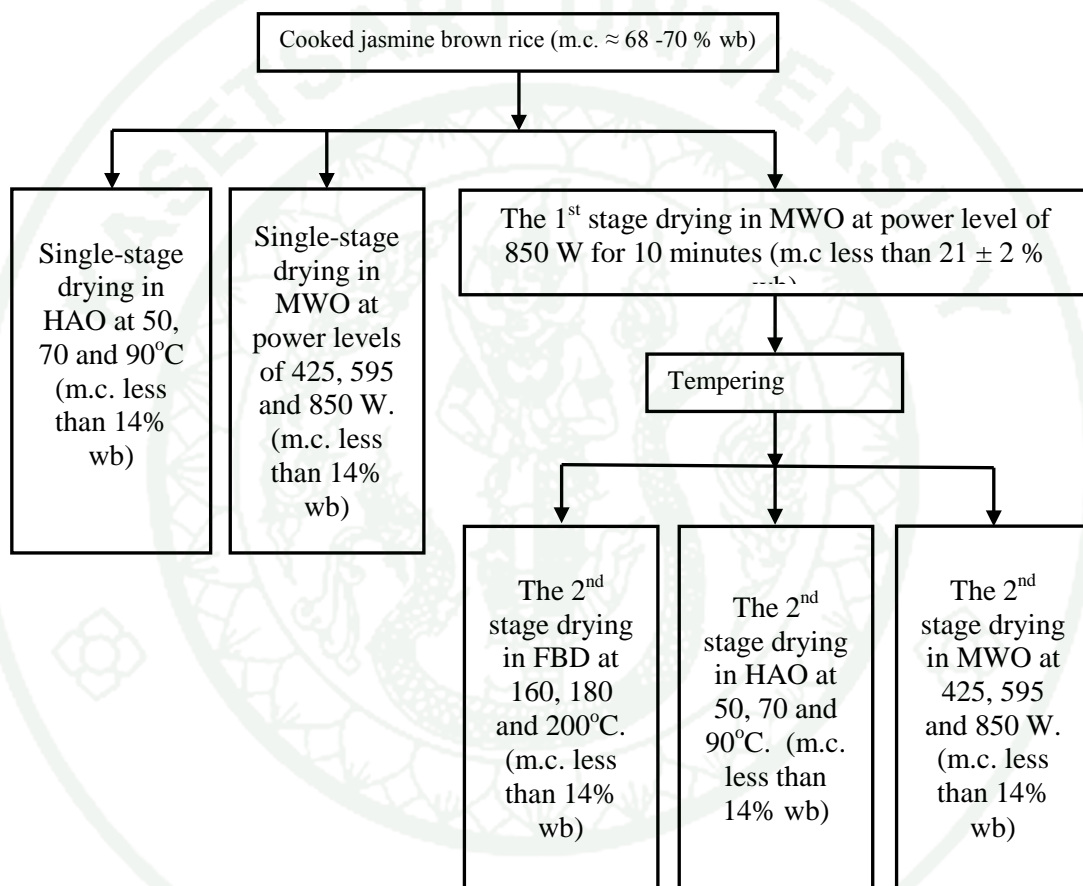


Figure 2 Experimental drying plan 1

All of the dryers used in this study were operated in the batch mode. The FBD, the HAO and the MWO with maximum output power of 850 W and operating frequency of 2,450 MHz was chosen.

The static bed depth of the samples in FBD was approximately 10 cm; on the other hand, the samples were dried as a single layer on a perforated tray and a

turntable dish (320 mm diameter) in HAO and MWO respectively. The FBD applied the superficial air velocities of 9 m/s. It was calculated by averaging the air velocities that were measured at different positions in the plenum. The drying air velocity above the samples in HAO was about 0.4 m/s. All the air velocities were measured using a hot-wire anemometer.

For the two-stage drying scheme, the tempering step was applied between drying stages by keeping samples in a sealed container overnight so that the moisture and temperature stresses within the grain would be relaxed.

The samples were collected during drying at each time interval (shown in Fig. 1) for moisture content determination, bulk, and true density measurement.

1.3 Physical property determination of dried cooked brown rice

1.3.1 Porosity determination

In this research, it is vital to understand the concept of bulk-particle porosity, defined as the volume fraction of voids outside the individual particle and open pore when stacked as bulk (Sun, 2008). In the other words, the space between rice grains and the open voids from the surface to interior of individual rice grain were estimated by bulk-particle porosity that can be calculated by the following equation.

$$\varepsilon = 1 - \frac{\rho_b}{\rho_p} \quad (1)$$

1.3.2 Bulk density

The method to determine the bulk density of sample was adapted from Prasert and Suwannaporn (2009). Dried-cooked brown rice (15g) was put in cylinder of 100ml, tapped 25 times, and recorded the volume as well as the weight.

$$\rho_b = \frac{\text{mass}}{\text{bulk volume}}, \frac{\text{kg}}{\text{l}} \quad (2)$$

1.3.3 True density determination

In this work, the true densities of cooked jasmine brown rice samples that were dried by a single-stage drying and two-stage drying were determined applying liquid displacement method. The true density is defined as the ratio of the sample weight to the true volume of sample (excluding air space between grains). An amount of rice samples were put into the 500 ml volumetric flask prior to filling up a portion of tap water at room temperature until reaching a specified volume of 500 ml. The weight and volume of filled water were known; thus, the true volume and subsequent true density could be calculated. To avoid the effects of moisture diffusion into the rice kernel and the sample swelling on the true density measurement, the measurement was conducted and recorded immediately after filling the water into the flask.

$$\rho_p = \frac{\text{mass}}{\text{particle volume}}, \frac{\text{kg}}{\text{l}} \quad (3)$$

1.3.4 Porosity and moisture content relationship

The porosity data versus moisture content was plotted to see the trend of this relationship. The relationship between the porosity and moisture content of samples was then fitted using the following polynomial equations, Eq. (4) for single-stage and Eq. (5) for two-stage drying. The least square method for non-linear regression analysis integrated in the statistical software package Statistica 5.5 (StatSoft, Inc. Tulsa, OK 74104 USA) was applied to determine all these constant parameters. Subsequently, the models were evaluated by root mean square error (RMSE), coefficient of determination (R^2) and the relative error percentage (PE). The Equations (8) to (10) are for calculating R^2 , RMSE, and PE shown in section 4.3.

$$\varepsilon = a_0 + a_1 mc + \frac{a_2}{mc^2} + \frac{a_3}{mc^3} \quad (4)$$

$$\varepsilon = a_0 + a_1 mc + a_2 mc^2 \quad (5)$$

1.4 Mathematical models for drying rice

1.4.1 Thin layer drying models

The drying experimental data were fitted into various thin layer-drying models as shown in Table 1.

Table 1 Thin Layer Drying Models.

Model name	Model equation	References
Page	$MR = \exp(-Kt^N)$	Karathanos and Belessiotis (1999)
Henderson and Pabis	$MR = A \exp(-Kt)$	Akpinar <i>et al.</i> (2003)
Hii <i>et al.</i>	$MR = A \exp(-K_1 t^N) + B \exp(-K_2 t^N)$	Hii <i>et al.</i> (2009a)
Midilli- Kucuk	$MR = A \exp(-K_1 t^N) + Bt$	Midilli & Kucuk (2003)
Verma	$MR = A \exp(-K_1 t) + (1-A) \exp(-K_2 t)$	Verma <i>et al.</i> (1985)
Modified Page	$MR = \exp\left((-Kt^N) \exp\left(-\frac{A}{T_k}\right)\right)$	Jittanit (2007)
Modified two-compartment	$MR = A_1 \exp\left((-K_1 t) \exp\left(-\frac{B}{T_k}\right)\right) + A_2 \exp\left((-K_2 t) \exp\left(-\frac{B}{T_k}\right)\right)$	Jittanit (2007)

The procedures of fitting the thin layer drying models were accomplished by the following steps:

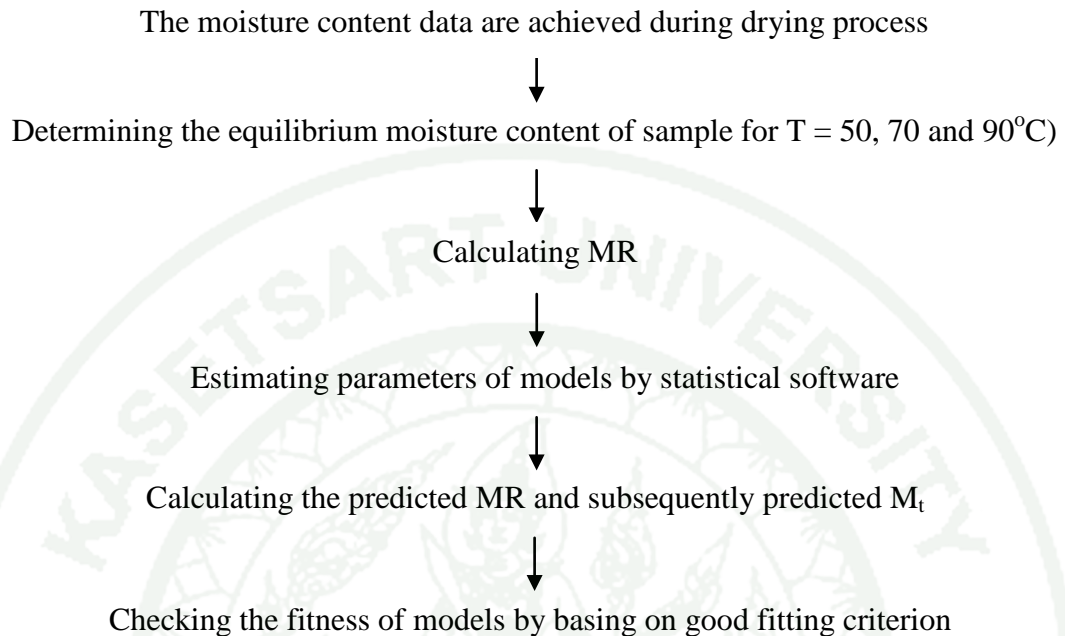


Figure 3 The procedures of fitting the thin layer drying models

1.4.2 Moisture content determination

During cooked brown rice drying, the samples were collected at each specified time interval (Fig.1) to determine their moisture contents. The moisture content can be calculated by the following formula.

$$\text{Moisture content} = \frac{(W_i - W_{bd})}{W_i} (\% \text{ wet basis}) \quad (6)$$

$$\text{Moisture content} = \frac{(W_i - W_{bd})}{W_{bd}} (\% \text{ dry basis}) \quad (7)$$

Where the subscript i and bd refer to the initial and bone-dry weight, respectively.

Moisture contents of samples were determined in duplicate (≈ 10 g for each sample) applying oven method at 105°C for 24 h (Swamy *et al.*, 1971).

The equilibrium moisture contents (M_e) in the cases of drying temperatures of 50, 70 and 90 °C were estimated by prolonging the drying process at corresponding temperature until reaching the constant weight. Dissimilarly, the M_e was zero if the drying temperature was higher than 100 °C (Taechapairoj *et al.*, 2003). In addition, the M_e was assumed to be zero for the drying in MWD because the sample temperature would be over 100 °C if continuing the drying procedure.

1.4.3 Statistical analysis

The entire model fitting in this work performed using the least square method for non-linear regression analysis. In these models, the moisture ratio (MR) is defined as below:

$$\text{MR} = \text{the dimensionless moisture ratio} = \frac{M_t - M_e}{M_i - M_e},$$

M_t = the moisture content (% db) at any time t during drying,

M_i = the initial moisture content (% db),

M_e = the equilibrium moisture content (% db),

T_K = the drying temperature (°K),

k , k_1 and k_2 are the drying rate constants and N , A , A_1 , A_2 and B are constants

For the model development of microwave drying, the temperature parameter in the model was replaced by microwave power level in the unit of Watt.

The model fitting in this work was performed applying the least square method for non-linear regression analysis. The statistical software package Statistica 5.5 was used. The goodness of fit of each model was evaluated by basing on root mean square error (RMSE), coefficient of determination (R^2) and the relative error percentage (PE) that were calculated by the Equations 9 to 11.

$$R^2 = 1 - \frac{\sum_{i=1}^n (\text{Measured } MR \text{ value} - \text{Predicted } MR \text{ value})^2}{\sum_{i=1}^n (\text{Measured } MR \text{ value} - \text{Average } MR \text{ value})^2} \quad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\text{Measured } M_t \text{ value} - \text{Predicted } M_t \text{ value})^2}{n}} \quad (9)$$

$$PE(\%) = \frac{100}{n} \sum_{i=1}^n \frac{|\text{Measured } M_t \text{ value} - \text{Predicted } M_t \text{ value}|}{\text{Measured } M_t \text{ value}} \quad (10)$$

1.5 Effective moisture diffusivity determination

The drying of most food materials usually occurs in the falling rate period indicating that the moisture transfer during drying was limited and controlled by internal diffusion (Wang and Brennan, 1992). The moisture diffusion from inner to the sample surface was described by the Fick's second law of diffusion as shown in Equation 4 (Crank, 1975).

$$\frac{\partial M}{\partial t} = \nabla \cdot (D_{eff} \nabla M) \quad (11)$$

Where, M is moisture content (kg water/kg dry matter) and D_{eff} is effective moisture diffusivity (m^2/s). For the determination of moisture diffusivity, the cooked brown rice was considered as a finite cylindrical shape. The analytical solution of Fick's second law of diffusion for finite-cylindrical shaped material, with the assumptions of moisture transfer by moisture diffusion, negligible shrinkage, and constant diffusion coefficients and temperature is provided by Equation 13 (Pomsa-ad *et al.*, 2002; Sootjarit *et al.*, 2011).

$$MR = \left(\frac{8}{\pi^2} \right) \sum_{m=1}^{\infty} \frac{4}{\lambda_m^2} \exp\left(-\frac{\lambda_m^2 D_{eff} t}{r_0^2} \right) \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{\pi^2 (2n+1)^2 D_{eff} t}{4l^2} \right) \quad (12)$$

Where λ_m is the root of Bessel function of the first kind and zero order, r_0 is radius of cooked brown rice, 1.65×10^{-3} m and l is half length of cooked brown rice, 4.07×10^{-3} m. From equation (12), if deeming only $m = 1, 2$ and $n = 0, 1$, the expansion of Equation (12) become the following equation:

$$MR = 0.561e^{-5.78N_{Fi}-2.46N_{Fo}} + 0.062e^{-5.78N_{Fi}-22.18N_{Fo}} + 0.107e^{-30.47N_{Fi}-2.46N_{Fo}} + 0.012e^{-30.47N_{Fi}-22.18N_{Fo}} \quad (13)$$

Where N_{Fi} is the Fick number $\left(\frac{D_{eff}t}{r_0^2}\right)$ and N_{Fo} is Fourier number $\left(\frac{D_{eff}t}{l^2}\right)$. Likely to Sootjarit *et al.* (2011), it is clear that the first term of the series solution in Equation (13) will dominate the rest. Thus, the Equation (13) was rewritten as follow:

$$MR \approx 0.561e^{-5.78N_{Fi}-2.46N_{Fo}} \quad (14)$$

Two methods were conducted in this research for determining the effective moisture diffusivity from the drying experimental data comprising regular regime method (Roberts *et al.* (2008); Jittanit, 2011; Sootjarit *et al.*, 2011) and slope method (Ramesh, 2003; Luangmalawat *et al.*, 2008).

1.5.1 The regular regime method and activation energy calculation

According to this method, for long drying time, the first term of the series solutions will dominate (Crank, 1975), thus, the effective diffusivity values was estimated by taking only the first term of equation (13) or equation (14). The natural logarithmic of the equation (14) is as below:

$$\ln(MR) = \ln(0.561) - \left(\frac{5.78}{r_0^2} + \frac{2.46}{l^2}\right) D_{eff}t \quad (15)$$

The effective moisture diffusivity can be determined from the slope of the normalized plot of the moisture ratio, $\ln(MR)$ versus time, using the following equation:

$$D_{eff} = \frac{-slope}{\left(\frac{5.78}{r_0^2} - \frac{2.46}{l^2}\right)} \quad (16)$$

According to Roberts *et al.* (2008), the effective moisture diffusivity for each seed variety increased with increasing temperature. Temperature dependence of the effective diffusivity followed an Arrhenius relationship:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{R_c T}\right) \quad (17)$$

Where D_o is the pre-exponential factor of the Arrhenius equation (m^2/s); E_a is the activation energy (kJ/mol); R_c is the universal gas constant (kJ/mol K); T is the absolute air temperature (K).

The activation energy is determined from the slope of the Arrhenius plot, $\ln(D_{eff})$ versus $1/T$.

1.5.2 The slope method

The moisture diffusivities were calculated applying the slope of the experimental drying curve, $(dMR/dt)_{exp}$, and that of the theoretical curve, $(dMR/dFo)_{theo}$, as the following steps.

From the formula of N_{Fi} and N_{F0} , N_{Fi} can be presented as a function of N_{F0} (18). Replacing N_{Fi} into Equation (15) and then differentiating with respect to N_{F0} (19).

$$N_{Fi} = N_{F0} \frac{l^2}{r_0^2} \quad (18)$$

$$\frac{\partial MR}{\partial N_{F0}} = 0.561 e^{\left(-\frac{5.78l^2}{r_0^2} - 2.46\right) N_{F0}} \left(-\frac{5.78l^2}{r_0^2} - 2.46\right) \quad (19)$$

Similarly, after substituting N_{Fi} and N_{F0} by $(D_{eff}t)/r_0^2$ and $(D_{eff}t)/l^2$ into Equation (19) respectively and then differentiating with respect to time (t), the solution will be

$$\frac{\partial MR}{\partial t} = 0.561e^{\left(-\frac{5.78l^2}{r_0^2} - 2.46\right)\left(\frac{D_{eff}t}{l^2}\right)} \left(-\frac{5.78l^2}{r_0^2} - 2.46\right) \left(\frac{D_{eff}}{l^2}\right) \quad (20)$$

As a result of manipulating the Equation (19) and (20), the effective moisture diffusivity of cooked brown rice can be calculated by Equation (21).

$$D_{eff} = \frac{(\partial MR/\partial t)}{(\partial MR/\partial N_{F0})} l^2 \quad (21)$$

It is noted here that for the determination of D_{eff} in this work, the value of $(\partial MR/\partial t)$ at each moisture content level of sample was calculated using the drying experimental results; whereas, that of $(\partial MR/\partial N_{F0})$ was calculated using the Equation (19) that is based on the diffusion theory (Luangmalawat *et al.*, 2008). The value of N_{F0} that is a variable in the Equation (19) was determined by taking natural logarithm (ln) for the Equation (19) and then replacing the measured values of MR , l and r_0 into the equation.

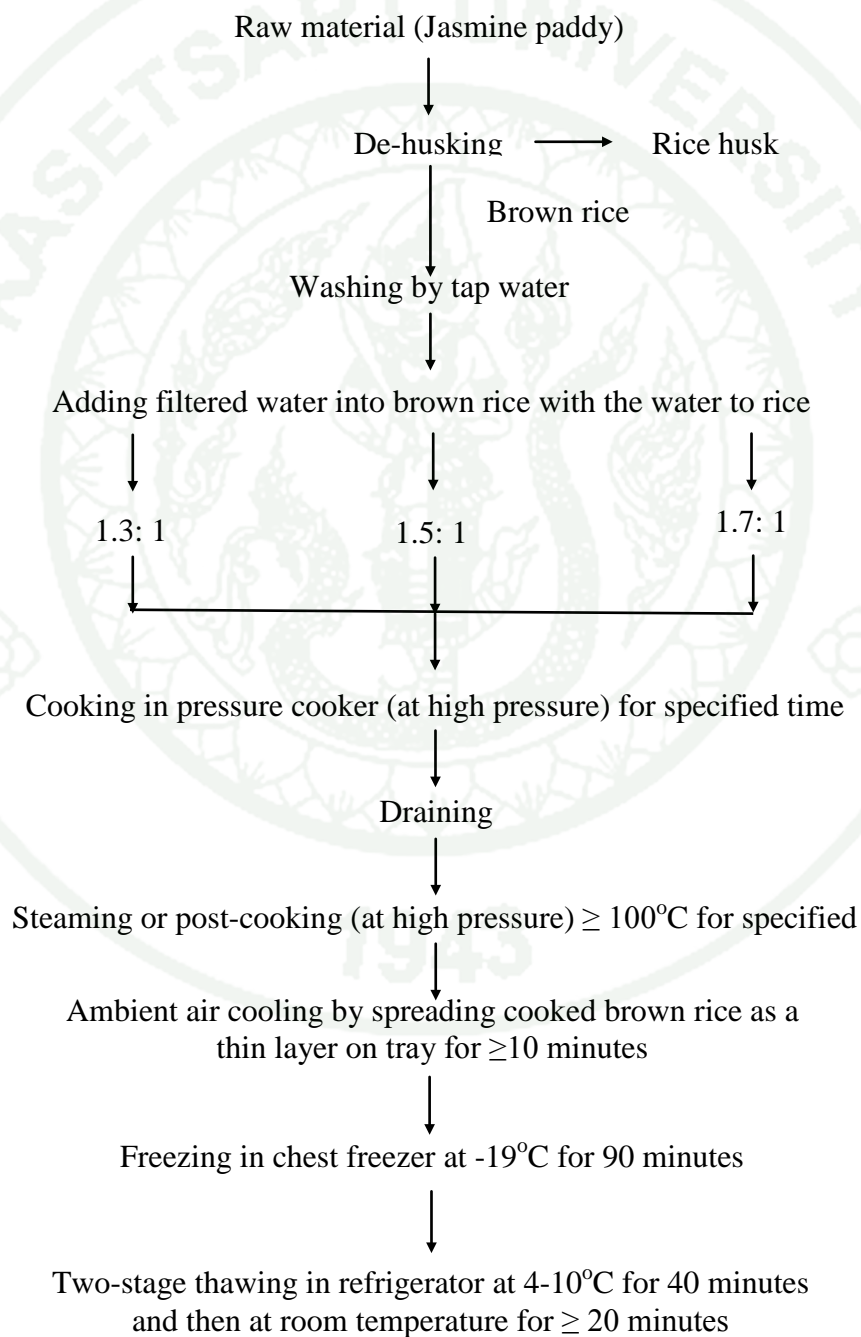
1.5.3 Diffusivity and moisture content relationship

The diffusivity values obtained by slope methods were plotted versus moisture contents. In addition, the relationship between the diffusivity and moisture content of samples was fitted using the following polynomial equations, (22) for single-stage and two-stage drying. The model fitting in this work was performed by applying the least square method for non-linear regression analysis. The statistical software package Statistica 5.5 (StatSoft, Inc. Tulsa, OK 74104 USA) was used. The models were evaluated by basing on root mean square error (RMSE), coefficient of

determination (R^2) and the relative error percentage (PE) that were calculated by the Equation (8) to (10).

$$D_{\text{eff}} = a + \frac{b}{mc} + \frac{c}{mc^2} + \frac{d}{mc^3} \quad (22)$$

2. Instant brown rice production



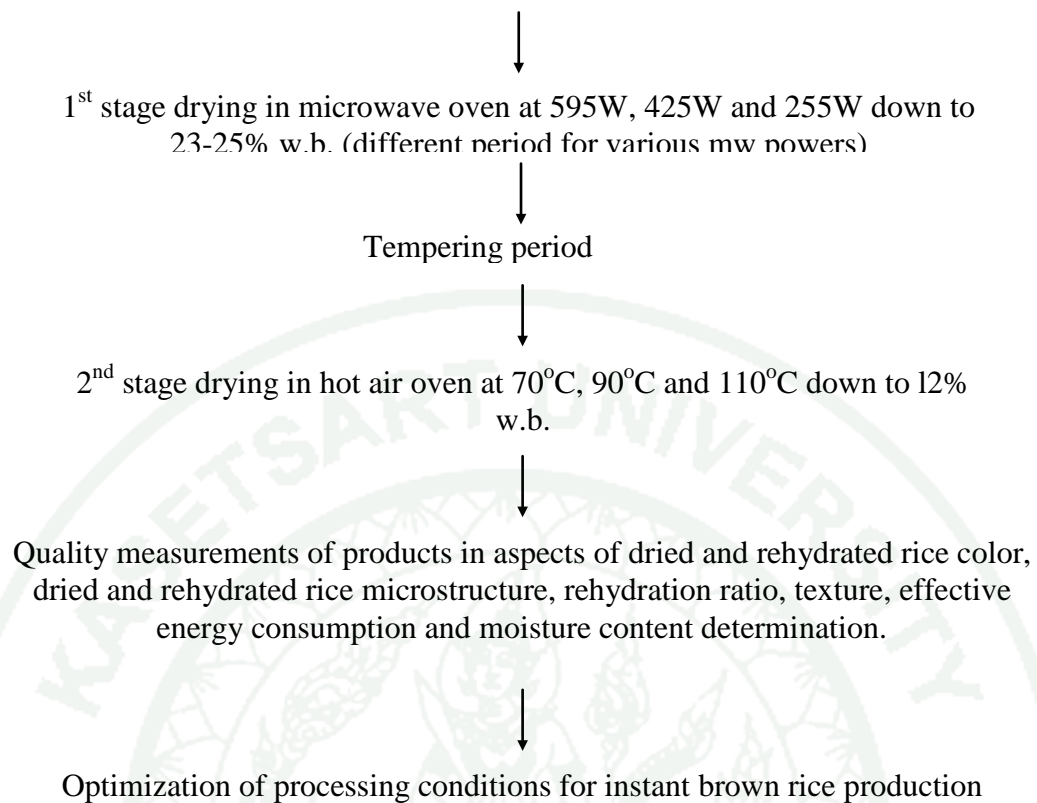


Figure 4 Experimental plan 2: Instant brown rice production

2.1 Quality determination of instant brown rice

2.1.1 Stereo microscopy capture

The images of dried cooked brown rice (moisture content < 14% wb) were captured by the stereo microscope (Leica, model S8APO, Leica Microsystems Imaging Solutions Ltd., UK) at 16x magnification operating with transmitted-light stand (Leica, model TL BFDF), digital camera for microscope (Leica, model DFC280) and Leica Application Suite (LAS) software so that the effect of drying conditions on the structure of rice would be seen. In addition to dried rice, the images of freshly cooked brown rice and the brown rice after cooking, freezing and thawing were captured in order to observe the consequence of freezing and thawing pretreatment on the structure of rice.

2.1.2 Texture analysis

Twenty grams of dried cooked brown rice were rehydrated by using microwave oven for 5 minutes. After rehydration and 5 minutes of draining, six kernels were picked up randomly among the rehydrated sample and placed separately in the line on the basement to measure the hardness and stickiness by texture analyzer (TA.XTPlus, Stable Micro System Ltd., UK). A cylindrical probe of 25 mm was used to compress the kernels to 85% deformation at the pre-test speed of 1 mm/s and post-test speed of 10mm/s (modified from Rewthong *et al.*, 2011). The force-deformation data of 8 replications and 2 repeated samples for each of operating conditions were measured.

2.1.3 Dried-cooked brown rice density measurement

Thirty grams of dried cooked brown rice were put in 100-ml cylinder and tapped 25–30 times (Prasert and Suwannaporn, 2009) to allow uniform compacting of grains, then recorded the volume and weighed the samples in the cylinder. Density was calculated by:

$$\text{Density} = \frac{\text{Weight of dried cooked brown rice (g)}}{\text{Volume of dried cooked brown rice (ml)}} \quad (23)$$

2.1.4 Rehydration ratio

Ten grams of dried cooked brown rice were immersed into water, boiled in microwave oven for 5 minutes and then drained for 5 minutes. The recorded weight of before and after rehydration were used to calculate the rehydration ratio (Maskan, 2001; Luangmalawat *et al.*, 2008) as the formula below:

$$\text{Rehydration ratio (\%)} = \frac{(\text{Weight of rehydrated brown rice} - \text{Weight of dried cooked brown rice})}{\text{Weight of dried cooked brown rice}} \quad (24)$$

The rehydration experiments were repeated for 3-5 times.

2.1.5 Color measurement

The surface color of dried and rehydrated cooked brown rice was measured by a Mini Lab colorimeter (Chromameter model CR-300, Japan) using the CIE system with color values of L*, a* and b*. Prior to each measurement, the colorimeter was calibrated with a standard white and black plate. The color of samples was expressed as L*-value, a*-value and b*-value through BI with a* and b* are the chromaticity coordinates, where “L*” represents lightness (whiteness), BI is color intensity and calculated by the following equation (Roy *et al.*, 2008).

$$B = \sqrt{(a^*)^2 + (b^*)^2} \quad (25)$$

The measurements were performed in two replications and were repeated 5 times per replicate for both dried and rehydrated samples.

2.1.6 Energy consumption

Electrical energy consumption were only calculated for drying process, first stage drying in microwave oven and second stage drying in hot air oven, using the digital clamp meter (Hioki 3282, HIOKI E. E. Corporation, Japan). The process of energy consumption determination was conducted as below, following Ngamnikom and Songsermpong (2011).

$$P = \frac{(A \times V)}{1000} \quad (26)$$

$$E = P \times t \quad (27)$$

$$E_s = \frac{E}{W} \quad (28)$$

Where P = electrical power (kW); A = ampere; V = volt (V); P.F = power factor (no unit); E = energy consumption during process (kJ), t = second (s); W = weight of initial sample (kg); Es = energy consumption per sample weight (kJ/kg).

2.2 Statistical analysis

The mathematical models were developed to describe the correlation between responses and factors with Box-Behnken design. Three important factors were water-rice ratio, microwave power levels and conventional drying temperature levels. These were done by involving three major steps (Nagarajan and Natarajan, 1999): (1) performing designed experiments, (2) estimating the coefficients in the mathematical model to predict the response and (3) checking the adequacy of model.

The predictive models were obtained by multi linear regression analysis. Each term in the models was checked the significant effect on the model predicting for each response by basing on the mean square of an effect and the mean squared error to determine the statistical significance of each effect. (p-value <0.05). The p-value associated with testing the null hypothesis that the coefficient for a selected effect equals 0, implying that the effect is not present. P-values below a critical level (such as 0.05 if operating at the 5% significance level) indicate that the corresponding effect is statistically significant at that significance level.

These parameters were used to interpret the main factor effects or the interaction between factors. The main effect of factor j is defined as the change in the response variable Y when X_j is changed from its low level to its high level, with all other factors being held constant midway between their lows and their highs. Two-factor interaction, in general, may be thought of as the additional effect of one factor over and above the main effect when the second factor is held at its high level.

The response surface and contour plots of each response were plotted as a function of different process conditions to describe the effects and demonstrate optimal points.

The model adequacy was checked basing on the predicted R², prediction error sum of squares, and lack of fit test using STATGRAPHICS Centurion version XVI (StatPoint Technologies, Inc. Warrenton, VA 20186, USA). The second-order model was selected to develop the predicting response models, expressed as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{22} X_2^2 + \beta_{23} X_2 X_3 + \beta_{33} X_3^2 \quad (29)$$

Where Y represented a response variable, β_0 is the intercept, β_1 , β_2 and β_3 are linear terms, β_{11} , β_{22} and β_{33} are quadratic terms, and X_1 , X_2 , and X_3 are independent variables.

2.3 Optimization process

To conduct the multiple response optimizations, model for each response was constructed separately and conducted optimizing for each response prior to combining multi-responses. The statistical model of multiple optimization was based on the desirability function is first defined for each response. The desirability function expresses the desirability of a response value equal to y on a scale of 0 to 1. This function takes one of three forms, depending upon whether the response is to be maximized, minimized, or a target value hit (the functions were shown in Appendix section).

For the single response, graphical method was applied; the contour plots showed the optimal points while for the multi-responses, the desirability optimization methodology involving of both conventional graphical method and desirable function methodology were applied to optimize multi responses (Corzo *et al.*, 2008).

3 Place and Duration

3.1 Places

Department of Food Science and Technology, Faculty of Agro-Industry, Kasetsart University, Bangkok, Thailand.

3.2 Duration

June 2010 – March 2012.

RESULTS AND DISCUSSION

1. Drying kinetics, physical properties and modeling

1.1 Drying kinetics

1.1.1 Single-stage drying in HAO and MWO

Drying kinetics of cooked brown rice during single-stage drying in HAO at 50, 70 and 90°C and in MWO at 425, 595 and 850 W were indicated in Figure 5 and 6 respectively. It is clear that at higher temperature and microwave power level, the amount of evaporated water was greater than that of lower conditions, which were shown as the steeper slope. Furthermore, the drying curves revealed a short initial period of the heating up and then the falling drying rate period afterward. The falling rate period occurred because the moisture evaporation rate was controlled by internal diffusion during this time until the final moisture content (less than 5 % d.b.).

It appeared that in order to dry the cooked brown rice from initial moisture content (205 % d.b.) down to approximately 16% d.b., it required 360, 270 and 150 minutes for the drying temperatures at 50, 70 and 90°C respectively while for MWO, it only required 17, 15 and 12 minutes at the corresponding microwave power of 425, 595 and 850W respectively. The drying rate of single stage drying in HAO found in this work was lower than that reported by Luangmalawat *et al.* (2008) at the comparable drying temperature. The differences should be due to different kinds of rice and drying equipment applied in the studies. Luangmalawat *et al.* (2008) used cooked white rice as the sample and drying air velocity of 0.4 m/s for their experiments.

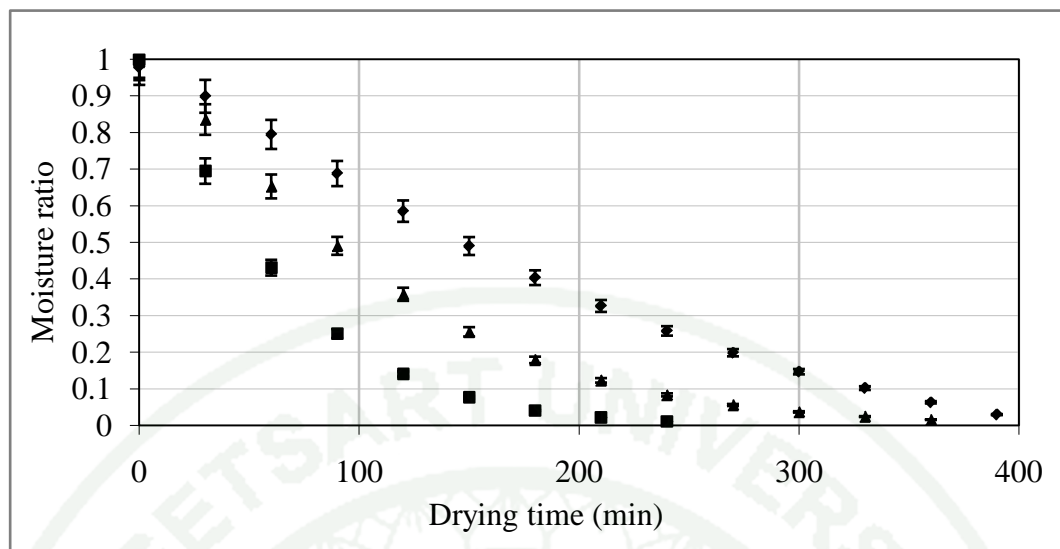


Figure 5 Drying characteristics of cooked brown rice during single-stage drying in HAO ($\diamond = 50^{\circ}\text{C}$; $\blacktriangle = 70^{\circ}\text{C}$; $\blacksquare = 90^{\circ}\text{C}$).

Moreover, the results revealed that the drying rate obtained by single stage drying in MWO was much higher than that of HAO (Fig.7). In hot air heating, heat is transferred to the surface of the material to be heated by conduction, convection, and/or radiation, and into the interior by thermal conduction. In contrast, in dielectric heating, heat is generated directly inside the material, making possible higher heat fluxes and thus a much faster temperature rise than in hot air heating (Sutar and Prasad, 2008). If comparing between the power level of 425 W and 595 W, the drying rate appeared to be not significantly different during the period of drying at the moisture content of sample higher than 35% d.b. However, at the later drying period the power level of 595 W obviously resulted in the higher drying rate. At the power level of 850W, the moisture evaporation rate of cooked brown rice was clearly faster than that of 425 and 595W. For microwave drying, the dehydration rate was increased as increase of microwave power levels since more heat is generated within the sample at higher microwave power, creating a larger vapour pressure difference between the centre and the surface of products (Lin *et al.*, 1998). The very high drying rate is usually needed for drying cooked brown rice in order to produce the instant rice with porous structure.

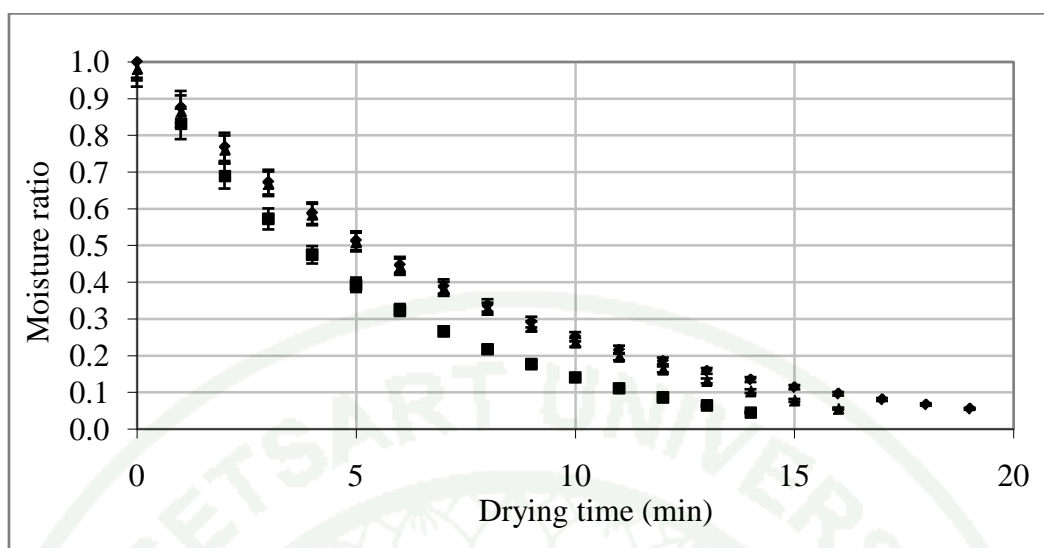


Figure 6 Drying characteristics of cooked brown rice during single-stage drying in MWO (\blacklozenge = 425 W; \blacktriangle = 595 W; \blacksquare = 850 W).

1.1.1 Second-stage drying in HAO, FBD and MWO

Drying characteristics of cooked brown rice during the second-stage drying in HAO, FBD, and MWO are presented in Figure 8 to 11. Prior to conducting the second-stage of drying, the samples were dried by MWO at power level of 850W for about 10 minutes and then rested for overnight. The initial moisture content of sample for second-stage drying schemes ranged between 27 and 30 % d.b. These moistures could be somewhat bound water type so that the drying rate slowed down for the second-stage drying in HAO and FBD especially at lower drying temperature. However, it appeared that moisture still evaporated fast for second-stage drying in MWO. This contributed to explain the unique characteristic of microwave drying at the falling rate period (Tang *et al.*, 2011) for drying cooked brown rice. MW drying speeds up the final drying in the falling rate region in which conventional drying becomes less effective and take a long time due to reduced heat and moisture transfer. The unique characteristic of dielectric heating by microwave is that due to interact directly with moisture in the core of sample, microwave heating provides a positive gradient for moisture to migrate toward the surface, thus significantly reducing drying time.

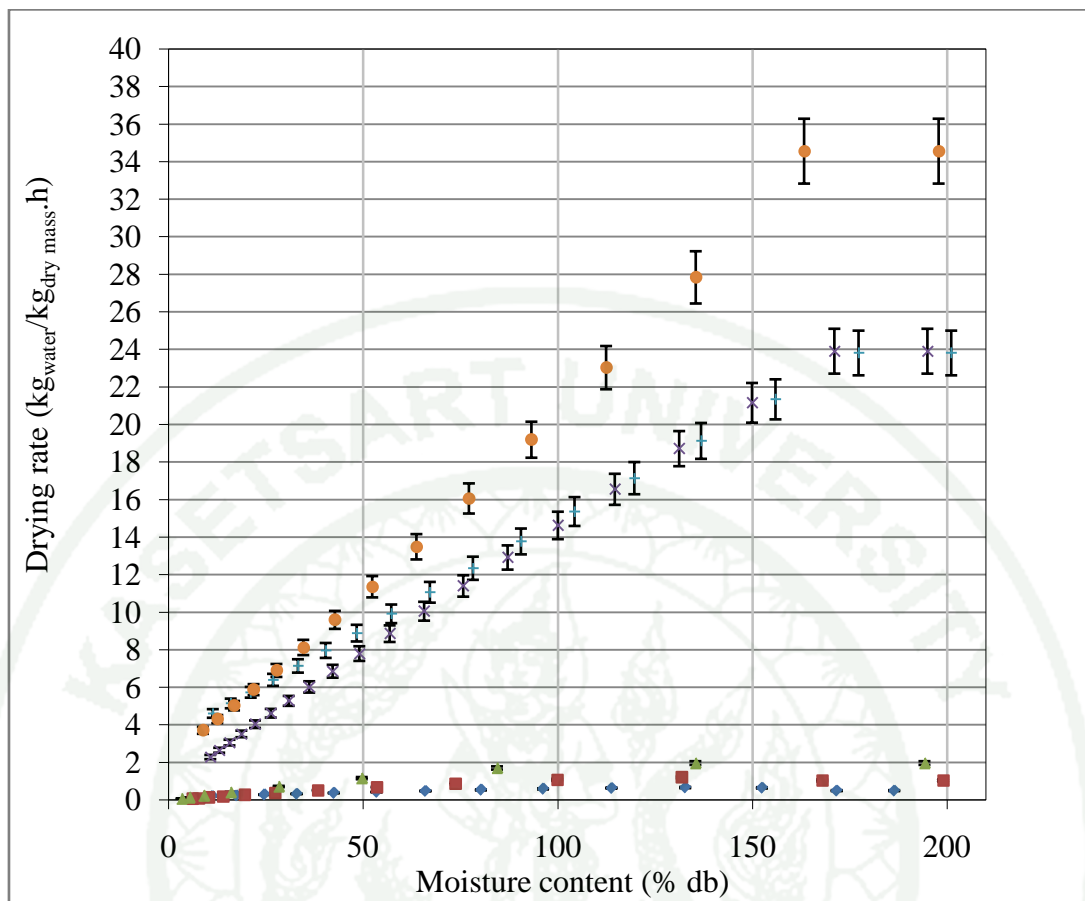


Figure 7 Drying rate curves of cooked brown rice during single-stage drying in HAO (♦ = 50°C; ■ = 70°C; ▲ = 90°C) and MWO (× = 425 W; + = 595 W; ● = 850 W).

In comparison between drying rate of second-stage drying in FBD and HAO (Fig. 11), it was clearly that drying rate in FBD is higher than that of HAO. This is due to the high drying air velocity and good vibrating in its drying chamber, the convective heat and moisture transfer coefficients increased for drying in FBD (Sootjarit *et al.*, 2011). Moreover, at the higher temperature the drying rate is raised for HAO but it appeared to be close to each other for FBD.

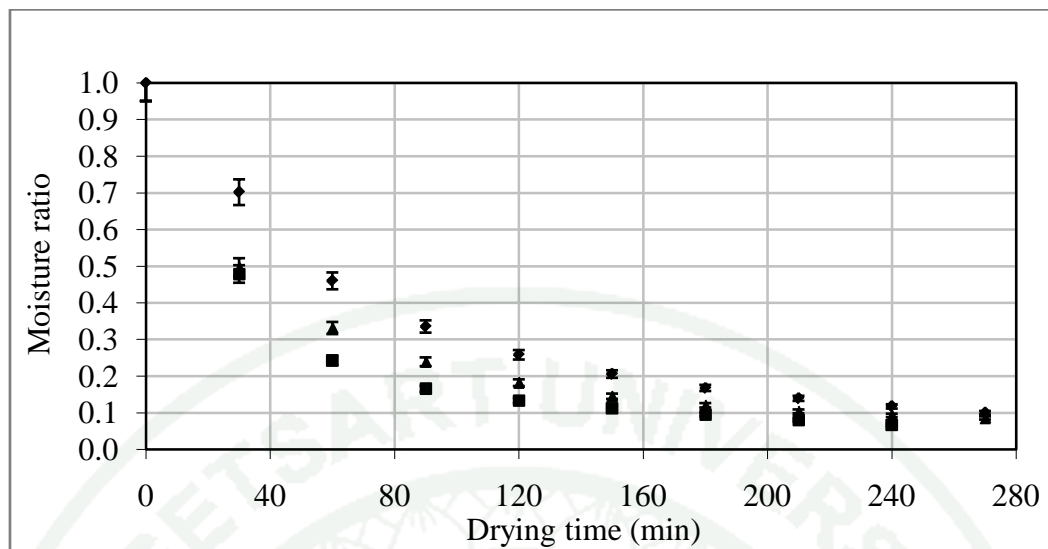


Figure 8 Drying characteristics of cooked brown rice during second-stage drying in HAO ($\diamond = 50^{\circ}\text{C}$; $\blacktriangle = 70^{\circ}\text{C}$; $\blacksquare = 90^{\circ}\text{C}$).

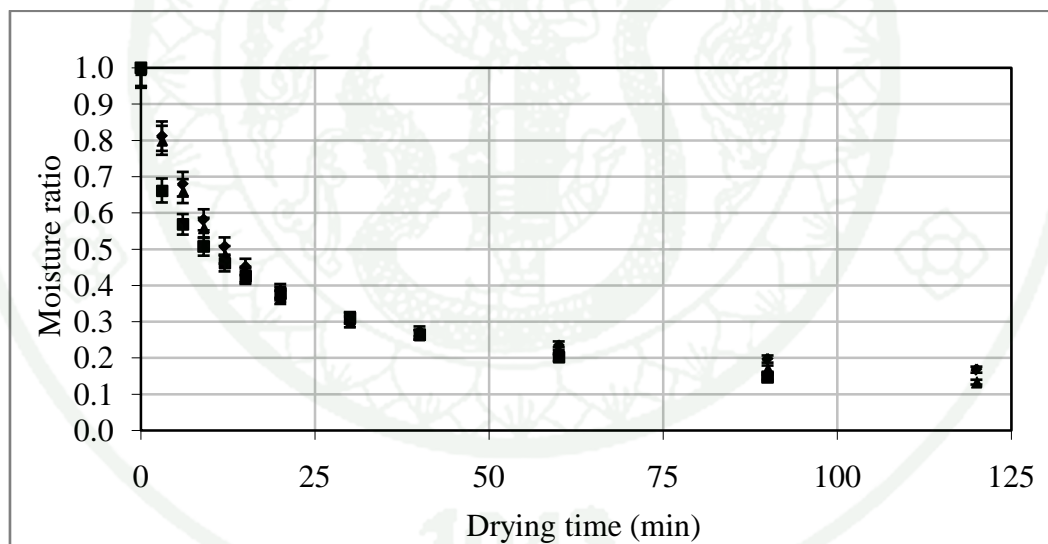


Figure 9 Drying characteristics of cooked brown rice during second-stage drying in FBD ($\diamond = 160^{\circ}\text{C}$; $\blacktriangle = 180^{\circ}\text{C}$; $\blacksquare = 200^{\circ}\text{C}$).

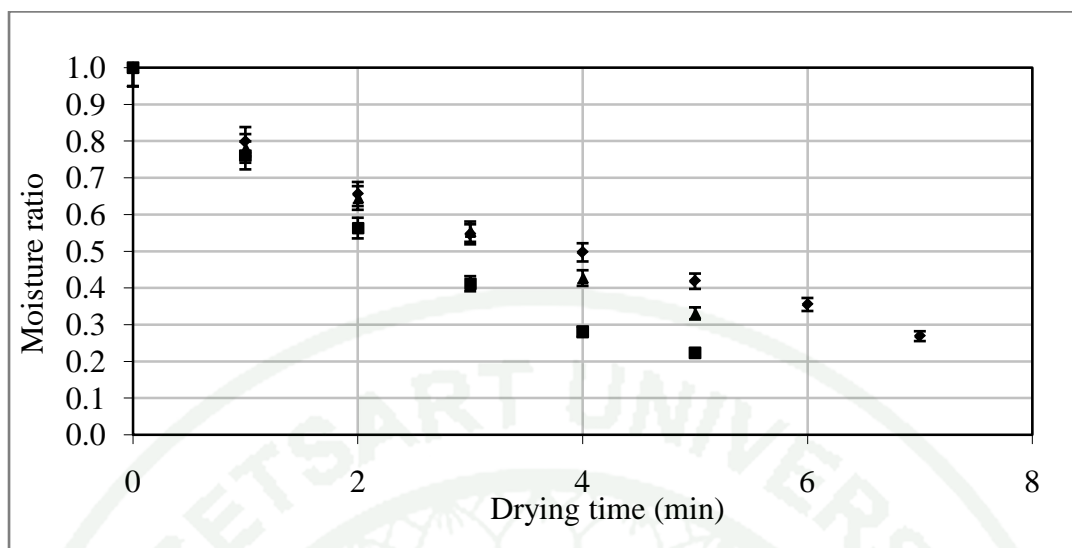


Figure 10 Drying characteristics of cooked brown rice during second-stage drying in MWO (\diamond = 425 W; \blacktriangle = 595 W; \blacksquare = 850 W).

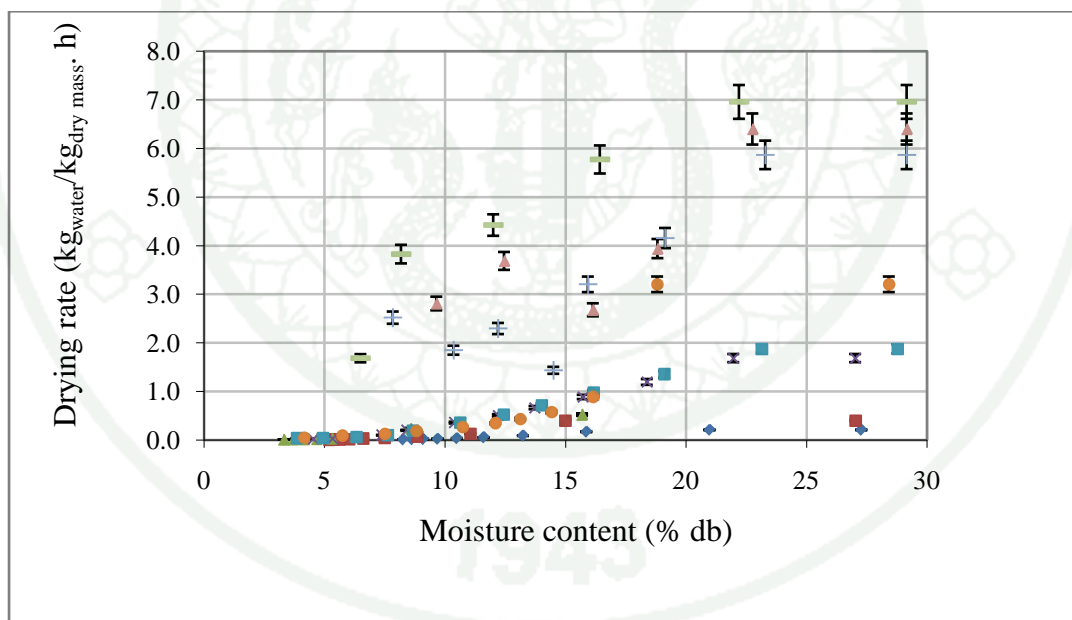


Figure 11 Drying rate curves of cooked brown rice during second-stage drying in HAO (\diamond = 50°C; \blacksquare = 70°C; \blacktriangle = 90°C), FBD (\times = 160°C; \blacksquare = 180°C; \bullet = 200°C) and MWO ($+$ = 425 W; \blacktriangle = 595 W; $-$ = 850 W).

1.2 Drying model development

The drying characteristics of cooked brown rice were fitted into selected thin-layer drying models by least square method. The summary of the result is shown in Appendix Table 2 to 6.

1.2.1 Single-stage drying in HAO

If deeming the best-fitting models by basing on their R^2 , RMSE and PE, there are several models which are well representing the drying of cooked brown rice during single-stage drying in HAO. Hii *et al.* (2009)'s model is the best fitted with the highest R^2 (0.9988, 0.9983 and 0.9996), the smallest RMSE (1.97, 2.57 and 1.20 % d.b.) and the lowest PE (2.43, 8.91 and 4.97 %). The Hii *et al.*'s model was found as the best fitting at this range of temperature for drying fermented beans (Hii *et al.*, 2009), for drying carrot pomace, Kumar (2011); Babalis *et al.* (2006) also applied this model when drying fresh figs.

Hii *et al.* (2009)'s model is the model that was combined between Page and two-term model which was developed for cocoa bean drying by Hii *et al.* (2009). The Page model was found in several literatures to be able to fit drying curves of various food products (Jayas *et al.*, 1991) while the two-term model is basically derived from the first two terms of the analytical solution of the diffusion equation. By combining the advantages of these two factors, Hii *et al.* (2009)'s model was found able to outperform other models tested. Similar to Hii *et al.* (2009), a short initial warm up period was observed and subsequent drying took place in the falling rate period in this study.

1.2.2 Single-stage drying in MWO

For 3 microwave power levels, Verma's and Midilli- Kucuk's models were found to be suitable for drying cooked brown rice. The findings of Soysal *et al.* (2006), Demirhan & Ozbek (2011) and Ganesapillai *et al.* (2011) also showed that Midilli & Kucuk's model and Verma's model were the suitable thin-layer

drying models for microwave drying. Soysal *et al.* (2006) stated that Midilli-Kucuk's model fitted well with the experimental values of drying of Parsley by microwave drying at MW power close to this study (900W) whereas Ganesapillai *et al.* (2011) stated that the Midilli- Kucuk model seems to be best model for microwave drying of banana. According to drying results of some vegetables and fruits, Akpinar (2006) said that the Midilli–Kucuk model adequately described the drying behavior of agricultural products such as potato, apple and pumpkin slices in the thin layer drying process.

1.2.3 Second-stage of drying in HAO, FBD, and MWO

For the second-stage drying in HAO, it appeared that Hii *et al.*'s model provided a highest R^2 (the lowest RMSE, 0.20 and 0.07 % d.b.) and the PE was less than 2% (1.14 and 1.01 %) for 50 and 90°C whereas Verma's model was the best-fitting for drying temperature of 70°C in HAO. However, both these models were good fitting models. Similarly, for the FBD drying at 160, 180 and 200°C, the best fitting models were Hi *et al.* and Verma models. For second stage drying in MWO, Midilli- Kucuk's and Verma's models were better fit in comparison with the other models.

Although the two modified models applied in this section are not the best-fitting models for all drying conditions, they are interesting models because of their wide applicable range of temperatures and MW power level as well as providing acceptable good fitting. On the other hand, the other models can be used only at a certain drying temperature or MW power level.

In short, the thin-layer drying models developed in this study can effectively estimate the moisture content change of cooked brown rice during drying process.

1.3 Effective moisture diffusivity

1.3.1 The moisture diffusivity determined by regular regime method.

The moisture diffusivity coefficients calculated from the regular regime method were shown in Table 2. Obviously, they were elevated if the drying temperature or MW power level increased. It is due to the higher drying temperature or MW power level led to the increasing transferred heat or generated heat into the sample and subsequently the moisture pressure inside the sample was raised (Lin *et al.*, 1999). The moisture pressure is directly related to the moisture diffusion from inside to outside of the cooked brown rice. Furthermore, it appeared that the diffusivity coefficient values of MWO were much higher than those of HAO and FBD. This should be caused by the different mechanisms for heat contribution in the sample between drying by conventional methods and MWO. For HAO, the moisture inside the sample received the heat by conduction from outer layer into the inner layer whereas for MWO, the heat was generated by changing the electromagnetic energy to be heat energy via the movement of ionic or polar substances including water inside the sample. Therefore, the moisture pressure and temperature inside the sample were higher in case of MWO than drying in HAO that must rely on the low heat conductivity of cooked brown rice for its heat transfer process.

The regime method determined the D_{eff} coefficients as a single value representing for the whole drying process so that although drying process were started at different initial moisture content (single-stage at 70% w.b and second-stage at 21 % w.b.), the moisture diffusivity coefficient could not be classified during the single stage drying or second stage drying (Table 2.).

The activation energy for moisture diffusion in this study was found to be within the range of those found by Sarma and Prasad (2004) who dried their garlic by combined microwave and convectional drying method. The research of Sarma and Prasad (2004) also indicated that the activation energy of the combined microwave and convectional drying method was much lower than convectional heating alone.

Table 2 The moisture diffusivity values determined by regular regime method and the parameters for Arrhenius relationship.

Drying process	Conditions	D_{eff} (m ² /s)	D_0 (m ² /s)	E_a (kJ/mol)	R^2
Single-stage drying in HA	50°C	3.60E-09	1.1172E-05	21.75	0.9902
	70°C	5.19E-09			
	90°C	8.39E-09			
Drying in MW	425W	6.62E-08	2.2946E-08	5.01	0.7745
	595W	7.48E-08			
	850W	1.01E-07			
Second-stage drying in HA	50°C	3.69E-09	2.7942E-07	13.95	0.9630
	70°C	3.72E-09			
	90°C	4.49E-09			
Second-stage drying in FBD	160°C	5.95E-09	2.7942E-07	13.95	0.9630
	180°C	6.64E-09			
	200°C	8.17E-09			
Second-stage drying in MWO	425W	7.69E-08	2.7942E-07	13.95	0.9630
	595W	9.42E-08			
	850W	1.36E-07			

1.3.2 The moisture diffusivity determined by the slope method

For the single-stage drying, the moisture diffusivities fell in the range between 13×10^{-10} and 168×10^{-10} m²/s for HAO and 589×10^{-10} and 1834×10^{-10} m²/s for MWO whereas for the second-stage drying they ranged between 12×10^{-10} and 159×10^{-10} m²/s for HAO and 26×10^{-10} and 748×10^{-10} m²/s for FBD and 239×10^{-10} and 1135×10^{-10} m²/s for MWO (Fig. 12). They are much higher than those of rough rice (between 0.256×10^{-10} and 0.792×10^{-10} m²/s) and brown rice (between 0.389×10^{-10} and 1.46×10^{-10} m²/s) calculated by Thakur and Gupta (2006) and those of cooked jasmine white rice (between 0.06×10^{-10} and 4.87×10^{-10} m²/s) determined by Luangmalawat *et al.* (2008). The causes of the higher diffusivities of cooked brown rice in this study are their husk removal, volume expansion, and soft texture after pressure cooking, pretreatment before drying and the applied drying methods. The values of diffusivities in case of single drying in MWO were higher than those of HAO because of the much higher vapor pressure occurring inside the rice kernel. The explanations are similar to previous parts basing on the differences in mechanism of microwave heating and

conventional heating. The heat is generated particularly in the wet area of sample since water is the dipolar molecule. Subsequently, the moisture inside the sample became vapor rapidly. This vapor pressure helped accelerating the moisture movement from inner to the sample surface. This process makes porous structure for dried cooked brown rice.

For the second-stage drying (Fig. 13), since the initial moisture of cooked brown rice was low (30 % d.b), thus, the remaining water was dominantly bound water type and hard to remove resulting in lower diffusivity value in comparison with the higher initial moisture content of the single-stage drying, generally. In terms of individual scheme, at higher temperature as well as microwave power, the moisture diffusivity was greater due to the higher drying force; the diffusivity coefficient value for second stage drying in MWO was high than that of counterparts.

The estimated parameter values for fitting the empirical of moisture diffusivity were shown in Appendix Table 7. It appeared that the third order polynomial model with inverse form described well relationship between moisture and diffusivity for single-stage drying in both MWO and HAO, especially for single-stage drying in MWO. This agrees well with the research of Luangmalawat *et al.* (2008) which used this type of model for single-stage drying in HA dryer for cooked white rice. However, it seemed to be not good model for second-stage drying schemes of this study, especially at higher drying temperature or microwave power levels. For the combined MWD and convectional drying for garlic reported by Sharma and Prasad (2004), the high order of polynomial with no inversed term in pattern was found representing well for drying experimental data.

It appeared that the trend of changes of moisture diffusivities with moisture content of single-stage drying was opposite to those of the second-stage drying (Fig. 13). The moisture diffusivities of samples in case of single-stage drying increased along the decreased moisture content during the drying process. The explanation for these phenomena is that for the single-stage drying, after a short period of constant drying rate the moisture transfer was chiefly relied on the diffusion

mechanism. However, as the drying continued, the porous structure was formed and meanwhile the moisture inside the sample was in the vapor form leading to an increase of effective moisture diffusivities. Conversely, for the second-stage drying, the sample was previously kept overnight so the moisture was redistributed throughout the kernel. Subsequently, at the starting period of drying, the surface of cooked brown rice was rather humid and after that as the drying progressed, the sample surface became dried. At this step, the moisture diffusivities dropped along the decreasing moisture content due to the difficulty of the remained bound moisture removal (Ramesh, 2003). In this case, the vapor was not much accumulated inside the sample due to the low moisture content and the low temperature within the sample as a consequence of tempering process. The similar trend of moisture diffusivities change with moisture content was also found for the other food products such as amioca starch gel (Karathanos *et al.*, 1990) and cooked rice (Luangmalawat *et al.*, 2008).

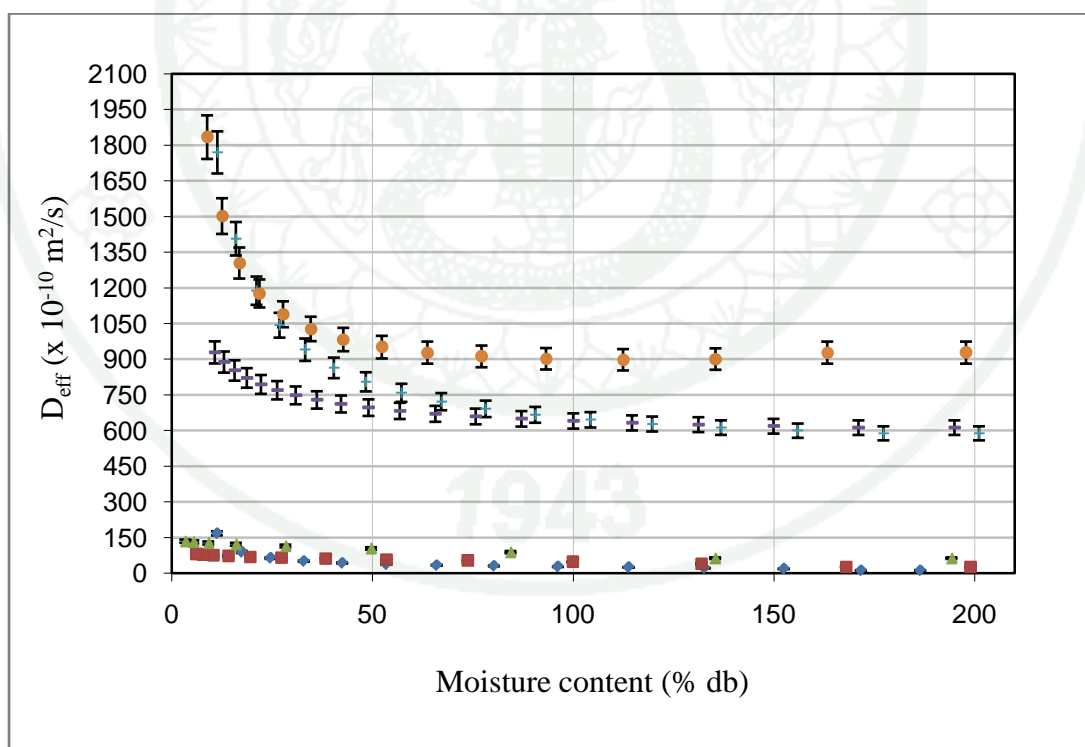


Figure 12 Effective moisture diffusivities determined by slope method for single-stage drying in HAO (\blacklozenge = 50°C; \blacksquare = 70°C; \blacktriangle = 90°C) and MWO ($-$ = 425 W; $+$ = 595 W; \bullet = 850 W).

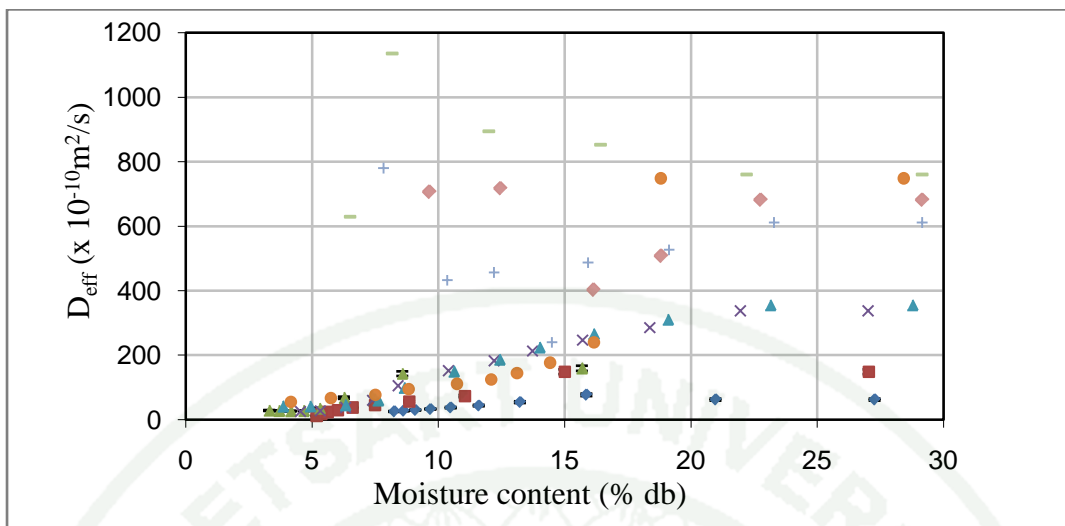


Figure 13 Effective moisture diffusivities determined by slope method for second-stage drying in HAO ($\blacklozenge = 50^\circ\text{C}$; $\blacksquare = 70^\circ\text{C}$; $\blacktriangle = 90^\circ\text{C}$), FDB ($\times = 160^\circ\text{C}$; $\blacktriangle = 180^\circ\text{C}$; $\bullet = 200^\circ\text{C}$) and MWO ($+$ = 425 W; $\blacklozenge = 595$ W; $-$ = 850 W).

1.3.3 Comparison between the moisture diffusivity determined by the slope method and regular regime method

The moisture diffusivity values determined by the slope method were presented in Figure 12-13. Unlike those determined by the regular regime method, they could be calculated at each moisture content level along drying process instead of calculating a single value for the whole drying process. Similar to the regular regime method, the moisture diffusivity values of MWO were much higher than those of HAO indicating that the water diffused from the inside to outside of sample is much faster in case of MWO.

For the single-stage drying in HAO and MWO, the maximum moisture diffusivities were found to $168 \times 10^{-10} \text{ m}^2/\text{s}$ and $1834 \times 10^{-10} \text{ m}^2/\text{s}$ for the slope method whereas those were much lower for the regular regime method (Table 7). Likewise, for the second-stage drying, it is to $159 \times 10^{-10} \text{ m}^2/\text{s}$ for HAO, $748 \times 10^{-10} \text{ m}^2/\text{s}$ for FBD and $1135 \times 10^{-10} \text{ m}^2/\text{s}$ for MWO; these values are much higher than those of the regular regime method. In addition, if comparing with the moisture diffusivity

determined by regular regime method, it appeared that the diffusivity values determined by regular regime method fell in the range of those determined by slope method. The values of diffusivity coefficients found in this work are also within range of values reported by many literatures (Dincer and Hussain, 2004; Sharma and Prasad, 2004; Thuwapanichayanan *et al.*, 2008; Sootjarit *et al.*, 201

1.4 Physical properties

1.4.1 Porosity of cooked brown rice during drying

The plots between the porosities and moisture contents of samples dried by different methods are shown in Figure 14-18. The relationship between porosity and moisture content of cooked brown rice followed the high order of polynomial form; results of fitting the experimental data for empirical model of instant brown rice drying are presented in Appendix Table 8. Basing on the criteria of model fitting, models were found rather good fitting.

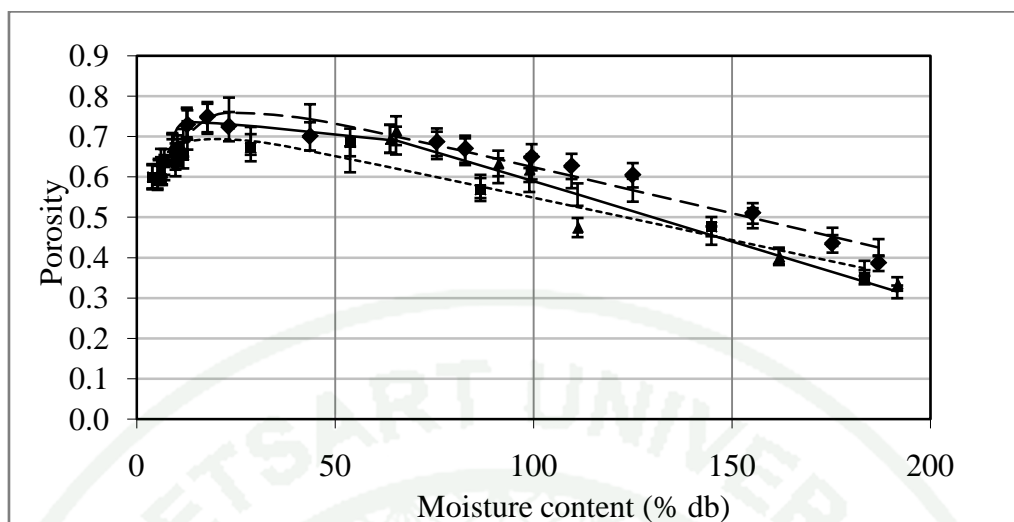


Figure 14 Porosity curves of cooked brown rice during single-stage drying in HAO (♦ = experimental 50°C; ▲ = experimental 70°C; ■ = experimental 90°C; - - - = predicted 50°C; — = predicted 70°C; = predicted 90°C).

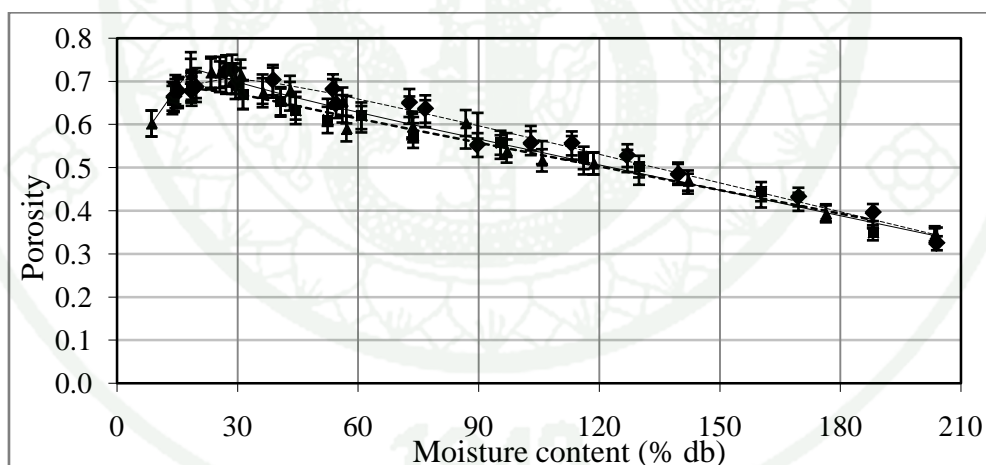


Figure 15 Porosity curves of cooked brown rice during single-stage drying in MWO (♦ = experimental 425 W; ▲ = experimental 595 W; ■ = experimental 895 W; - - - = predicted 425 W; — = predicted 595 W; = predicted 895 W).

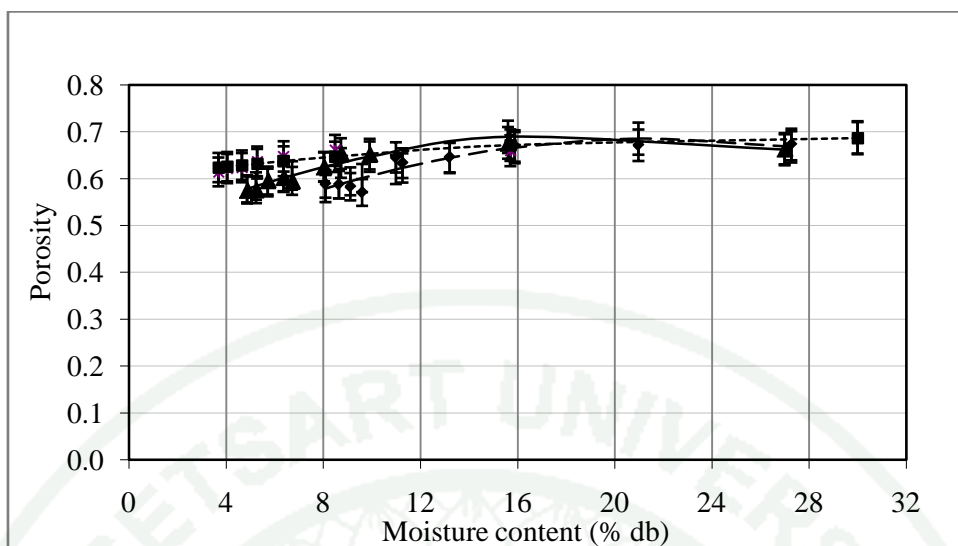


Figure 16 Porosity curves of cooked brown rice during second-stage drying in HAO

(♦ = experimental 50°C; ▲ = experimental 70°C; ■ = experimental 90°C; - - - = predicted 50°C; — = predicted 70°C; = predicted 90°C).

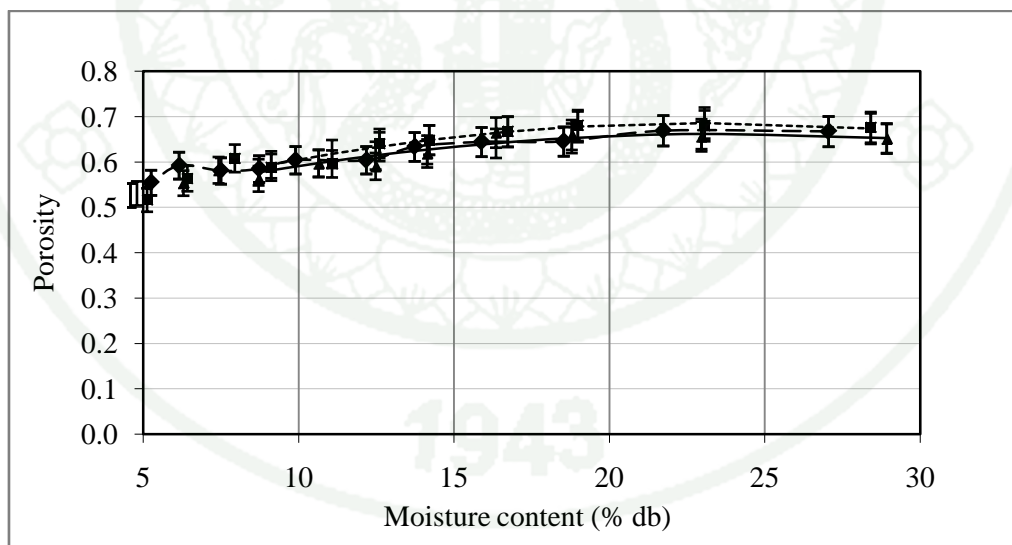


Figure 17 Porosity curves of cooked brown rice during single-stage drying in FBD

(♦ = experimental 160°C; ▲ = experimental 180°C; ■ = experimental 200°C; - - - = predicted 160°C; — = predicted 180°C; = predicted 200°C).

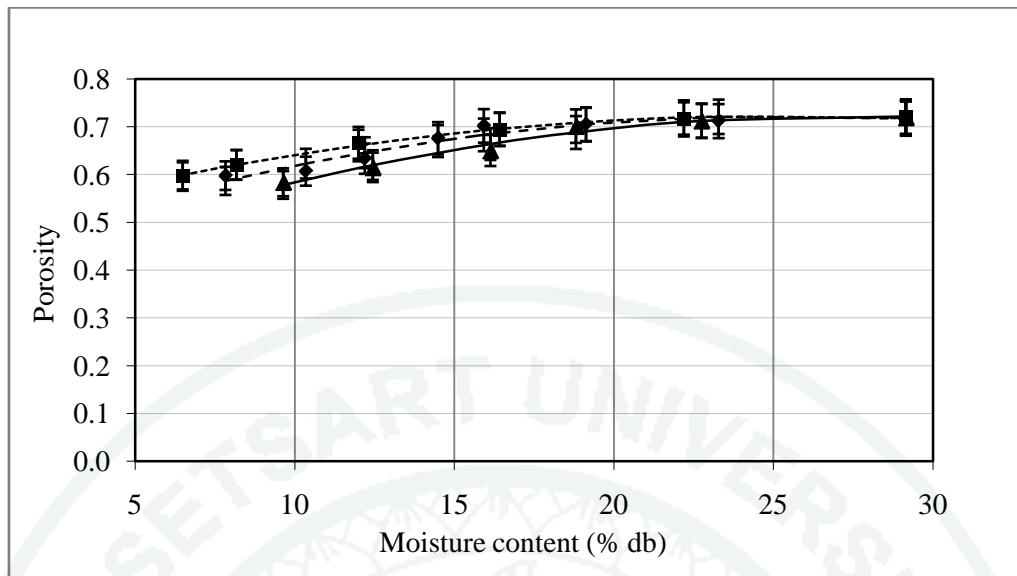


Figure 18 Porosity curves of cooked brown rice during second-stage drying in MWO (◆ = experimental 425 W; ▲ = experimental 595 W; ■ = experimental 850 W; - - - = predicted 425 W; — = predicted 595 W; = predicted 850 W).

The porosity of dried cooked brown rice changed significantly from the beginning of drying until final drying process along with the decreased moisture content. However, it appeared that the porosity of cooked brown rice was less affected by various drying temperature and various microwave power levels although the differences between various drying mechanisms could be seen. Conversely, all cases were insignificant different when the moisture content down to less than 12 % (w.b.).

The porosity of dried cooked brown rice for second-stage drying schemes decreased at the beginning of drying process, corresponding with the similar moisture content level that were conducted for the single-stage drying. The level of moisture content obtained the decreased porosity was a range of 3-23 % (w.b.) and roughly less than 23 ± 1 % (w.b.). For single-stage drying in MWO, the values of moisture content obtained the decreased porosity were higher than those of single-stage drying in HAO. Beyond the moisture content of about 23 % (w.b.), the increase of porosity versus decreased moisture was as the linear function especially for

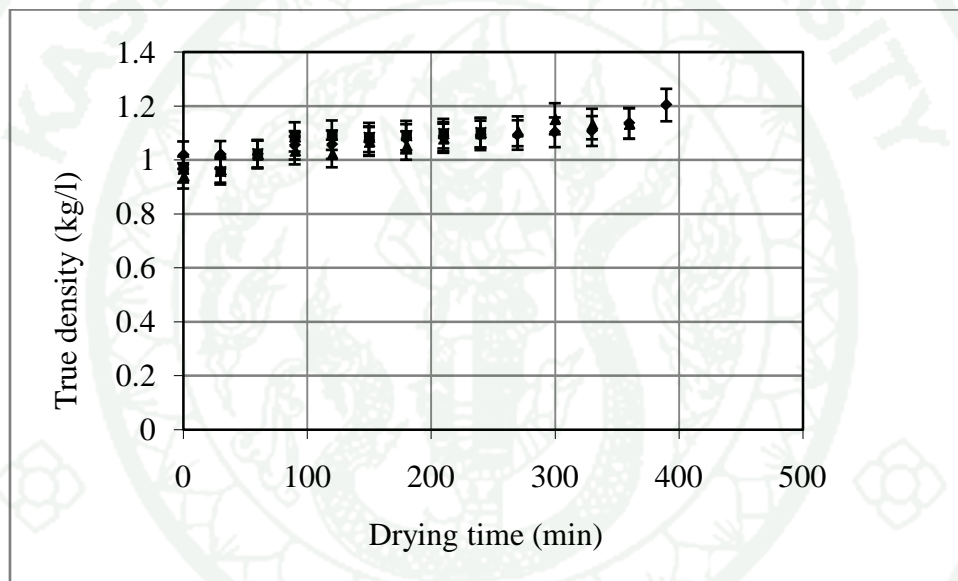
microwave drying and not really various for different microwave power level. However, the slight significant difference could be seen in case of 50 and 90°C for single-stage drying at moisture content greater than 20-23 % (w.b.). It would be explained that because of longer drying time, the shrinkage and collapse were taken place for HAO. Otherwise, for microwave power level of 425 W and 850 W of single stage drying, the slight difference could be seen at the middle stage of drying. This is because of a slim collapse or shrinkage taken place deal with the unique characteristics of microwave heating; the moisture evaporation was accelerated at the middle of microwave drying (Li *et al.*, 2011). The faster drying rate of microwave drying is result of inducing pressure gradients, which greatly accelerate the thermo-migration mechanism and thereby modify the physical properties of the product (Lefeuvre *et al.*, 1990). In addition, at the moisture content less than 10% db, the minor differences could be seen for second-stage drying in HAO and MWO whereas those were quite similar among various temperatures of second-stage drying in FBD.

In short, the porosity calculated through bulk and true densities with displacement method can provide the evident of physical changes due to various drying methods. The porosity of dried cooked brown rice was insignificant different for various microwave power levels. The significant difference of porosity can be found between 50 and 90°C of single stage drying in HAO.

1.4.2 True density

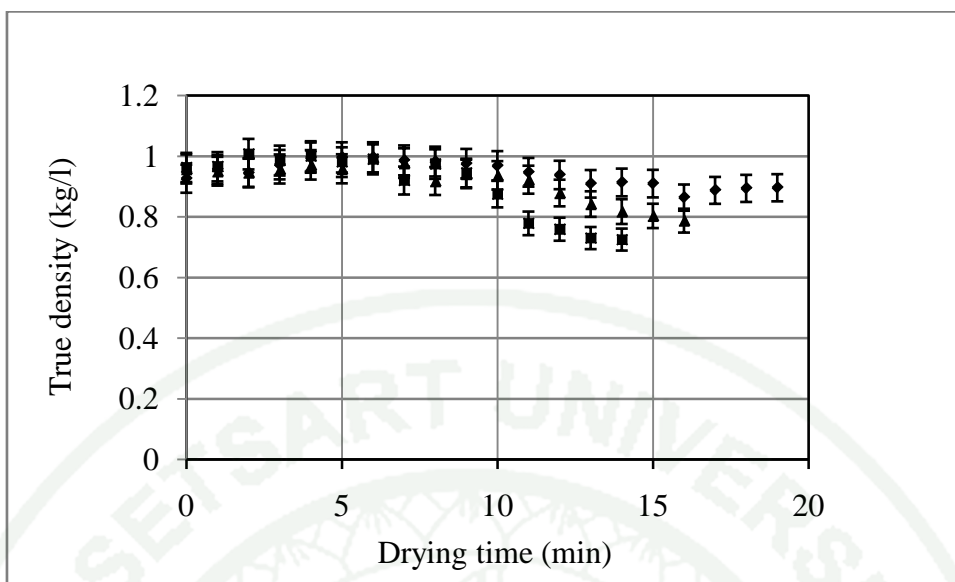
The relationships between the true densities of cooked brown rice and drying times are illustrated in Figure 19. For the single-stage drying in HAO, the true density of sample appeared to increase along the drying time. It is due to the shrinkage taking place after the water loss of sample. The differences of true densities between drying temperatures of 50, 70 and 90 °C are not obvious. Opposite to the HAO, for the drying in MWO, the true density of sample remarkably dropped along the drying process especially after a period of drying time. For second-stage drying in HAO, FBD and MWO, the true density was not significantly different at various drying temperature and microwave power level. The true density of the second-stage

drying in MWO tended to decrease, especially for higher microwave power level, whereas the increase was found at the final process for drying in HAO and FBD. The reason is that for the MWO the moisture within the sample was rapidly heated and accumulated vapour pressure after a period of time; as a result, the puffing or volume expansion arised leading to the decrease of true density (Fig. 19b and 19e). The higher microwave powers applied, the less true densities were found. This puffing effect is usually required for the quick-cooking or instant food products that the porous structure is needed to facilitate the rehydration process (Prasert and Suwannaporn, 2009). The porous kernel for drying in MWO could be observed in Fig. 20.

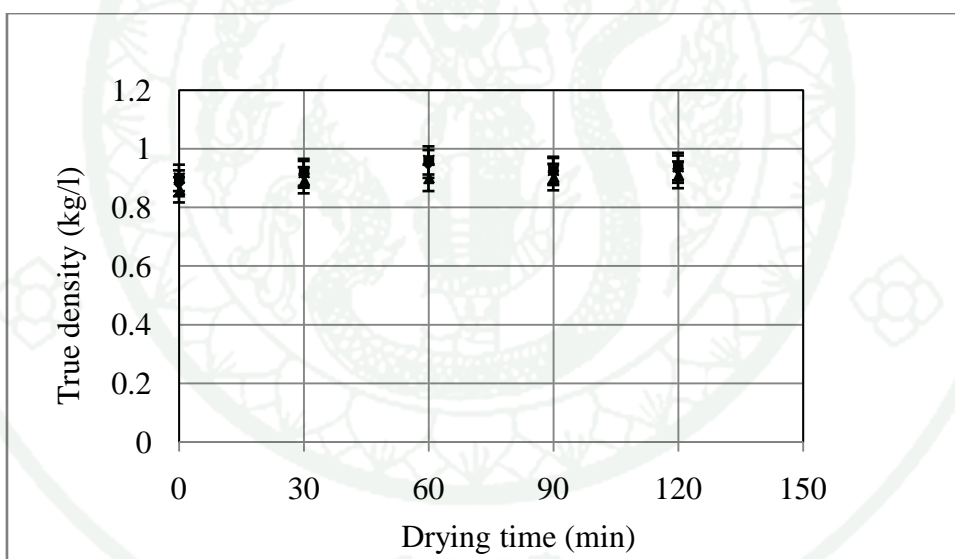


(a)

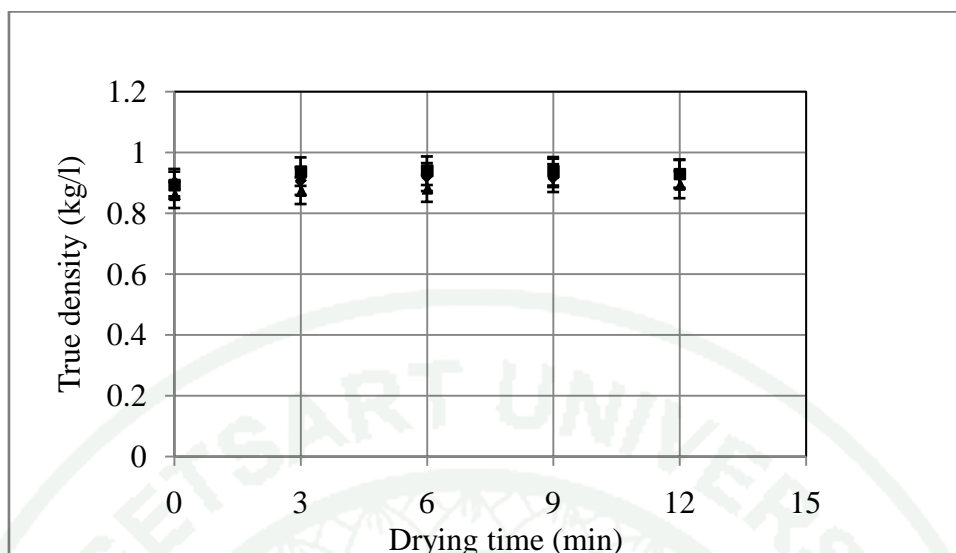
1943



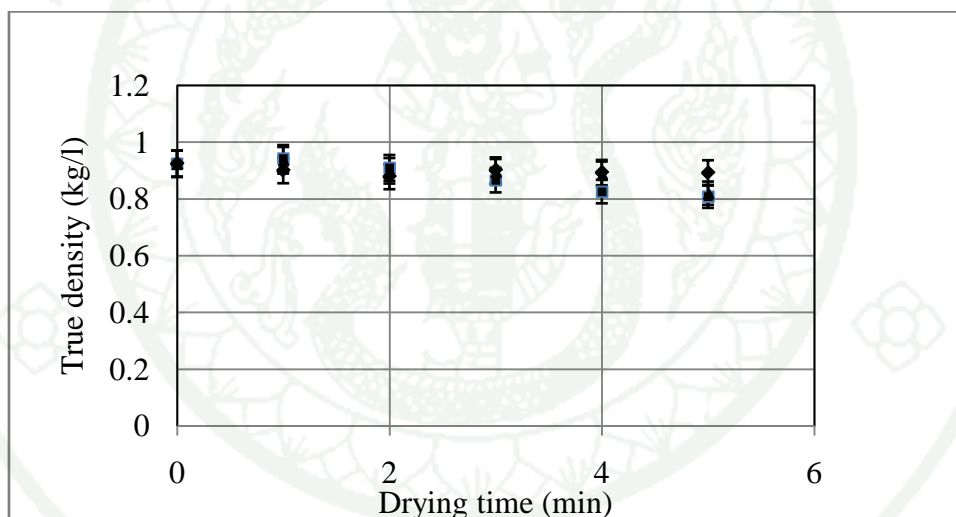
(b)



(c)



(d)



(e)

Figure 19 True density of cooked brown rice after drying by (a) Single-stage drying in HAO ($\blacklozenge = 50\text{ }^{\circ}\text{C}$; $\blacktriangle = 70\text{ }^{\circ}\text{C}$; $\blacksquare = 90\text{ }^{\circ}\text{C}$); (b) Single-stage drying in MWO ($\blacklozenge = 425\text{ W}$; $\blacktriangle = 595\text{ W}$; $\blacksquare = 850\text{ W}$); (c) Second-stage drying in HAO ($\blacklozenge = 50\text{ }^{\circ}\text{C}$; $\blacktriangle = 70\text{ }^{\circ}\text{C}$; $\blacksquare = 90\text{ }^{\circ}\text{C}$); (d) Second-stage drying in FBD ($\blacklozenge = 160\text{ }^{\circ}\text{C}$; $\blacktriangle = 180\text{ }^{\circ}\text{C}$; $\blacksquare = 200\text{ }^{\circ}\text{C}$); (e) Second-stage drying in MWO ($\blacklozenge = 425\text{ W}$; $\blacktriangle = 595\text{ W}$; $\blacksquare = 850\text{ W}$).

Briefly, the true densities of samples that were dried in HAO are higher than those dried in MWO indicating the more porous structure in the microwave-dried samples and less shrinkage. The low temperature of single HAO drying caused the dense structure of dried cooked rice.

1.4.3 Images captured by stereo microscopy

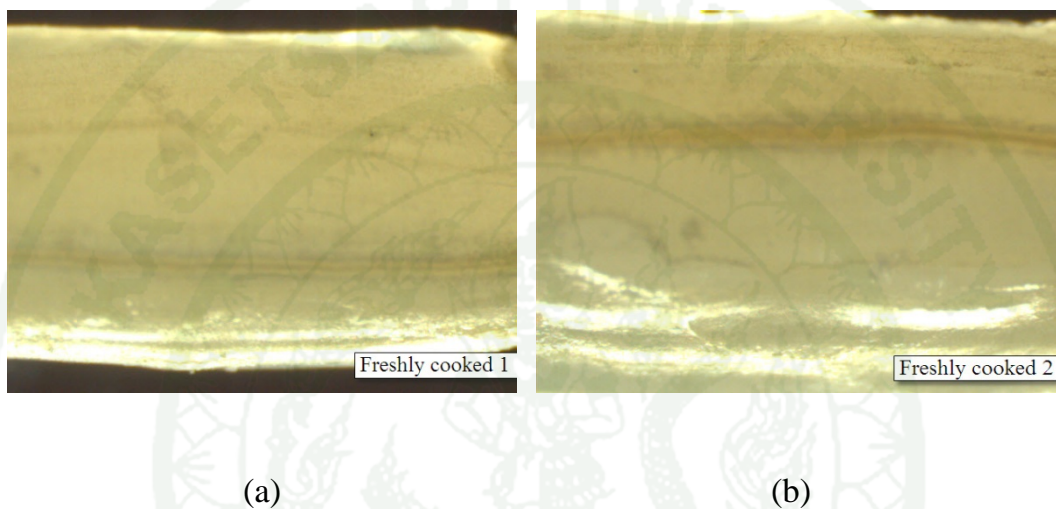


Figure 20 Images of samples captured from stereo microscope at 16× magnification: (a) Freshly cooked brown rice sample no.1; (b) Freshly cooked brown rice sample no.2; (c) Cooked brown rice after freezing and thawing pretreatment; (d) Sample after single-stage drying in hot-air dryer (HAO); (e) Sample after single-stage drying in microwave dryer (MWO); (f) Sample after two-stage drying in MWO and HAO; (g) Sample after two-stage drying in MWO and fluidized bed dryer (FBD); (h) Sample after two-stage drying in MWO and MWO.

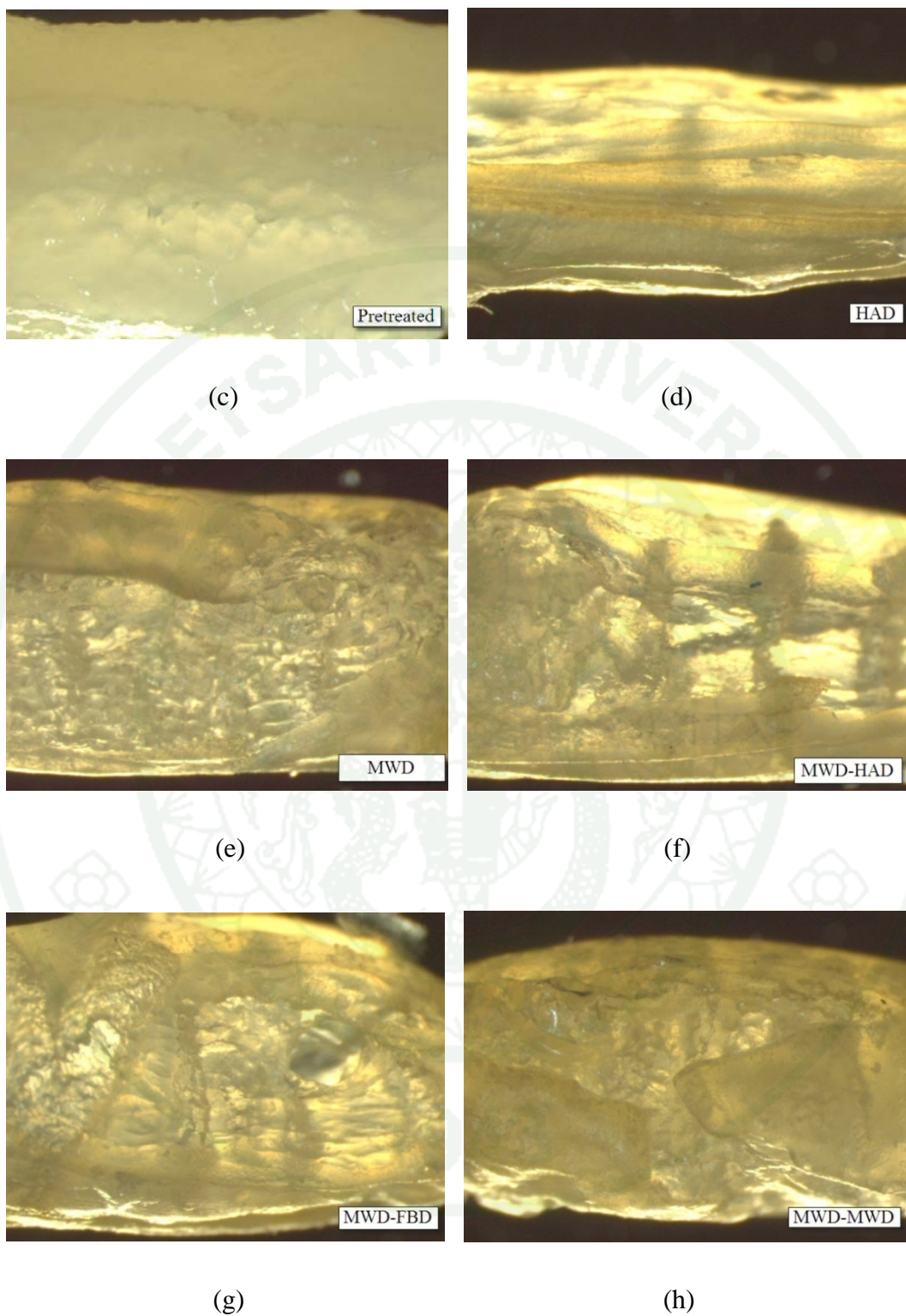


Figure 20 (Continued)

The images of (1) freshly cooked brown rice, (2) brown rice after cooking and pretreatment and (3) brown rice after cooking, pretreatment and drying taken by the stereo microscope were depicted in Figure 20. It is visible that the structure of cooked brown rice became spongier after freezing and thawing pretreatment indicating that the pretreatment helped enhancing the porosity of sample structure. As a consequence, the moisture transfer in either drying or rehydration process would be facilitated. This finding confirmed the report of Ozai-Durrani (1965) claiming that the instant rice would be more porous and faster to rehydrate if after cooking the cooked rice is frozen and slowly thawed prior to drying process due to the influence of volume expansion of ice crystal during freezing. The pressure-cooking caused brown rice softer that facilitates for void formation of thawed cooked brown rice. On the other hand, it appeared that all of samples after freezing and thawing processes seemed to be plump and brighter color.

In short, the freezing and thawing pretreatment steps provided the changes of cooked brown rice such as voids, and plump size. The freezing step combined with controlled thawing prior to drying facilitated the drying rate due to increased voids and surface.

After conducting experimental plan 1, it was suggested that instant brown rice product should be dried by MWO. The outcome of porosity and density revealed that after the moisture content of about 23 ± 1 (w.b.), the physical properties of dried cooked rice is less affected by drying method. However, these results have not yet strongly provided the best quality. To obtain the optimal quality of instant brown rice, it should be applied optimization methodology with two-stage in drying including MWO at the first stage drying and HAO in the second stage by applying various initial water-rice ratios in cooking.

2. Instant brown rice production

2.1 Model fitting and statistic analysis

The quadratic models of the variables as a function of ratio of water to rice (X_1), microwave power levels (X_2) and hot air temperature (X_3) were shown in Eqs. (30), (31), (32), (33), and (34), where Y_1 , Y_2 , Y_3 , Y_4 , and Y_5 represent for rehydration ratio, lightness, color intensity, hardness, and stickiness of rehydrated cooked brown rice respectively. Note that most of equations were not removed their insignificant coefficients.

$$Y_1 \text{ (Ratio of rehydration)} = -291.845 + 397.146X_1 - 0.115613X_2 + 3.85979X_3 - 96.7708X_1^2 + 0.122794X_1X_2 - 2.09583X_1X_3 - 0.0000399366X_2^2 - 0.0000147059X_2X_3 - 0.00440625X_3^2 \quad (30)$$

$$Y_2 \text{ (Lightness)} = 64.0148 - 5.88333X_1 + 0.00202451X_2 + 0.0246667X_3 - 2.04167 X_1^2 + 0.0227941X_1X_2 + 0.0260417 X_1X_3 - 0.0000217993 X_2^2 - 0.000159559 X_2X_3 + 0.000322917 X_3^2 \quad (31)$$

$$Y_3 \text{ (color intensity)} = -183.123 + 334.346 X_1 + 0.395098 X_2 + 3.87782 X_3 - 100.736X_1^2 - 0.00369559 X_1X_2 - 1.08212 X_1X_3 - 0.000174884 X_2^2 - 0.00380986 X_2X_3 - 0.00694693 X_3^2 \quad (32)$$

$$Y_4 \text{ (Hardness)} = 1172.14 - 1006.75 X_1 + 0.208141 X_2 - 9.72476 X_3 + 277.521 X_1^2 - 0.0711732 X_1X_2 + 2.48233 X_1X_3 + 0.000137161 X_2^2 - 0.00351578 X_2X_3 + 0.052711 X_3^2 \quad (33)$$

$$Y_5 \text{ (Stickiness)} = 57.9807 - 55.4197 X_1 - 0.063279 X_2 - 0.0967951 X_3 + 18.9497 X_1^2 - 0.0119387 X_1X_2 + 0.0130556 X_1X_3 + 0.0000984924 X_2^2 + 0.000153366 X_2X_3 + 0.000538646 X_3^2 \quad (34)$$

The statistical model of quadratic type with 10 coefficients for each of response was analyzed respectively as shown in Table 3. The terms with p-values below 0.05 indicate that their effect on the model is significant at the 5.0% significance level. The high value of R-squared statistic shows the smaller of variation percentage in the response explaining the better of fitted model. According to the fitting models shown in Table 3, the R-squared values ranges were various relatively

high, 50.39 %, 86.72%, 68.15%, 60.32%, and 85.53 % respectively for rehydration ratio, lightness, colour intensity, hardness, and stickiness.

Table 3 Regression coefficients of polynomial function, Analysis of Variance and coefficients of determination (R^2).

Source	Rehydration ratio		Lightness		Color intensity		Hardness (N)		Stickiness (N)	
	Estimate	<i>p</i>	Estimate	<i>p</i>	Estimate	<i>p</i>	Estimate	<i>p</i>	Estimate	<i>p</i>
constant	-291.845		64.0148		-183.123		1172.14		57.9807	
X_1	397.146	0.0982	-5.88333	0.3226	334.346	0.0000	-1006.75	0.0168	-55.4197	0.0172
X_2	-0.115613	0.0003	0.002025	0.0000	0.395098	0.0175	0.208141	0.0586	-0.06328	0.0000
X_3	3.85979	0.2085	0.024667	0.0000	3.87782	0.0005	-9.72476	0.3506	-0.09679	0.0000
X_1X_1	-96.7708	0.0607	-2.04167	0.5546	-100.736	0.1057	277.521	0.0022	18.9497	0.0165
X_1X_2	0.122794	0.0491	0.022794	0.0000	-0.00369	0.9601	-0.07117	0.4898	-0.01194	0.1984
X_1X_3	-2.09583	0.0002	0.026042	0.4631	-1.08212	0.0908	2.48233	0.0068	0.013056	0.8671
X_2X_2	-0.000039	0.5677	-0.000022	0.0000	-0.00017	0.0444	0.000137	0.2484	0.000098	0.0000
X_2X_3	-0.000014	0.9807	-0.000156	0.0004	-0.00381	0.0000	-0.00352	0.0014	0.000154	0.1008
X_3X_3	-0.004406	0.3842	0.000323	0.3517	-0.00695	0.2602	0.052711	0.0000	0.000539	0.4802
Lack-of-fit		0.0798		0.5525		0.5138		0.0015		0.2550
R-squared (%)	50.3902		86.7164		68.1526		60.3245		85.5335	

Ratio of water to rice (X_1), microwave power level (X_2) and hot air temperature (X_3)

P-value < 0.05 is significant at $\alpha = 0.05$

The lack of fit test was designed to determine whether the selected model is adequate to describe the observed data, or whether a more complicated model should be used. The test is performed by comparing the variability of the current model residuals to the variability between observations at replicate settings of the factors. The p-value for lack-of-fit in the ANOVA table is greater or equal to 0.05, which means that the model appears to be adequate for the observed data at the 95.0% confidence level. In current study, the lack of fit test for rehydration ratio, lightness, color intensity, and stickiness indicate that the quadratic models provide the good fitting for these attributes whereas the second order model seemed to be insufficient fitting for the hardness. More interaction effects of three factors might affect the hardness. Therefore, for hardness attribute, it is necessary to add more terms with interaction between three factors or detect more factor effects.

2.2 Optimization values for individual response

For rehydration ratio, it is expected to obtain the maximum value since the higher rehydration ratio indicates that the reconstitution of dried sample is closer to freshly cooked brown rice quality (Sun, 2008). Therefore, the maximum value of rehydration ratio was used as the criterion for this attribute optimization. In addition, the moisture content of rehydrated instant brown rice also was compared to that of freshly cooked brown rice in support of rehydration ratio optimization.

A control sample (freshly cooked brown rice by pressure-cooking) was used for controlled responses. It appeared that after rehydration, the stickiness and color intensity of instant brown rice are lower than those of freshly cooked brown rice whereas lightness is higher. Usually, the regular value of stickiness is needed to ensure the sensory whereas low color intensity and higher lightness (whiteness) are preferred.

Traditional graphical method with surface-contour plot was applied; the optimal values of factors corresponding with each desirable response goal were obtained as shown at Table 4. From the Table 4, it can easily see that for different attributes, the optimal operating parameters of process were different.

Table 4 Optimal parameters corresponding with each response.

Factor	Setting values		Rehydration ratio	Lightness	Color intensity	Stickiness(N)
	Low	High	Optimum for operating process conditions			
Ratio of water to rice	1.3	1.7	1.69997	1.68399	1.7	1.3
Microwave power level	255.0	595.0	595.0	593.727	591.182	594.341
Hot air temperature	50.0	90.0	50.0	89.998	90.0	89.9214
Optimum value for response			148.303	64.8816	187.336	11.2924

2.3 Effect on rehydration ratio

The rehydration properties or reconstitution of dehydrated products is defined as the amount and rate of water absorption directly relating to sensorial properties and convenient preparation time. The shrinkage and collapse was found during hot air drying resulting in low transport rate of water, prolonged drying time and therefore tough texture (Maskan, 2001). According to Table 3, microwave power level (MWI) was the main effect on the rehydration ratio. From the surface-contour plot on Fig 22, it appeared that at high level of ratio of water to rice (WRr) of 1.7:1, when MWI increased, the rehydration ratio also increased. This could be explained that at higher WRr, the cooked brown rice obtained higher moisture content (68-69% w.b) comparing to counterparts (62-63 % w.b. for 1.3:1 and 1.5:1 WRr). The higher moisture content of cooked brown rice could be facilitated by higher temperature or microwave power during drying that resulted in faster drying rate (Sun, 2008; Prasert and Suwannaporn, 2009).

In a microwave drying system, the microwaves can easily penetrate the inner layers of material to be absorbed directly by the moisture or dielectric properties. The quick energy can be aborted by dielectric properties of material and

generate into heat and causes rapid evaporation (boiling) of water creating an outward flux of rapidly escaping vapour. This outward flux can help to prevent the collapse (shrinkage) of tissue structure, which prevails in most conventional air-drying techniques (Lyons *et al.*, 1972; Prabhanjan *et al.*, 1995). Therefore, the very fast drying rate in this study was due to increase of MWI leading to the less shrinkage of kernel or increasing volume and pore in structure. Hence, the increased rehydration ratio can be obtained at higher MWI. Al-Duri & McIntyre (1991), Prabhanjan *et al.* (1995) and Gowen *et al.* (2008) agreed that the better rehydration characteristics could be found in the presence of microwave-dried products. The study on thin-layer drying of carrot by Prabhanjan *et al.* (1995) undergoing conventional and microwave-assisted convective drying showed that product shrinkage was minimal at the highest power level of microwave application.

Moreover, the microwave energy could cause the interaction between amylose and amylopectin weaken and improve their dispersion as well as separation instead of leaching as convectional treatment; the amylose that leaches into supernatant decreased with increasing heating rates (Palav and Seetharaman, 2007). The higher value of amylose content was obtained after drying in MWO (Lewandowicz *et al.*, 2000). The amylose content is directly related to water absorption, volume expansion, fluffiness and separability of cooked grain (Delwiche *et al.*, 1996). Therefore, the higher rehydration ratio was obtained corresponding with increased MWI.

1943

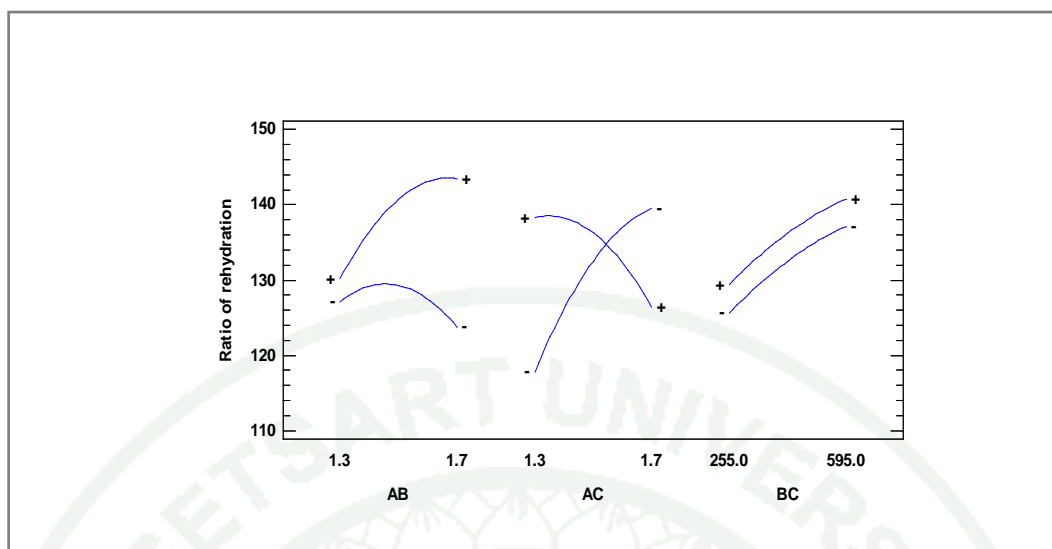


Figure 21 Interaction plot of WRr (A) with MWI (B) and HAt (C) for rehydration ratio.

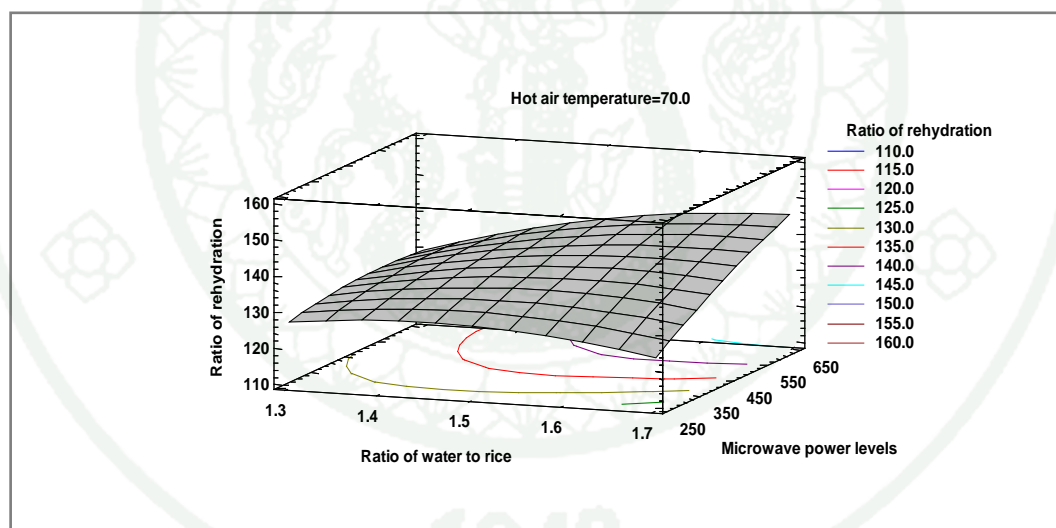


Figure 22 Surface-contour plot for rehydration ratio of dried cooked brown rice as a function of different processing conditions.

The interaction plot and surface-contour plot revealed the interaction effect between MWI and WRr at the significant level ($p < 0.05$) on rehydration ratio. Holding hot air temperature (HAt) at the constant level of 70°C , at the lower WRr, 1.3:1, the rehydration ratio slightly increased as increase of MWI whereas at the

higher WRr, the rehydration ratio increased dramatically of increased MWI. It appeared that the MWI showed the most influence on the rehydration ratio at higher WRr but less effect at the lower WRr. In the other words, at the higher WRr, higher MWI provided the better rehydration ratio. In addition, the extreme interaction effect between WRr and HAt was found for rehydration ratio. Fig. 23 indicates that at the constant of MWI (425W), it could be seen that when brown rice was cooked at the lower WRr, the rehydration ratio increased significantly as increase of HAt whereas at the higher WRr, the rehydration ratio slightly decreased as increase of HAt. This might relate to the partial starch gelatinization during drying. As brown rice was cooked at lower WRr, the gelatinization of starch may be incomplete; as the HAt increased, more starch is gelatinized since the starch gelatinization could be partly taken place during drying process (Meeso *et al.* 2004).

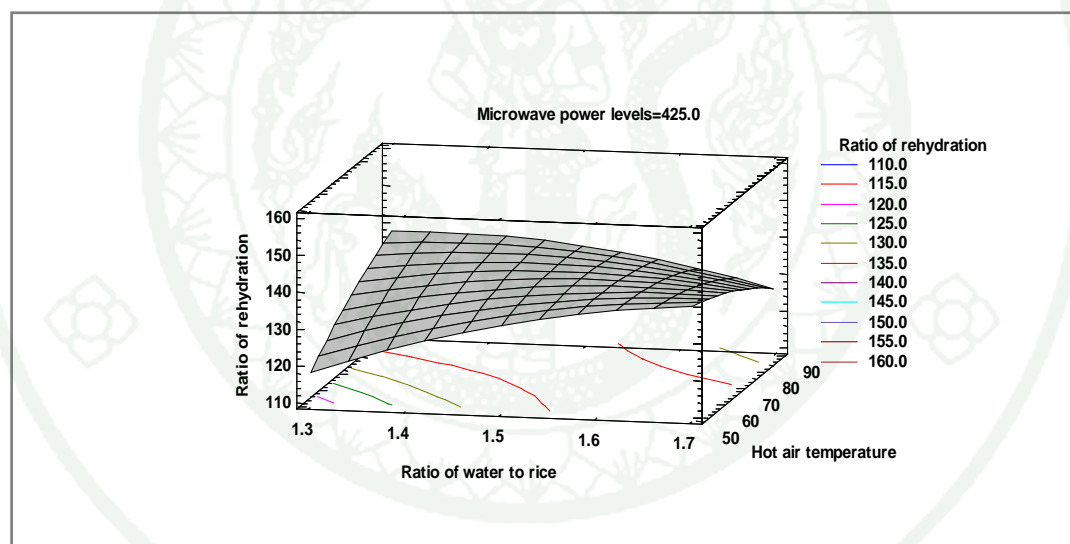


Figure 23 Surface-contour plot for rehydration ratio of dried cooked brown rice as a function of different processing conditions.

In short, higher WRr and higher MWI and HAt improved the rehydration ratio. Higher value of MWI and HAt resulted in shorter drying period and due to the fact that the rehydration ratio is the ratio of mass of the rehydrated sample to that of dehydrated sample (Vadivambal and Jayas, 2007), it can conclude that less shrinkage and more pores were taken place during these drying conditions.

2.4 Effects on color

2.4.1 Effect on lightness

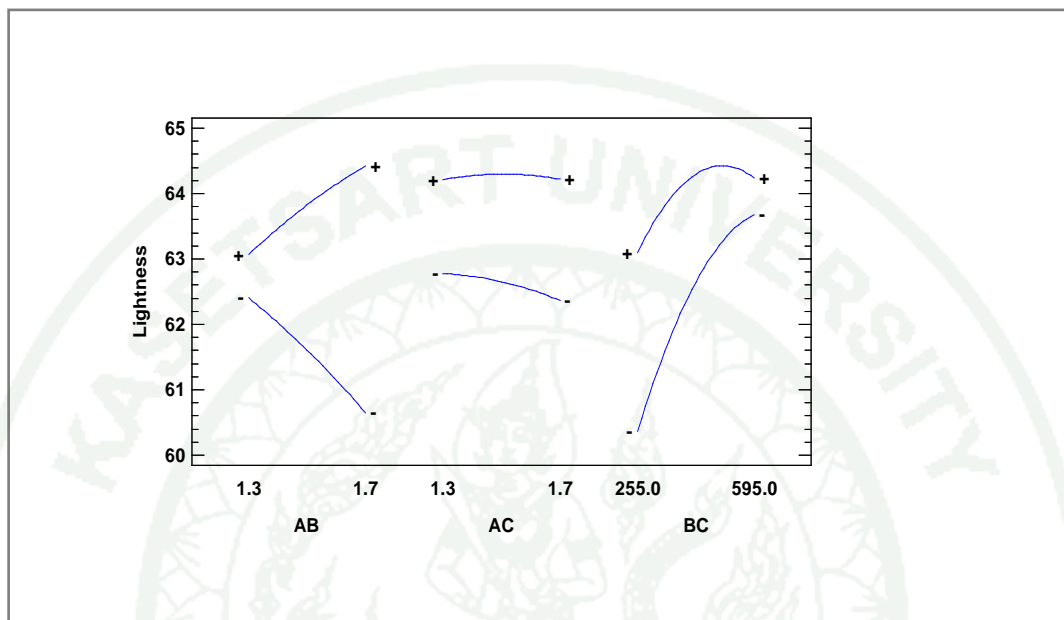


Figure 24 Interaction plot of MWI (B) with WRr (A) and HAt (C) for lightness.

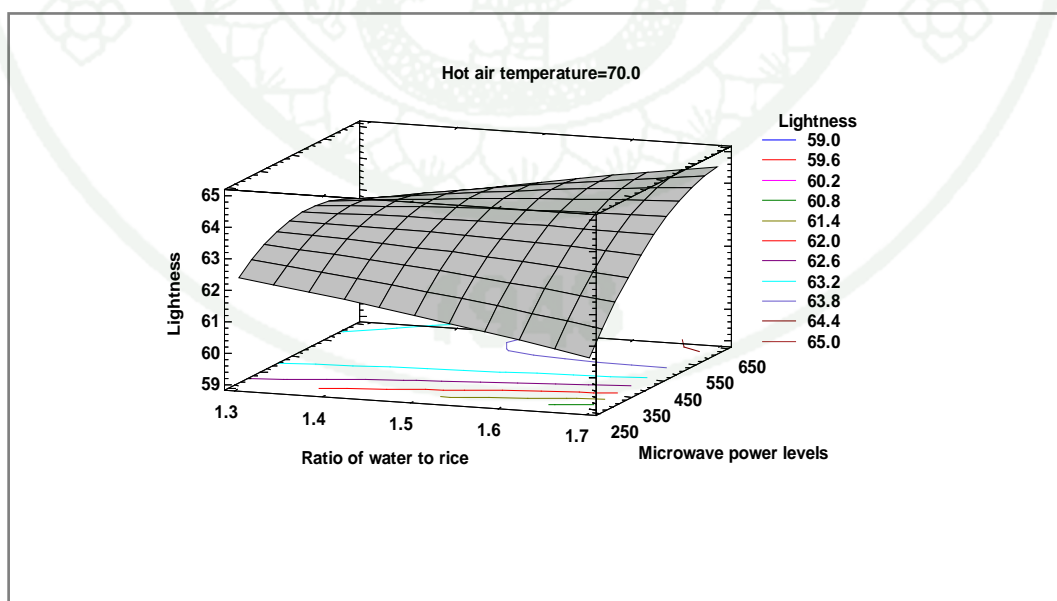


Figure 25 Surface-contour plot for lightness of rehydrated cooked brown rice as a function of different processing conditions.

Likewise rehydration ratio, MWI played the dramatically important role on lightness, especially at the higher WRr applied in cooking. The lightness increased as a function of microwave power (rice surface is whiter) due to the fact that the drying time for the second-stage drying in HAO is shorter if higher MWI was applied at the first-stage. The longer drying time is considered as a cause of poor sample color due to the dense structure leading to lower in luminosity (Elbert *et al.*, 2001). The lightness was reducing as a consequence of longer drying time (Maskan, 2001). Briefly, the higher lightness obtained as increase of MWI at higher WRr.

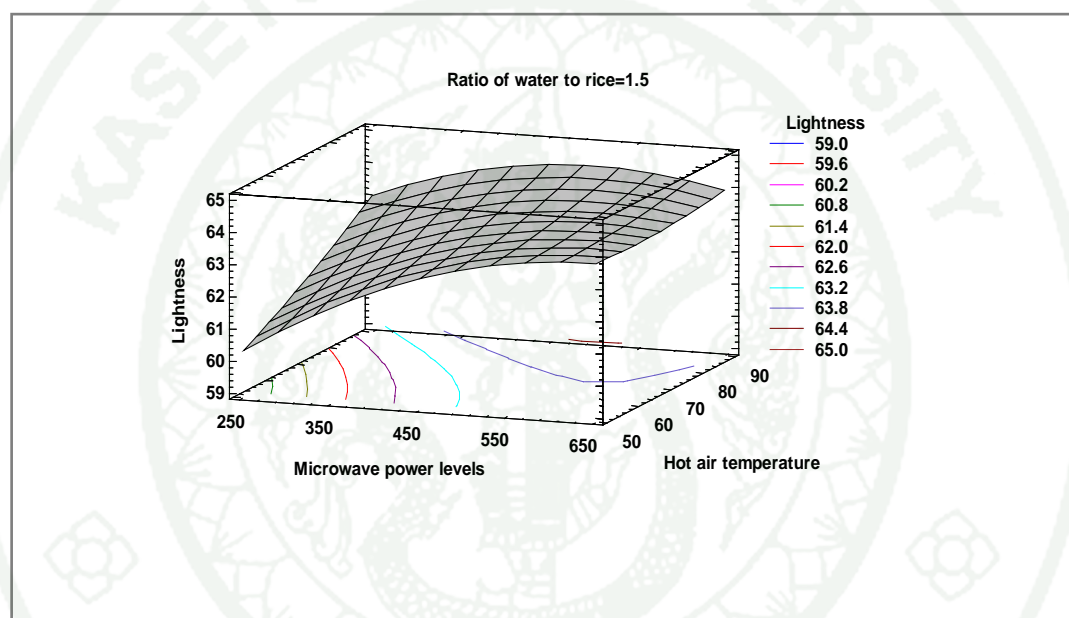


Figure 26 Surface-contour plot for lightness of rehydrated cooked brown rice as a function of different processing conditions.

In addition, the lightness greatly increased as increase of HAt at the lower MWI applied at the first stage drying (Fig. 26). However, the effect of HAt on lightness reduced at the higher MWI. It appeared that at the highest MWI applied, the lightness was insignificant different by increasing temperature from 50 to 90°C. It is due to the fact that at higher MWI led to higher temperature generated into sample, thus, water removed very faster and simultaneously the product dried faster. The pigment was destructed resulting in brighter in colour.

MWl and HAt were found as the main factors affecting on lightness of instant brown rice in this research ($p < 0.05$); increasing MWl and HAt led to an increased lightness. Luangmalawat *et al.* (2008) also obtained higher lightness of cooked white rice as dried in HA dryer at temperature greater 100°C. Nevertheless, Fig. 26 indicates that the surface plot tended to be bent down as increase MWl higher than 593 W. This behaviour is possibly due to the presence of heat sensitive reactions involving the degradation of thermolabile pigments, which in turn resulted in formation of dark compounds that reduced luminosity (Abers and Wrolstad, 1979; Skrede, 1985; Salunkhe *et al.*, 1991; Ibarz *et al.*, 1999 and Maskan, 2001; Sumnu *et al.*, 2005; Gowen *et al.*, 2008). Moreover, as shown at Fig 24 and 25, the interaction effect between WRr and MWl on lightness could be observed.

In short, the lightness increased as increase of WRr, MWl, and HAt. The maximum lightness obtained at the 1.6:1 for WRr, 593 W for MWl, and 80°C for HAt.

2.4.2 Effect on color intensity

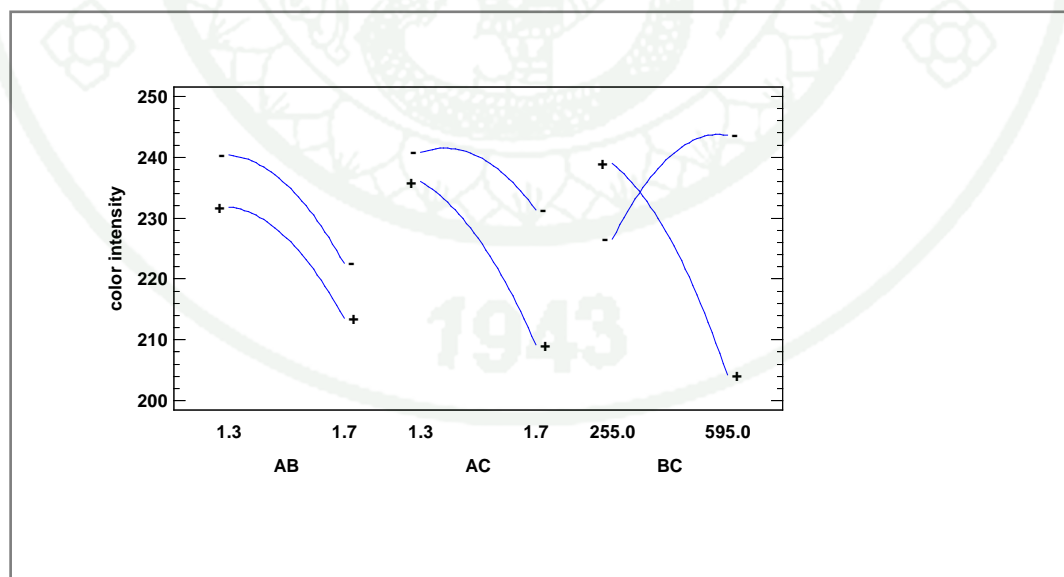


Figure 27 Interaction plot between MWl (B) and HAt (C) for color intensity.

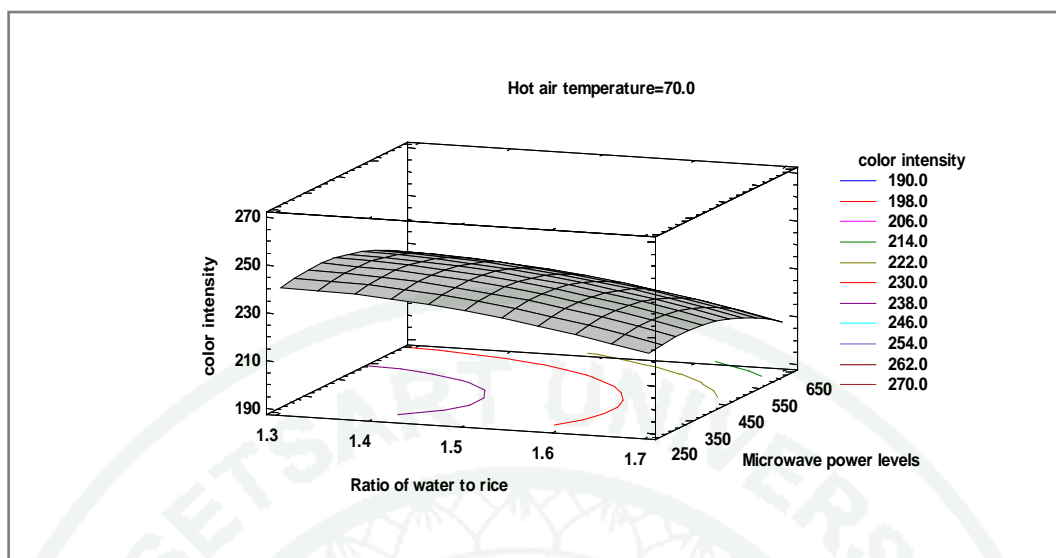


Figure 28 Surface-contour plot for color intensity of rehydrated cooked brown rice as a function of different processing conditions.

It could observe in Fig. 28 that increase of WRr led to decrease of colour intensity (brighter) which could be explained by leached color substances present in the brown layer (Framalingham and Anthony Raj, 1996). Also, higher MWI that provided lower color intensity was explained by pigment destruction due to faster drying rate (Alibas, 2007). As higher MWI and HAt used, drying process was taken place in shorter time so that colour was much more preserved. Applying MW drying for instant brown rice product, the higher lightness or color intensity could be obtained. This result agree well with the research of Sharma and Prasad (2004) that studied the combined MW-HA drying of garlic (*Allium sativum*) and Velu *et al.* (2006) that dried milled-maize (*Zea mays L.*) by microwave. Moreover, MWI also showed the quadratic effect on colour intensity.

The interaction effect appeared between MWI and HAt on color intensity. The color intensity was much lower as increase of HAt at higher MWI. The most interaction effect of HAt showed greatly when higher MWI was applied.

All factors showed the significant effect ($p < 0.05$) on colour intensity of rehydrated brown rice (ANOVA Table) as the main factor in which the

WRr is the most effect. The HAt showed greatly effect on colour intensity at higher MWI; the increase WRr, MWI and HAt altogether in this study provided better acceptable product colour for instant brown rice.

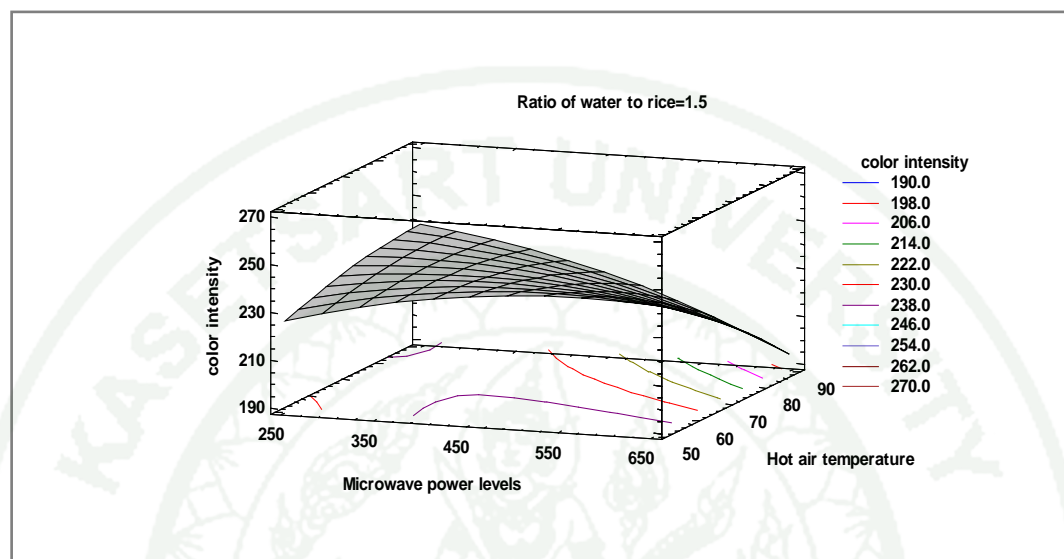


Figure 29 Surface-contour plot for color intensity of rehydrated cooked brown rice as a function of different processing conditions.

2.4.3 Color change upon rehydration

Interestingly, the rehydrated cooked brown rice had higher lightness and lower color intensity than those of dried cooked brown rice (Table 5) which is similar to the study about parboiled rice of Islam *et al.* (2004). Possibly, it was due to the presence of surface water as rehydrated that increases the luminosity of the sample resulting higher in lightness. Moreover, the explanation could be based on the contribution of pigments to coloration of the products. Framalingham and Anthony Raj (1996) supported that the bran compounds (lipids) leached out during parboiling and cooking whereas the leaching rate depend on temperature and time of steaming (Islam *et al.*, 2004) so that the lightness of cooked parboiled brown rice was higher while the colour intensity was lower than those of dried brown rice.

Table 5 Mean values and standard deviation of dried cooked brown rice and rehydrated cooked brown rice color.

W Rr	Microwave power levels(W)	Hot air temperature (°C)	Rehydrated lightness	Dried lightness	Rehydrated color intensity	Dried intensity	Sig
1.3	255	70	62.46 ± 0.5903	51.5567 ± 0.1986	240.441± 9.1544	361.648 ± 2.1355	*
1.3	255	70	62.46 ± 0.5903	51.5567 ± 0.1986	240.441± 9.1544	361.648 ± 2.1355	*
1.7	255	70	60.4567 ± 0.6357	50.7867± 0.3190	219.274± 7.5336	327.441 ± 6.0279	*
1.3	595	70	63.2633 ± 0.3355	55.3633± 0.1950	235.115± 14.0272	381.377 ± 3.9809	*
1.7	595	70	64.36 ± 0.4681	51.7433± 0.1365	213.445± 4.6491	363.148 ± 2.5478	*
1.3	425	50	62.6367 ± 0.4708	49.5533± 0.2916	237.738± 7.2030	320.216 ± 14.7624	*
1.7	425	50	62.4833 ± 1.0510	51.3833± 0.1250	231.667± 14.3898	365.964 ± 6.9418	*
1.3	425	90	64.0967 ± 0.6786	50.82± 0.1044	235.678± 7.4926	363.665 ± 3.1808	*
1.7	425	90	64.36 ± 0.4681	54.8067± 0.2458	212.294± 9.0501	375.849 ± 10.2282	*

Table 5 (Continued)

W Rr	Microwave power levels(W)	Hot air temperature (°C)	Rehydrated lightness	Dried lightness	Rehydrated color intensity	Dried intensity	Sig
1.5	255	50	60.4533 ± 0.4424	50.19± 0.1179	229.471± 10.5032	355.781± 5.7994	*
1.5	595	50	63.6167 ± 0.7932	53.76± 0.4	243.42± 10.7625	389.84± 4.6850	*
1.5	255	90	63.16 ± 0.3260	51.3233± 0.3630	239.126± 5.7645	331.179± 3.6281	*
1.5	595	90	64.1533 ± 0.6010	53.5133± 0.2930	201.261± 8.3876	368.764± 3.4115	*
1.5	425	70	63.3467 ± 0.1553	51.7067± 0.0833	236.152± 8.1592	349.723± 5.1328	*

WRr: Ratio of water to rice

* Significant different for t-test at 95 % confidence level for each pair between rehydrated and dried sample ($n \geq 3$).

2.4.5 Effect on stickiness

All factors influenced the stickiness and there was no interaction effect between factors for the stickiness; however, the effects were revealed in term of quadratic of MWI and WRr.

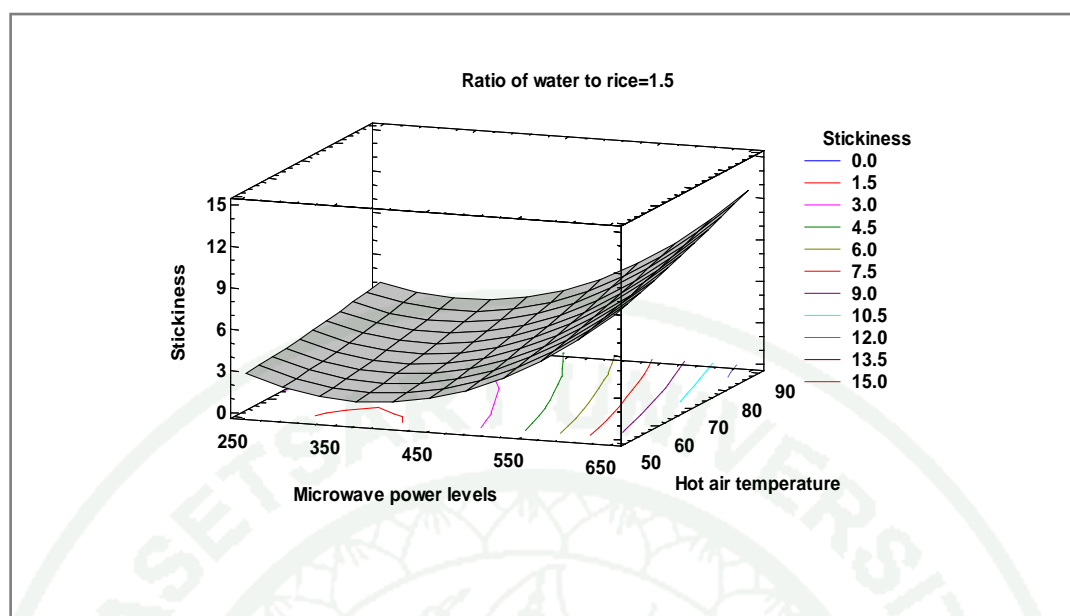


Figure 30 Surface-contour plot for stickiness of rehydrated cooked brown rice as a function of different processing conditions.

Stickiness and hardness are related each other as tested by texture analyzer. Three current factors were found showing the main effect on stickiness. The WRr is very important factor for stickiness since most of process of gelatinization was taken place during cooking process. Amylose and short chain of amylopectin are leaching out during cooking process that is directly related to stickiness and hardness (Rewthong *et al.*, 2011).

The stickiness increased as a function of increased MWI and HAt altogether, especially for the increased MWI (Fig 31). The amylose content and short chain amylopectin are the main compositions affecting to stickiness and hardness (Rewthong *et al.*, 2011) which was referred to for explaining this case. The increase of apparent amylose content leads to the higher in hardness but better in adhesiveness of cooked rice (Zhao *et al.*, 2007). Increase of MWI led to maintaining of higher level of amylose content (Delwiche *et al.*, 1996; Palav and Seetharaman, 2007). During microwave heating, the branch chains of amylopectin could be re-associated impacting to changes in viscosity properties of starch (Abraham, 1993; Ward *et al.*, 1994; Anderson and Guraya, 2006). Jiang *et al.* (2010) found that

the microwave treatment caused a higher cohesiveness of starch gel than that of conventional heating.

The stickiness and hardness has a non-linear negative correlation. Therefore, in order to maintain the consumer acceptance of rehydrated cooked brown rice, it is suggested to compromise between hardness and stickiness.

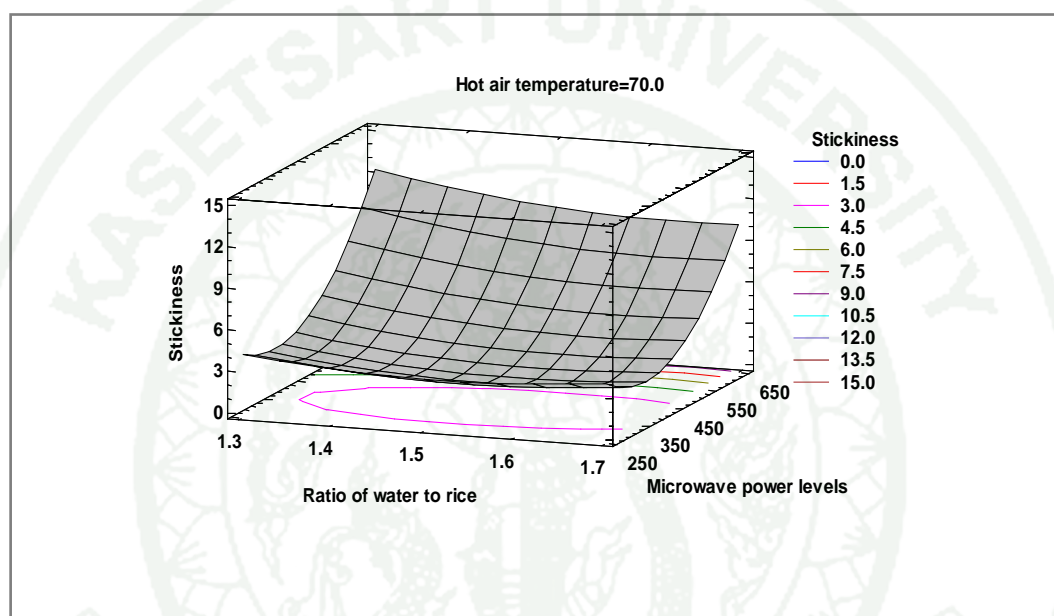


Figure 31 Surface-contour plot for stickiness of rehydrated cooked brown rice as a function of different process conditions.

2.5 Physical properties and eating quality of instant brown rice

Table 6 shows Pearson correlations between each pair of variables. These correlation coefficients range between -1 and +1 and indicate the strength of the linear relationship between the variables. The number shown in parentheses is the number of pairs of data values used to compute each coefficient. The third number in each location of the table is a p-value which tests the statistical significance of the estimated correlations. P-values below 0.01 indicate statistically significant non-zero correlations at the 99.0% confidence level. The following pairs of variables have P-values below 0.01: hardness had a positive correlation with bulk density; lightness had a negative correlation with bulk density but a positive correlation with

rehydration ratio; rehydration ratio has negative relation with bulk density; stickiness had a positive correlation with lightness of dried cooked brown rice.

The negative correlation between rehydration ratio and bulk density was significantly different with zero at 99.0 % confident level which means that the lower the bulk density was, the higher the rehydration ratio was obtained resulting in lower hardness due to higher water uptake. The lower bulk density could be obtained from the higher dried brown rice volume or the increased surface. Volume increases as a result of expanding of grain size or surface of rice grain; this facilitates water uptake leading to increase of rehydration ratio (Prasert and Suwannaporn, 2009). Moreover larger volume facilitated the leaching of some pigment during rehydration cooking; thus, the rehydrated cooked brown rice become whiter after heating in water. This expressed the positive correlation between rehydration ratio and lightness.

Table 6 Correlation coefficients between texture and physical properties of instant brown rice.

	Bulk density	Dried color intensity	Dried Lightness	Ratio of rehydration
Hardness	0.4140	0.0845	-0.1605	-0.3072
	(51)	(51)	(51)	(51)
	0.0025	0.5554	0.2607	0.0283
Lightness	-0.3815	-0.1762		0.3777
	(51)	(51)		(51)
	0.0057	0.2161		0.0063
Ratio of rehydration	-0.5103	-0.2298	0.3777	
	(51)	(51)	(51)	
	0.0001	0.1048	0.0063	
Stickiness	-0.2527	-0.3072	0.3806	0.0704
	(51)	(51)	(51)	(51)
	0.0737	0.0283	0.0059	0.6233

Remark: Pearson correlations; P-value < 0.05 and 0.01 is significant at $\alpha = 0.05$ and 0.01 respectively.

The number in the first row is correlation coefficients.

The number in the parentheses of the second row is pairs of data values used to compute each coefficient.

The number in the third row is p value.

The stickiness has a positive correlation with dried cooked brown rice lightness. This may be due to a consequence of water diffusion during cooking leading to leaching of some pigments at the outer layer of rice (bran layer) into the cooking liquid reducing color intensity and increasing the lightness. On the other hand during water uptake and volume expansion in cooking process, the granule expansion caused rupture and hence amylose leached (Leelayuthsoontorn and. Thipayarat, 2006). The outer layer of brown rice can be flaked off leading to releasing of endosperm during cooking and subsequent drying process. These flaked surfaces

could facilitate the leached starches generated as a coated film at the surface of rice grain that can increase the stickiness (Leelayuthsoontorn and Thipayarat, 2006).

2.6 Energy consumption

The specific energy consumption was calculated for the two-stage drying process conducted in MWO for 1st stage and HAO for 2nd stage shown in Table 7. Drying time for each drying run was prolonged to dry the sample until reaching the safe moisture content level.

Table 7 Specific energy consumption of different experimental runs.

Run no.	Replication	Water-rice ratio	Microwave power level (W)	Hot air temperature (°C)	Specific energy consumption (kJ/kg)	Drying time (h)
1	3	1.5	595	90	10543.5±71.7909	0.87
2	3	1.3	255	90	11042.9 ± 112.402	1.02
3	3	1.7	425	90	11042.9 ± 112.402	0.90
4	3	1.7	595	70	13020.4 ± 193.39	1.20
5	3	1.3	595	70	13020.4 ± 193.39	1.20
6	3	1.5	425	70	13519.8 ± 316.901	1.23
7	3	1.5	255	90	14233.5 ± 243.925	1.02
8	3	1.3	255	70	16710.4 ± 80.5929	1.35
9	3	1.5	595	50	17008.8 ± 354.18	1.70
10	3	1.7	255	70	17369.8 ± 91.0073	1.43
11	3	1.3	425	50	18827.0 ± 578.012	1.73
12	3	1.7	425	50	19486.4 ± 599.803	1.98
13	3	1.5	255	50	22677.0 ± 263.339	2.10

Specific energy consumption values are the mean ± standard deviation (n = 3).

The results indicated that when lower MWI and HAt were used for drying, the energy consumption would be much higher. It is because the longer drying

time when using lower MWI and HAt led to higher energy consumption than shorter drying time when using higher MWI and HAt.

This result found was along with that of Li *et al.* (2011). In this study, the lowest energy consumption obtained at WRr of 1.5:1, MWI of 559 W and HAt of 90 °C.

2.7 Optimizing multi-responses by desirability methodology and overlay plot.

Basing on the desirability methodology, most of predicted attributes could reach high desirability especially for lightness and hardness, equivalently 100 and 94.40 % of desirability, respectively. The optimal setting of the experimental factors were determined and displayed in the Table 8. At these settings, the response variables generate a desirability index of 81.50%.

Table 8 Predicted response values at optimum by desirability function.

Response	Optimized	Prediction	Lower 95.0% Limit	Upper 95.0% Limit	Desirability
Ratio of rehydration	yes	139.395	131.496	147.294	0.724798
Lightness	yes	64.541	64.0323	65.0496	1.0
color intensity	yes	198.0	188.949	207.051	1.0
Hardness	no				
Stickiness	yes	9.43511	8.28384	10.5864	0.634809

Remarks: Optimized desirability for multi-responses = 0.823597

*Uncounted for overall desirability function

Desirability was calculated by the equations (5-8) shown in the Appendix section.

Table 9 Factor settings at optimum for multi-responses.

<i>Factor</i>	<i>Setting</i>
Ratio of water to rice	1.58237
Microwave power levels (Watt)	595.0
Hot air temperature (°C)	90.0

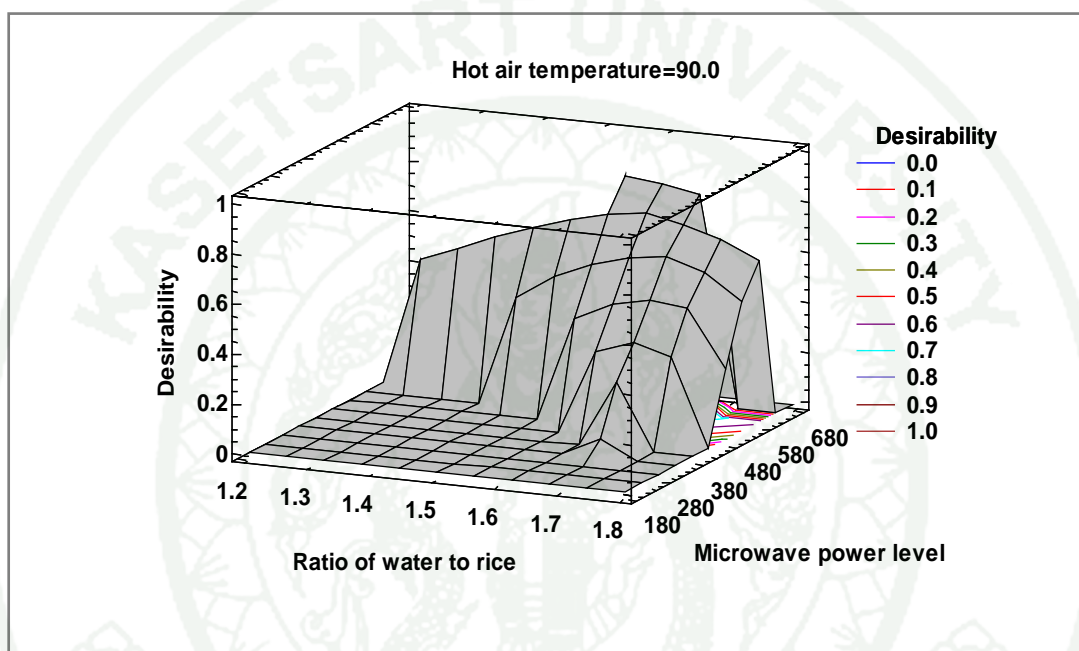
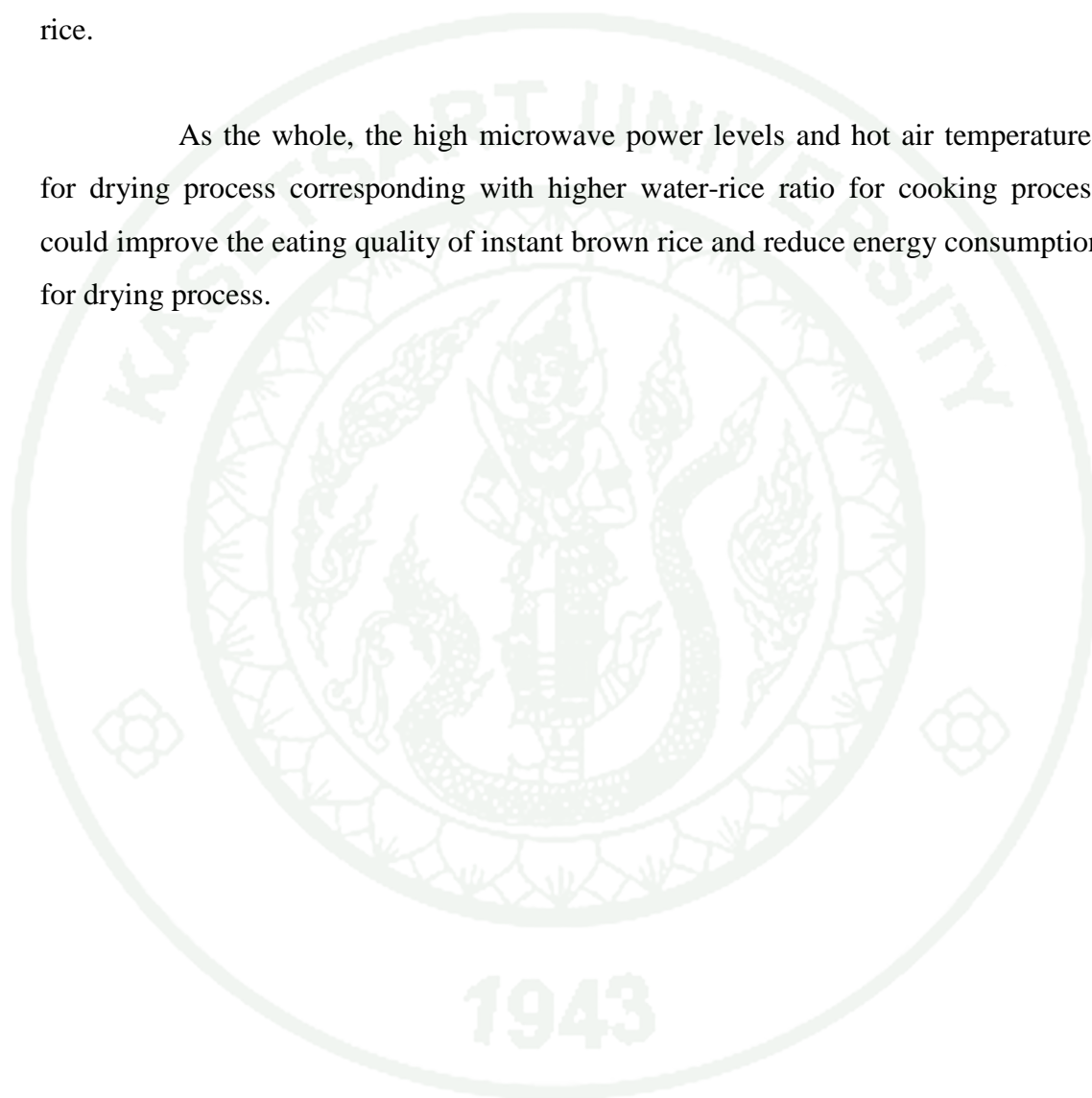
**Figure 32** Desirability plot for multi-optimization of dried cooked brown rice as a function of different processing conditions.

Figure 32 indicates the desirability value as a function of ratio of water to rice and microwave power level at the temperature of 90°C. The surface had a well-defined maximum near the center right of the plot. The optimum location is clearly seen within the space of the ratio of water to rice; however, it located at the edge for MW power and hot air temperature (see Fig. 32).

In summary for instant brown rice productions, the optimization of processing parameters for two-stage drying was successfully performed by using a Box-Behnken design. The second order polynomial mathematical models that were developed could predict the rehydration ratio, lightness, colour intensity and

stickiness of instant brown rice with a degree of accuracy. In addition, the traditional graphical method and desirability methodology integrated in Stagraphit version 16 were applied for optimization. The optimal condition of 1.58237, 595 W, and 90 °C was found for water-rice ratio, microwave power and hot air temperature respectively. This condition provides a better physical property and eating quality of instant brown rice.

As the whole, the high microwave power levels and hot air temperatures for drying process corresponding with higher water-rice ratio for cooking process could improve the eating quality of instant brown rice and reduce energy consumption for drying process.



CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In summary, the results obtained from this research are below:

1. Freezing and thawing pretreatments provided the more porous structure of dried cooked brown rice.
2. Cooked brown rice was dried by FBD, HAO and MWO with different drying methods; it was found that drying in MWO was much faster than that of HAO. Microwave drying is an attractive technique for drying cooked brown rice for producing the quick cooking brown rice or instant brown rice owing to its exceptionally high drying rate resulting in the required porous structure of product. The microwave drying can be applied either for the whole drying process of cooked brown rice or only for the first drying stage.
3. For the mathematical model development for estimating the moisture content changes, effective moisture diffusivity and some physical properties of cooked brown rice during drying process, the results showed the model developed in this study can be efficiently used.
4. The ratio of water to rice, microwave power level and hot air temperature were three main factors affecting to the quality of instant rice product. Box-Behnken experimental design was suitable to optimize the operating process parameters. Basing on the physical properties, energy consumption and eating qualities, the optimal operating process parameters of instant brown rice production were obtained. If considering the combination of multi-responses in aspects of physical and eating properties, the desirability index of 82.3% was obtained at the condition of 1.58237 for ratio of water to rice, 595 W for microwave power level and 90 °C for hot air temperature.

5. The energy consumption for two-stage drying process of cooked brown rice was calculated. The results indicated that if the higher microwave power and higher hot air temperature were applied, the energy consumption would be lessened due to its short drying period. The lowest energy consumption was obtained at the condition of 1.5 for ratio of water to rice, 595 W for microwave power level and 90 °C for hot air temperature.

The application of high microwave power levels and hot air temperature as the first and the second stage drying together with the appropriately high water-rice ratio for cooking process improved the eating quality of instant brown rice and reduced energy consumption for drying process. Microwave drying appeared to be crucial step for instant brown rice production. Microwave drying of cooked brown rice took advantage of the special heating behavior of the microwave energy to the commodity. Some of the advantages of the microwave heating in the drying of instant rice products over the conventional drying methods are fast and volumetric heating, higher drying rate, short drying time, reduced energy consumption and quality of the product.

Recommendations

The further study should be conducted at higher range of microwave power levels in order to gain more information about the microwave drying of cooked brown rice. (1) The larger microwave dryer scale should be applied to find out the effect of higher microwave power on instant rice production. (2) The microwave dryer should be designed as conveyer belt in hermetic chain process that has agitation to mix. In addition, in terms of drying combination, the creation of machine might combine both of microwave, convectional or even steaming spraying in the closed system to maximize the product efficiency. (3) The other interaction of non-starch or starch composition should be analyzed to clarify how they affect on eating quality.

Acknowledgement

A part of this research was funded by Center of Advanced Studies for Agriculture and Food, Institute for Advanced Studies, Kasersart University.



LITERATURE CITED

- Abers, J.E., and R.E. Wrolstad. 1979. Causative factors of colour deterioration in strawberry preserves during processing and storage. **J. Food Sci.** 44: 75-78, 81.
- Abraham, T.E. 1993. Stabilization of paste viscosity of cassava starch by heat moisture treatment. **Starch/Stärke.** 45: 131-135.
- Aguilera, J.M. 2005. Why food microstructure. **J. Food Eng.** 67: 3-11.
- Ahromrit, A., D.A. Ledward and K. Niranjana. 2006. High pressure induced water uptake characteristics of Thai glutinous rice. **J. Food Eng.** 72: 225-233.
- Akpınar, E.K., Y. Bicer and C. Yildiz. 2003. Thin layer drying of red Pepper. **J. Food Eng.** 59(1): 99-104.
- Al-Duri, B., and S. McIntyre. 1991. Comparison of drying kinetics of foods using a fan-assisted convection oven, a microwave oven and a combined microwave/convection oven. **J. Food Eng.** 15: 139-155.
- Ali, S.Z. and K.R. Bhattacharya. 1976. Starch retrogradation and starch damage in parboiled rice and flaked rice. **Starch/Stärke.** 28: 233-240.
- Alibas, I. 2007. Microwave, air and combined microwave-air-drying parameters of pumpkin slices. **LWT** 40: 1445-1451.
- Anderson, A.K & H.S. Guraya. 2006. Effects of microwave heat moisture treatment on properties of waxy and non-waxy rice starch. **Food Chem.** 97: 318-323.
- Bardet, G.V., C. Berkeley and R.C. Giesse. 1961. Processing of brown rice. **U.S. Patent** 2,992,921.

- Bakshi, A.S., R.P. Singh. 1982. Modeling rice parboiling process. **LWT - Food Science and Technology**. 15: 89–94
- Baz, A.A., J.Y. Hsu and E. Scoville. 1992. Preparation of quick cooking rice. **U.S. Patent** 5,089,281.
- Bello, M., M.P. Tolaba and C. Suarez. 2004. Factors affecting water uptake of rice grain during soaking. **Lebensm.-Wiss. U.-Technol.** 37: 811-816.
- Bett-Garber, K.L., E.T. Champagne, D.A. Ingram and A.M. McClung. 2007. Influence of water to rice ratio on cooked rice flavor and texture. **Cereal Chem.** 84(6): 614-619.
- Bhattacharya, K.R and P.V. Subba Rao. 1966. Processing conditions and milling yield in parboiled rice. **J. Agri. Food Chem.** 14: 473–475.
- Bruce, D.M. 1985. Exposed-layer barley drying, three models fitted to new data up to 150°C. **J. Agri. Engineering Res.** 32: 337–347.
- Buffler, C.R. 1993. **Microwave cooking and processing: Engineering fundamentals for the food scientist**. Van Nostrand Reinhold. New York.
- Calay, R.K., M. Newborough, D. Probert and P.S. Calay. 1995. Predictive equations for the dielectric properties of foods. **Int. J. Food Sci. Tech.** 29:699–715.
- Campbell, H.A and F. Hollis. 1954. Process of preparing quick cooking rice. **U.S. Patent** 2,696,156.
- Carlson, R.A., E. Cerrito, R.L Robert and F. Daniel. 1979. Processing for preparing quick-cooking rice. **U.S. Patent** 4,133,898.

- Chou, S.K. and K.J. Chua. 2001. New hybrid drying technologies for heat sensitive foodstuffs. **Trends Food Sci. and Tech.** 12: 359-369.
- Clark, D.E. 1996. Microwave processing of materials. **Annu. Rev. Mater. Sci.** 26: 299-331.
- Cohen, J.S and T.C.S. Yang. 1995. Progress in food dehydration. **Trends in Food Sci. & Tech.** 6 (1): 20-25.
- Corzo, O., N. Bracho, A. Va'squez and A. Pereira. 2008. Optimization of a thin layer drying process for coroba slices. **J. Food Eng.** 85: 372-380.
- Crank, J. 1975. **The Mathematics of Diffusion.** 2nd Ed. Clarendon Press, Oxford, UK. London.
- Crowhurst, D. G and P.G. Creed. 2001. Effect of cooking method and variety on the sensory quality of rice. **Food Serv. Tech.** 1: 133-140.
- DeCareau, R.V. 1985. The microwave sterilization process. **Microwave World** 16(2):12-15.
- Delwiche, S.T., K.S. Mckenzie and B.D. Webb. 1996. Quality Characteristics in Rice by Near-Infrared Reflectance Analysis of Whole-Grain Milled Samples. **Cereal Chem.** 73(2):257-263.
- Derringer, G. and R. Suich. 1980. Simultaneous Optimization of Several Response Variables. **J. Quality Tech.** 12(4): 214-219.
- Demirhan, E. and B. Ozbek. 2011. Thin-Layer Drying Characteristics and Modeling of Celery Leaves Undergoing Microwave Treatment. **Chem. Eng. Comm.** 1198(17): 957-975.

- Diamante, L.M. and P.A. Munro. 1991. Mathematical modeling of hot air drying of sweet potato slices. **Int. J. Food Sci. Tech.** 26: 99–109.
- Dincer, I. and M.M. Hussain. 2004. Development of a new Biot number and lag factor correlation for drying applications. **Int. J. Heat Mass Transfer.** 47: 635–658.
- DoyMaz, I. 2005. Drying behaviour of green beans. **J. Food Eng.** 69: 161–165.
- Elbert, G., M.P. Tolaba and C. Suarez. 2001. Effects of drying conditions on head rice yield and browning index of parboiled rice. **J. Food Eng.** 47: 37–41.
- Feng, H., and J. Tang. 1998. Microwave finish drying of diced apples in a spouted bed. **J. Food Sci.** 63: 679–683.
- Filipic, M. 2010. **Brown rice, not white, a whole grain, Ohio State University Extension**, Ohio Agricultural Research and Development Center. Available source: <http://www.ag.ohio-state.edu/~news/files/chow.rice.pdf>, October 4, 2010.
- Fortes, M. and M.R Okos. 1981. Non-equilibrium thermodynamics approach to heat and mass transfer in corn kernels. **Trans. ASAE.** 22: 761–769.
- Framlingham, N. and S. Anthony Raj. 1996. Short communication: Studies on the soak water characteristics in various in paddy parboiling methods. **Biores. Tech.** 55: 259–261.
- Ganesapillai, M., I. Regupathi and T. Murugesan. 2011. Modeling of Thin Layer Drying of Banana (Nendran Spp) under Microwave, Convective and Combined Microwave-Convective Processes. **Chem. Prod. Process Model.** 6(1): Article 10.

- Ghamsemi, E., M.T. Hamed Mosavian and M.H. Haddad Khodaparast. 2009. Effect of stewing in cooking step on textural and Morphological properties of cooked rice. **Rice sci.** 16(3): 243-246.
- Giner, S.A. and A. Calvelo. 1987. Modeling of wheat drying in fluidized beds. **J. Food Sci.** 52(5): 1358-63.
- Gowen, A.A., N. Abu-Ghannam, J. Frias and J. Oliveira. 2008. Modelling dehydration and rehydration of cooked soybeans subjected to combined microwave-hot-air drying. **Innovative Food Sci. Eme. Tech.** 9: 129-137.
- Groesbeck, C., J.Y. Hsu and G.J. Larson. 1990. Preparation of dried precooked rice product. **U.S. Patent** 4,902,528.
- Han, J.A. and S.T. Lim. 2009. Effect of Presoaking on Textural Thermal, and Digestive Properties of Cooked Brown Rice. **Cereal Chem.** 86(1): 100-105.
- Henderson, S.M. and S. Pabis. 1961. Grain drying theory I: Temperature effect on drying coefficient. **J. Agric. Research Eng.** 6: 169-174.
- Henderson, S.M. 1974. Progress in developing the thin layer drying equation. **Trans. ASAE.** 17: 1167-1172.
- Hess, D. 1984. Comparison of processing economics of different starch dryers. **Food pro.** 36(11): 369-373.
- Hii, C.L., C.L. Lae and M. Cloke. 2009. Modeling using a new thin layer drying model and product quality of cocoa. **J. Food Eng.** 90: 191-198.
- Hirokawa, T., K. Oki, Y. Kumagai and H. Sasaki. 1986. Method for heat treating brown rice. **U.S. Patent** 4,582,713.

- Horigane, A.K., H. Toyoshima., H. Hemmi., W. M. H. G. Engelaar., A. Okubo and T. Nagata. 1999. Internal Hollows in Cooked Rice Grains (*Oryza sativa* cv. Koshihikari) Observed by NMR Micro Imaging. **J. Food Sci.** 64, No. 1.
- Hutchinson, D. and L. Otten. 1983. Thin layer air-drying of soybeans and white beans. **J. Food Tech.** 18: 507–524.
- Ibarz, A., J. Pagan and S. Garza. 1999. Kinetic models for colour changes in pear puree during heating at relatively high temperatures. **J. Food Eng.** 39: 415–422.
- Islam, M.R., N. Shimizu and T. Kimura. 2002. Effect of processing condition on thermal properties of parboiled rice. **Food Sci. and Tech. Res.** 8(2): 131-136.
- _____, _____, and _____. 2004. Energy requirement in parboiled and its relationship to some important quality indicators. **J. Food Eng.** 63(4): 433-439.
- Jayas, D.S., S. Cenkowski, S. Pabis and W.E. Muir. 1991. Review of thin layer drying and wetting equations. **Drying Tech.** 9 (3): 551–558.
- Jaisut, D., S. Prachayawarakorn, W. Varayanond & P. Tuntrakul. 2009. Accelerated aging of jasmine brown rice by high-temperature fluidization technique. **Food Research Int.** 42: 674–681.
- Jiang, H., M. Campbell, M. Blanco and J.L. Jane. 2010. Characterization of maize amylose-extender (ae) mutant starches: Part II. Structure and properties of starch residues remaining after enzymatic hydrolysis at boiling water temperature. **Carbohydr. Polym.** 80: 1–12.
- Jittanit, W. 2007. **Modeling of seed drying using a two-stage drying concept.** PhD Thesis. University of New South Wales, Sydney, Australia.

- Jittanit, W. 2011. Kinetics and Temperature Dependent Moisture Diffusivities of Pumpkin Seeds During Drying. **Kasetsart J. (Nat. Sci.)**. 45: 147 - 158.
- Joshi, D.C., S.K. Das and R.K. Mukherjee. 1993. Physical properties of Pumpkin Seeds. **J. Agric. Eng. Res.** 54: 219-229.
- Kadan, R.S., M.G. Robinson, D.P. Thibodeaux and J.A.B. Pepperman. 2001. Texture and other physicochemical properties of whole rice bread. **J. Food Sci.** 66: 940–944.
- Karababa, E. 2006. Physical properties of pop corn kernels. **J. Food Eng.** 72: 100-107.
- Karathanos, V.T. and V.G. Belessiotis. 1999. Application of a thin layer equation to drying data of fresh and semi-dried fruits. **J. Agri. Engineering Res.** 74: 355-361.
- _____, G. Villalobos and G.D. Saravacos, 1990. Comparison of two methods of estimation of the effective moisture diffusivity from drying data. **J. Food Sci.** 55: 218-223.
- Kohlwey, D.E. 1987. Process for producing improved dehydrated rice and product. **U.S. Patent** 4,649,055.
- Krokida, M. K. and Z. B. Maroulis. 1999. Effect of microwave drying on some quality properties of dehydrated products. **Drying Tech.** 17: 449–466.
- Lai, V.M.F., S. Lu and C.Y. Lii. 2000. Molecular characteristics influencing retrogradation kinetics of rice amylopectin. **Cereal Chem.** 77: 272-278.
- Leelayuthsoontorn, P. and A. Thipayarat. 2006. Textural and morphological changes of Jasmine rice under various elevated cooking conditions. **Food Chem.** 96: 606-631.

- Lefeuvre, S., M. Sadeghi, M. Majdabadino and M. Audhuy. 1990. Shrinkage of porous materials during microwave drying. **Drying Tech.** 8 (5): 1049-1060.
- Lewandowicz, G., T. Jankowski and J. Fornal. 2000. Effect of microwave radiation on physico-chemical properties and structure of cereal starches. **Carbohydr. Polym.** 42: 193–199.
- Lewicki, P.P. and G. Pawlak. 2003. Effect of drying on microstructure of plant tissue. **Drying Tech.** 21: 657–683.
- Li, Z., G.S.V. Raghavan, N. Wang and C. Vigneault. 2011. Drying rate control in the middle stage of microwave drying. **J. Food Eng.** 104: 234-238.
- Lin, T.M., T.D. Durance, C.H. Scaman. 1998. Characterization of vacuum microwave air and freeze dried carrot slices. **Food Research Int.** 4: 111–117.
- Lu, T.J., J.L. Jane and P.L. Keeling. 1998. Temperature effect on retrogradation rate crystalline structure of amylose. **Carbohydr. Polym.** 33: 19–26.
- Luangmalawat, P., S. Prachayawatakorn, A. Nathakaranakule and S. Soponronnarit. 2008. Effect of temperature on drying characteristic and quality of cooked rice. **LWT.** 41: 716-723.
- Luh, B.S. and R.R. Mikus. 1980. **Rice Production and Utilization.** AVI, Westport.
- Lyons, D. W., J.D. Hatcher and J.E. Sunderland. 1972. Drying of a porous medium with internal heat generation. **Int. J. Heat Mass Transfer**, 15: 897.
- Maskan, M. 2001. Kinetics of colour change of kiwifruits during hot air and microwave drying. **J. Food Eng.** 48: 169-175.
- Mayor, L. and A.M. Sereno. 2004. Modelling shrinkage during convective drying of food materials: a review. **J. Food Eng.** 61: 373–386.

- McMinn, W.A.M and T.R.A. Magee. 1999. Studies on the effect of temperature on moisture sorption characteristics of potatoes. **J. Food Pro.** 22: 113–128.
- Meeso, N., A. Nathakaranakule, T. Madhiyanon and S. Soponronnarit. 2004. Influence of FIR irradiation on paddy moisture reduction and milling quality after fluidized bed drying. **J. Food Eng.** 65: 293–301
- Midilli, A. and H. Kucuk. 2003. Mathematical modeling of thin layer drying of pistachio by using solar energy. **Energ. Convers. Manag.** 44(7): 1111-1122.
- Min, Z., C.L. Li, G.N. Xiao, L. Shan, C. Cao and L. Zhou. 2005. Dehydrated sword beans: the squeezing process and accelerated rehydration characteristics. **Drying Tech.** 23 (7): 1581–1589.
- Mohamed, A., S.C. Peterson, L.A. Grant and P. Rayas-Duarte. 2006. Effect of jet-cooked wheat gluten/lecithin blends on maize and rice starch retrogradation. **J. Cereal Sci.** 43: 293–300.
- Moss, J.R and L. Otten. 1989. A relationship between color development and moisture content during roasting of peanut. **Can. Inst. Food Sci. Technol. J.** 22: 34–39.
- Myers, G.E. 1971. **Analytical Methods in Conduction Heat Transfer.** McGraw-Hill, New York.
- Nagarajan, G and K. Natarajan. 1999. The use of Box-Behnken design of experiments to study in vitro salt tolerance by *Pisolithus tinctorius*. **World J. Microbiol Biotechnol.** 15: 197-203.
- Ngamnikom, P. and S. Songsermpong. 2011. The effects of freeze, dry, and wet grinding processes on rice flour properties and their energy consumption. **J. Food Eng.** 104: 632-638.

- Nijhuis, H. H., H.M. Topping, S. Muresan, D. Yuksel, C. Leguijt and W. Kloek. 1998. Approaches to improving the quality of dried fruit and vegetables. **Trends Food Sci. Tech.** 9: 13–20.
- Ong, M. H. & J.M.V. Blanshard. 1995. Texture determinants in cooked, parboiled rice I: rice starch amylose and the fine structure of amylopectin. **J. Cereal Sci.** 21: 251–260.
- Ozai-Durrani, A.K. 1948. Quick-cooking rice and process for making same. **U.S. Patent** 2,438,939.
- _____. 1965. Process for producing quick cooking rice. **U.S. Patent** 3,189,461.
- Özdemir, M and Y.Onur Devres. 1999. The thin layer drying characteristics of hazelnuts during roasting. **J. Food Eng.** 42 (4): 225–233.
- Palay, T. & K. Seetharaman. 2007. Impact of microwave heating on the physico-chemical properties of a starch–water model system. **Carbohydr. Polym.** 67(4): 596–604.
- Parry, J.L. 1985. Mathematical modeling and computer simulation of heat and mass transfer in agricultural grain drying. **J. Agri. Engineering Res.** 32: 1–29.
- Parti, M. 1993. Selection of mathematical models for drying grain in thin layers. **J. Agri. Engineering Res.** 54: 339–352.
- Poomsa-ed, N., S. Soponronnarit, S. Prachayawarakorn, and A. Terdyothin. 2001. Effect of tempering on subsequent drying of paddy using fluidization technique. **Drying Tech.** 20(1): 195–210.

- Prabhanjan, D.G., H.S. Ramaswamay and G.S.V. Raghavan. 1995. Microwave-assisted air drying of thin layer carrots. **J. Food Eng.** 25: 283–293.
- Prasert, W. and P. Suwannaporn. 2009. Optimization of instant jasmine rice process and its physicochemical properties. **J. Food Eng.** 95: 54–61.
- Priestley, R.J. 1977. Studies on parboiled rice: Part II. Quantitative study of the effects of steaming on various properties of parboiled rice. **Food Chem.** 1:139–148.
- Rahman, M.S and J. Lamb. 1991. Air drying behavior of fresh and osmotically dehydrated pineapple. **J. Food Process Eng.** 14: 163–171.
- Rahman, M.S. 2001. Towards prediction of porosity in foods during drying: a brief review. **Drying Tech.** 19 (1): 3–15.
- Ramesh, M. N. 2003. Moisture transfer properties of cooked rice during drying. **LWT** 36: 245-255.
- . and P.N. Srinivasa Rao. 1996. Drying studied of cooked rice in a Vibrofluidised bed drier. **J. Food Eng.** 27: 389-396.
- Rewthong, O., S. Soponronnarit, C. Taechapairoj, P. Tungtrakul and S. Prachayawarakorn. 2011. Effects of cooking, drying, and pretreatment methods on texture and starch digestibility of instant rice. **J. Food Eng.** 103: 258–264.
- Robert, R.L. 1952. Production of quick-cooking rice. **U. S. Patent** 2,610,124.
- . 1972. **Rice: Chemistry and Technology.** Association of American Cereal Chemist, St. Pual, Minn, USA. 381–397.

- Roberts, J.S., D. R. Kidd and O. Padilla-Zakour. 2008. Drying kinetics of grape seed. **J. Food Eng.** 89: 460-465.
- Roy, P., T. Ijiri, H. Okadome, D. Nei, T. Orikasa, N. Nakamura and T. Shiina. 2008. Effect of processing conditions on overall energy consumption and quality of rice (*Oryza sativa*. L). **J. Food Eng.** 89: 343-348.
- Salunkhe, D.K., H. R. Bolin, and N.R. Reddy. 1991. **Storage, processing, and nutritional quality of fruits and vegetables** (Vol. 2). Boca Raton, FL: CRC Press.
- Sharma, G.P and S. Prasad. 2006. Optimization of process parameters for microwave drying of garlic cloves. **J. Food Eng.** 75: 441-446.
- _____, and _____. 2004. Effective moisture diffusivity of garlic cloves undergoing microwave-convective drying. **J. Food Eng.** 65: 609–617.
- Skrede, G. 1985. Color quality of blackcurrant syrups during storage evaluated by Hunter. **J. Food Sci.** 50: 514–517, 525.
- Smith, D.A., R.M. Rao, J.A. Liuzzo and E. Champagne. 1985. Chemical treatment and process modification for producing improve quick cooking rice. **J. Food sci.** 50 (4): 926–931.
- Sootjarit, S., W. Jittanit, S. Phompan and P. Rerkdamri. 2011. Moisture sorption behavior and drying kinetics of pre-germinated rough rice and pre-germinated brown rice. **Trans. ASABE.** 54(1): 255-263.
- Soysal, Y., S. Oztekin and O. Eren. 2006. Microwave Drying of Parsley: Modelling, Kinetics, and Energy Aspects. **Biosystems Eng.** 93 (4): 403–413.
- Sturgeon, L.F. 1984. Process for preparing quick cooking food products. **U.S. Patent** 4,473,593.

- Suarez, C., P. Viollaz and J. Chirife. 1980. Diffusional analysis of air srying of grain sorghum. **J. Food Tech.** 15: 221–232.
- Sumnu,G., E. Turabi and M. Oztop. 2005. Drying of carrots in microwave and halogen lamp–microwave combination ovens. **LWT.** 38: 549–553.
- Sun, D.-W. 2008. **Advances in Food Dehydration.** Edited by Cristina Ratti. CRC Press. New York.
- Sutar, P.P and S. Prasad. 2008. Microwave Drying Technology-Recent Developments and R&D Needs in India. **In proceedings of 42nd ISAE Annual Convention**, during February 1-3.
- Swamy, Y.M.I., S. Z. Ali and K.R. Bhattacharya. 1971. Hydration of raw and parboiled rice and paddy at room temperature. **J. Food Sci. Tech.** 8: 20–22.
- Taechapiroj, C., I. Dhuchakallaya, S. Soponronnarit, S. Wetchacama and S. Prachayawarakorn. 2003. Superheated steam fluidized bed paddy drying. **J. Food Eng.** 58: 67-73.
- Tang, J., F. Hao & M. Lau. 2011. **MICROWAVE HEATING IN FOOD PROCESSING, CHAPTER I**, Department of Biological Systems Engineering, Washington State University Pullman, WA 99164-6120, USA. Available source: <http://www.worldscibooks.com/lifesci/4763.html>.
- Thakur, A.K. and A.K. Gupta. 2006. Tow stage drying of high moisture paddy with intervening rest period. **Energ. Convers. Manag.** 47: 3069-3083.
- Thuwapanichayanan, R., S. Prachayawarakorn and S. Soponronnarit. 2008. Drying characteristics and quality of banana foam mat. **J. Food Eng.** 86: 573–583.

- Tong, C. H. & D.B. Lund. 1990. Effective moisture diffusivity in porous materials as a function of temperature and moisture content. **Biotechnol. Prog.** 6(1): 67–75.
- Vadivambal, R. and D.S. Jayas. 2007. Changes in quality of microwave-treated agricultural products—a review. **Biosystems Eng.** 98: 1–16.
- Varith, J., P. Dijknarakul, A. Achariyaviriya and S. Achariyaviriya. 2007. Combined microwave-hot air-drying of peeled longan. **J. Food Eng.** 81: 459–468.
- Velu, V., A. Nagender, P.G.P. Rao and D.G. Rao. 2006. Dry milling characteristics of microwave dried maize grains (*Zeamays L.*). **J. Food Eng.** 74: 30-36.
- Verma, L.R., R. A. Bucklin, J. B. Endan and F.T. Wratten. 1985. Effects of drying air parameters on rice drying models. **Trans. ASAE.** 28: 296-301.
- Vilche, C., M. Gely and E. Santalla. 2003. Physical Properties of Quinoa Seeds. **Biosystems Eng.** 86 (1): 59–65.
- Wang, C. Y. & R.P. Singh. 1978. Use of variable equilibrium moisture content in modeling rice drying. **ASAE Paper** 78-6505, ASAE, St. Joseph, MI 49085.
- Wang, N. and J.G. Brennan. 1993. Change in structure, density and porosity of potato during dehydration. **J. Food Eng.** 24: 61-76.
- Ward, K.E.J., R.C. Hosney and P.A. Seib. 1994. Retrogradation of amylopectin from maize and wheat starches. **Cereal Chem.** 71: 150–155
- Watson, E.L. and V.K Bhargava. 1974. Thin layer studies on wheat. **Can. Agr. Eng.** 16: 18–22.

- Weibye, B. 1983. Quick cooking rice and process for making the same. **U.S. Patent** 4,385,074.
- Whistler, R.L. and J.N. BeMiller. 1999. **Carbohydrate Chemistry for Food Scientists**. The American Association of Cereal Chemists, INC., Minnesota.
- Yamakura, M., K. Haraguchi, H. Okadome, K. Suzuki, T.U. Uyen, A.K. Horigane, M. Yoshisa, S. Homa, A. Sasagawa, A. Yamazaki and K. Ohtsubo. 2005. Effect of soaking and high pressure treatment on the qualities of cooked rice. **J. Appl. Glycosci.** 52: 85-93.
- Yamamoto, T., F. Sano and K. Matsuo. 2005. Quality improved cooked rice. **U.S. Pub. No.** 0019465 A1.
- Yu. S., Y. Ma and D.W. Sun. 2010a. Effects of freezing rates on starch retrogradation and textural properties of cooked rice during storage. **LWT - Food Science and Technology** 43: 1138-1143.
- _____, T. Liu, L. Menager and _____. 2010b. Impact of cooling rates on the staling behavior of cooked rice during storage. **J. Food Eng.** 96: 416-420.
- Zhang, M., C.L. Li and X.L. Ding. 2005. Effects of heating conditions on the thermal denaturation of white mushroom suitable for dehydration. **Drying Tech.** 23 (5): 1119-1125.
- _____, _____, and _____. 2003. Optimization for preservation of selenium in sweet pepper under low-vacuum dehydration. **Drying Tech.** 21 (3): 569-579.
- Zhao, S., S. Xiong, C. Qiu and Y. Xu. 2007. Effect of microwaves on rice quality. **J. Stored Products Res.** 43: 496-502.

Zhou, Z., K. Robards, S. Helliwell and C. Blanchard. 2002. Composition and functional properties of rice. **Int. J. Food Sci. and Tech.** 37: 849-868.





APPENDICES



Appendix A

Pre-treatment and drying preliminary tests

1. Pre-treatment and preliminary tests

1.1 Washing

The initial moisture content of raw brown rice was determined before washing.

A sample (300-500g) of raw brown rice was washed in tap water to remove the dust particles and then poured into the net basket to drain water out. After washing, the weight of rice is much higher than that before washing. Water draining time was at least 5 minutes prior to cooking.

1.2 Preliminary test for cooking condition

The normal cooker was used to cook brown rice by boiling and steaming method in order to compare the product quality with the sample boiled and steamed by the pressure cooker. The results indicated that at the same ratio of rice to water, the normal electric cooker required long time to reach the moisture content of 68 and 70% wet basis (over 40 mins).

On the other hand, the brown rice was also boiled with pressure rice cooker using both excess water and exact water at the ratio of water to rice of 1.5 to 1. The samples were boiled from 22 minutes and then drained excess water out (if any) and finally steamed for another period of 22 minutes. The result showed that the number of broken cooked brown rice when using excess water method was much higher and required longer cooking period in comparison with those of exact water method. During cooking brown rice by exact method, after the first period of cooking (finish setting time of cooker), if cooker was instantly continued to heat by pressing the cooking button of pressure cooker, the cooked brown rice became too soft (personal eating test). Moreover, after the first period, the cooked brown rice was wet, not dried enough and unsuitable for drying. Thus, it is better to open the lid to exhaust the water to outside and then press the button to steam function.

1.3 Pretreatment before drying

The cooked rice was spread out as a thin layer and single layer on an open container for ambient air cooling for a period of 5 minutes in order to avoid the cooked rice stickiness or clumping. The preliminaries indicated that this step should be employed at single layer to well-separate cooked rice grains. Note that the cooked rice should be spreaded immediately after opening the lid of cooker to avoid rice grouping since when temperature dropped, the cooked brown rice tended to stick together resulting in longer freezing step.

For freezing step, the cooked brown rice was put into tray as a thin layer and placed in the chest freezer at temperature of -19°C for various times (90 minutes is freezing time that was selected from preliminary results, studied from 30 to 120 minutes). After that, the frozen sample was thawed.

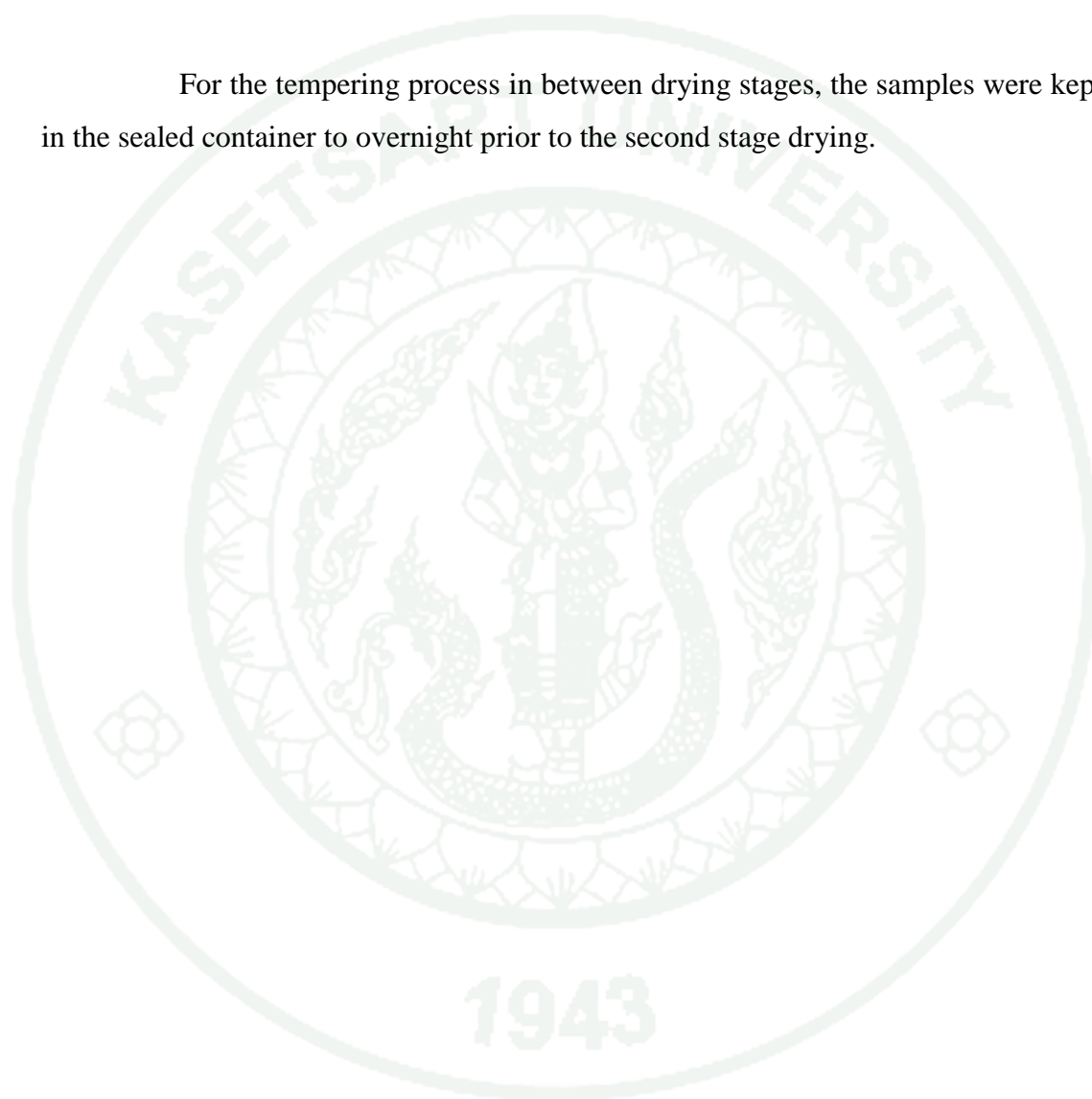
In this study, for the thawing pretreatment, the frozen rice was subjected to two thawing steps including spraying cold water. In the first step, the frozen sample was put into the refrigerator setting temperature at $4-10^{\circ}\text{C}$ for 40 minutes. In the second step, the sample was exposed to the surrounding air at room temperature for period of 20 minutes. It was found that during the thawing time, the cold water should be sprayed since it helped separating rice clump well leading the convenience when putting sample as a single layer in the turnable plate of MWO.

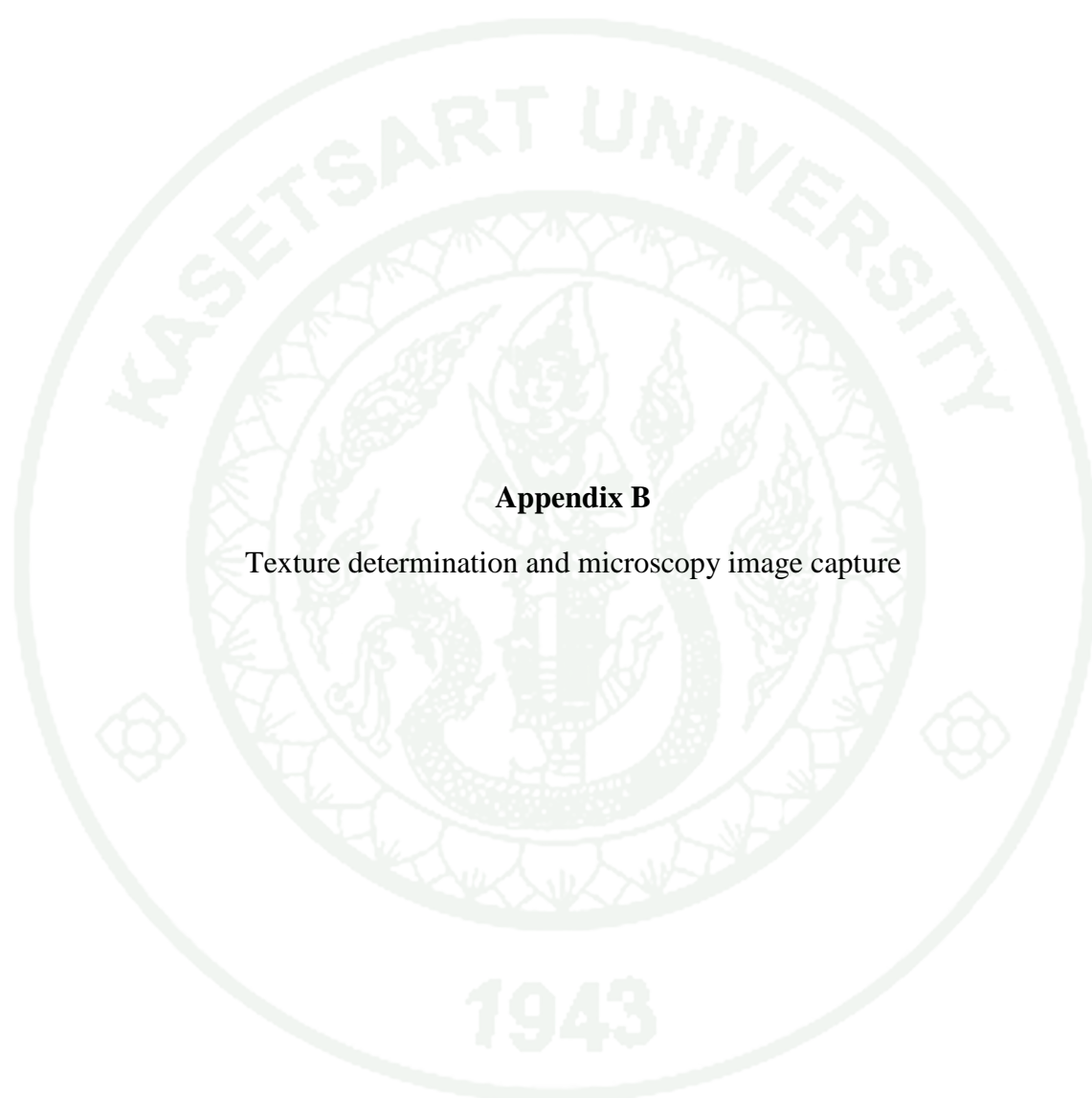
1.4 Suitable drying condition

The idea was that for instant brown rice production, cooked rice must be dried rapidly to remove moisture and create more porosity which encouraged the rehydration capability. Therefore, in the preliminary tests, fluidized bed dryer or microwaves drying equipment were selected. For fluidized bed drying, the drying temperature levels were 130, 160, 180 and 200°C by varying fluidization velocity between 0-9 m/s. However, it was found that the cooked brown rice was too sticky was and could not be fluidized. For microwave drying, the samples were dried by both microwave lab scale dryer (conveyor type) and microwave oven at specified

power levels comprising 85, 255, 425, 595 and 850 W and drying time also selected for each of power levels. However, the microwave dryer (conveyor type) took very long time since the drying process has to be done for many cycles until obtaining the desired moisture content. Hence, the microwave oven was chosen for microwave drying in this research.

For the tempering process in between drying stages, the samples were kept in the sealed container to overnight prior to the second stage drying.





Appendix B

Texture determination and microscopy image capture

1. Texture Determination

1.1 Apparatus

- Texture Analyser (TA.XTPlus, Stable Micro System Ltd., UK).
- Base Table (Platform) for TA.Plus Texture Analyzer using 5kg load cell.

1.2 Rehydrated preparation

A sample (10 grams of dried-cooked brown rice + 120 grams of filter water) was put in the ceramic cup and then heated by MWO. The rehydration period was 10 minutes involving 5 min for heating, and 5 minutes for draining. After that, the sample was exposed to textural determination. Testing should be performed immediately after rehydration to minimize the effect of long time storage.

1.3 Description of measuring conditions

The TA-XTPlus was set as the condition below;

Mode: Measure Force in compression

Cylindrical probe: 25 mmØ

Option: Return to start

Pre-Test Speed: 1.0 mm/s

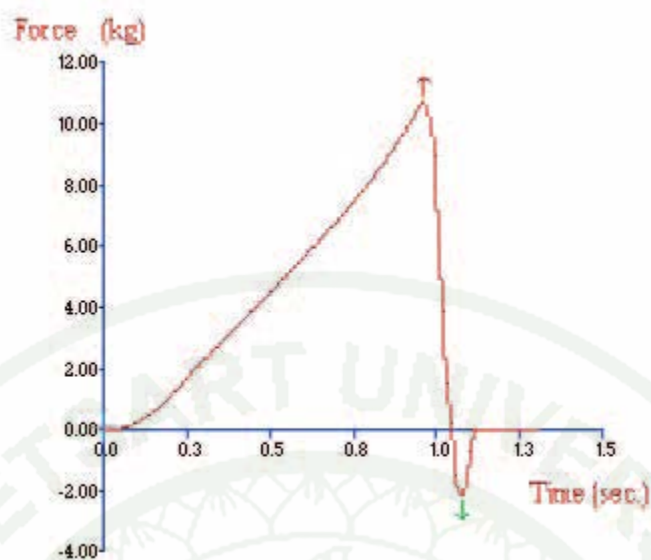
Test Speed: 10.0 mm/s

Post-Test Speed: 10.0 mm/s

Stain (Deformation): 85%

Trigger Type: Auto - 5g

Data Acquisition Rate: 400pps



Appendix Figure B1 Force vs. time plot from measuring the texture of instant brown rice.

Hardness (N or kg) is defined as the maximum force achieved during the compression phase and stickiness is the calculated area under the negative force curve.

2. Capture of microscopy images of samples

2.1 Apparatus

- The Leica stereomicroscope (S8APO, Leica Microsystems Imaging Solutions Ltd., Cambridge CB1 3XJ, UK).

- The digital camera for microscope (Leica DFC280, Leica Microsystems Imaging Solutions Ltd., Cambridge CB1 3XJ, UK).

- Leica Application Suite (LAS) software.

- Leica TL BFDf transmitted-light stand.

2.2 Sample preparation

The representative samples were picked up to capture their images. The image capture was performed at the same setting condition for different kernels.

2.3 Description of image capture conditions:

Camera conditions were set as below;

Exposure: 660.0 ms

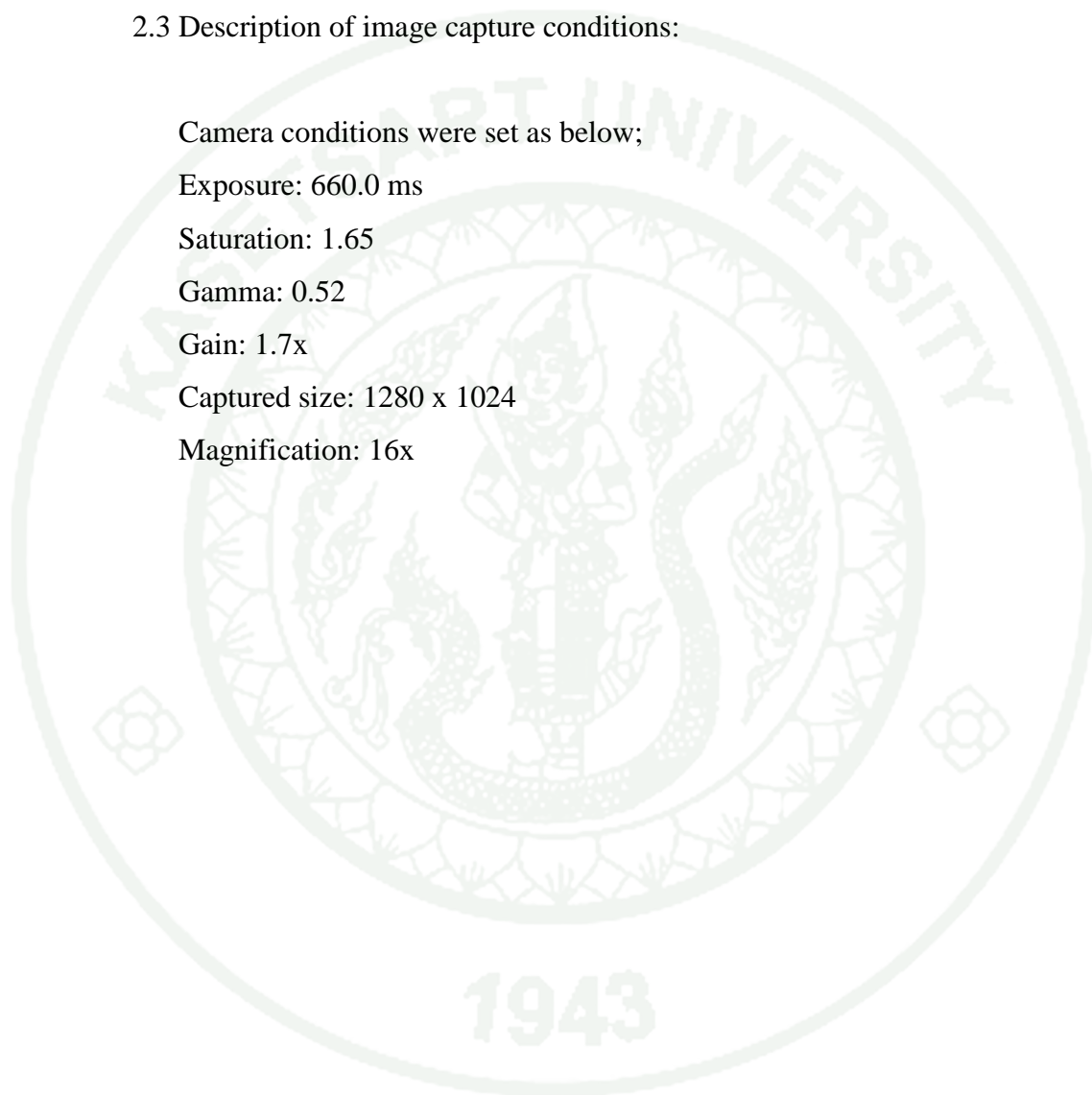
Saturation: 1.65

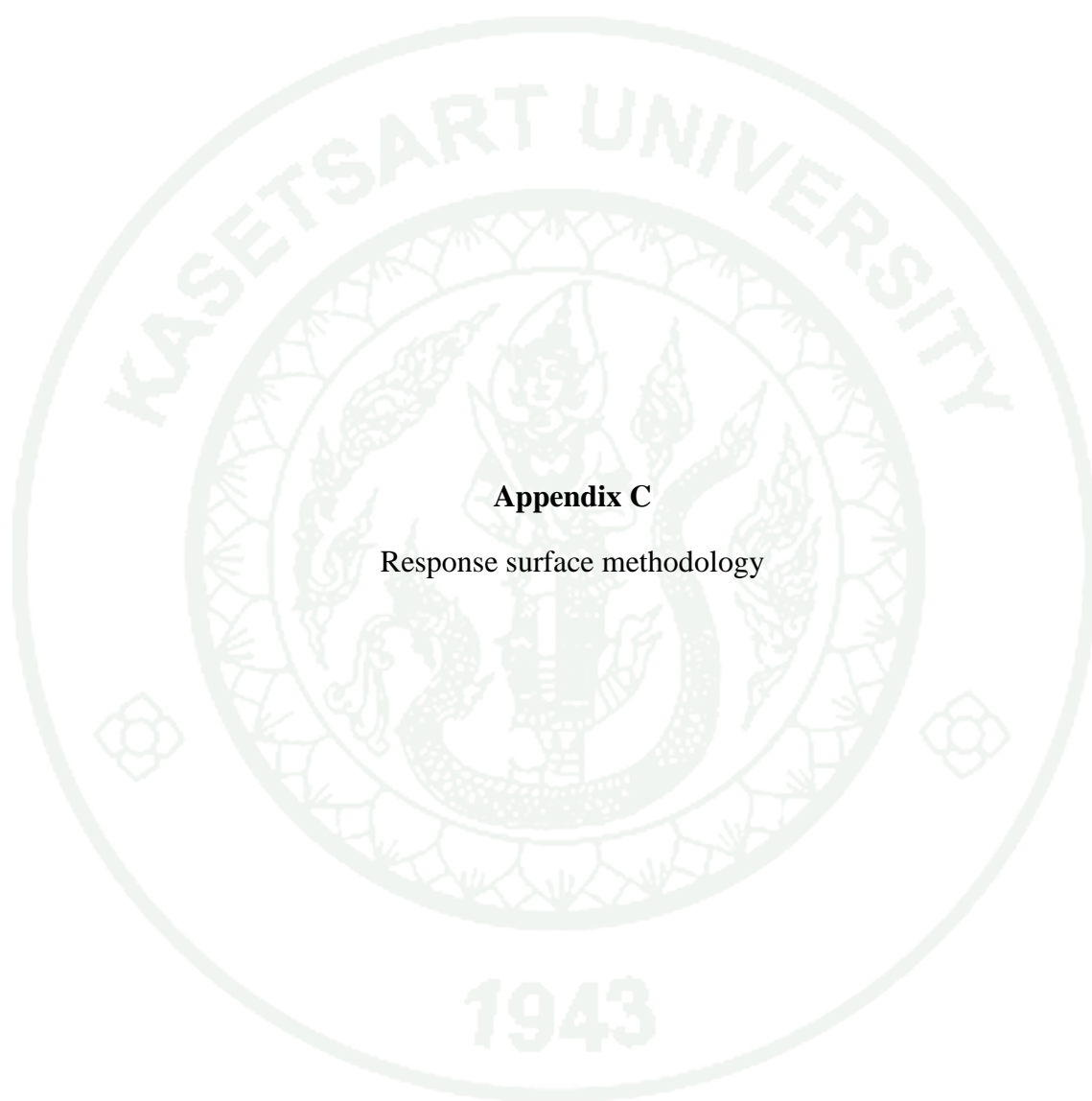
Gamma: 0.52

Gain: 1.7x

Captured size: 1280 x 1024

Magnification: 16x





Appendix C

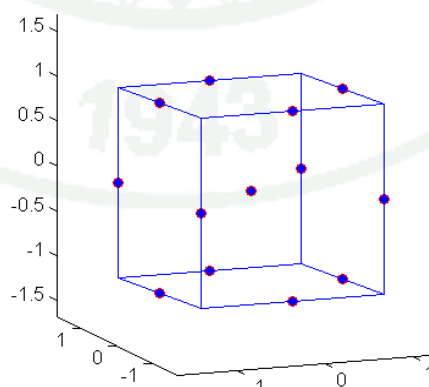
Response surface methodology

1. Response surface methodology

Methodologies that help the researchers reaching the goal of optimum response are referred to as Response Surface Methods. These methods are exclusively used to examine the "surface" or the relationship between the response and the factors affecting the response. Regression models that show the relationship between the response and the factors are used for the analysis of the response.

A type of design that presents a reasonable alternative to the central composites was developed by Box and Behnken. The Box-Behnken design is 3-level design including a subset of the runs in the full three level factorial design. For this type of design, the researchers could run only three levels of the factors and desire a design that is close to rotatable. Moreover, the usual justification for the Box-Behnken design is to avoid the situation where the corner points in the central composite design are very extreme, i.e. they are at the highest level of several factors, which are not desired by researchers due to product quality or can be out of supplying by the machines or instruments. In this case, the Box Behnken may look a lot more desirable since there are more points in the middle of the range and they are not as extreme (Appendix Figure 2) .

The geometry of a Box-Behnken design is illustrated in the following figure.

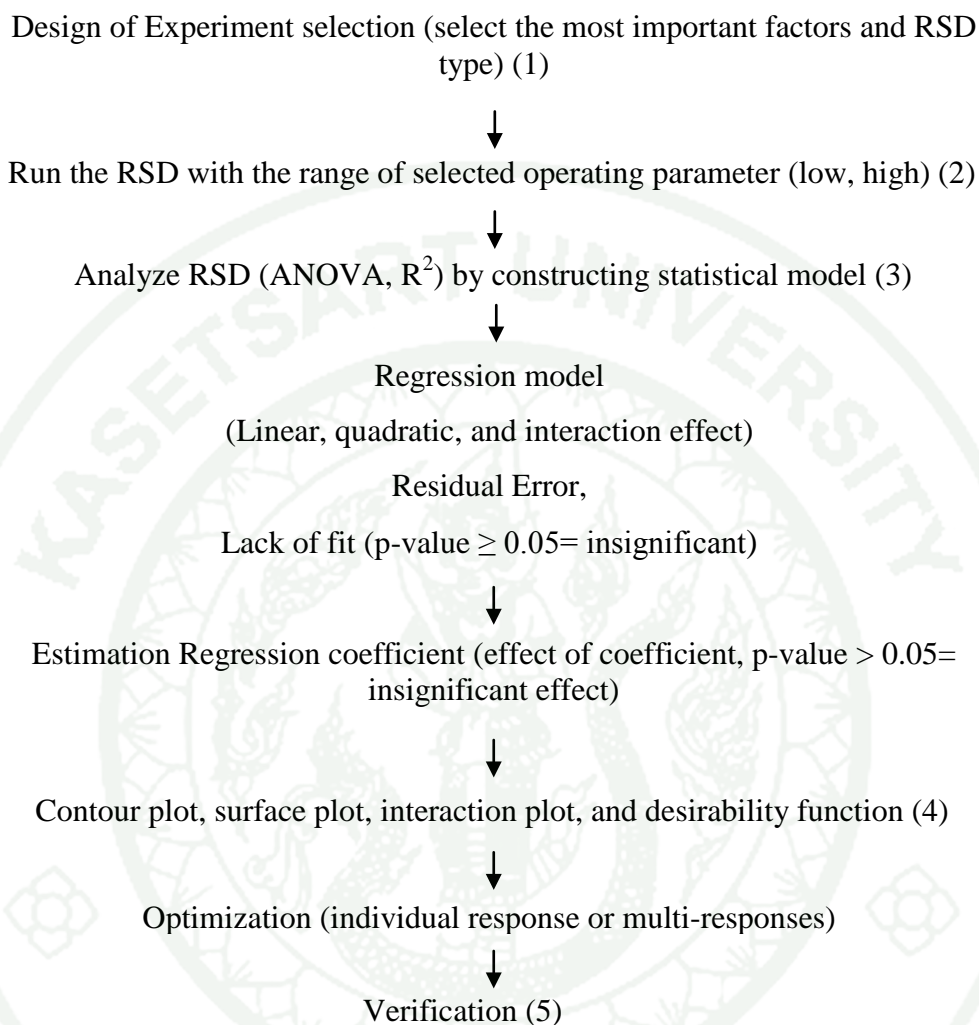


Appendix Figure C1 Design points are at the midpoints of edges of the design space and at the center.

The geometry of this design suggests a sphere within the process space such that the surface of the sphere protrudes through each face with the surface of the sphere tangential to the midpoint of each edge of the space. At this point, the Box-Behnken design is very useful in the same setting as the central composite design. Their primary advantage is in addressing the issue of where the experimental boundaries should be, and in particular to avoid treatment combinations that are extreme. By extreme, we are thinking of the corner points and the star points, which are extreme points in terms of region in which we are doing our experiment. The Box-Behnken design avoids all the corner points, and the star points. One way to think about this is that in the central composite design we have a ball where all of the corner points lie on the surface of the ball. In the Box-Behnken design the ball is now located inside the box defined by a 'wire frame' that is composed of the edges of the box. If you blew up a balloon inside this wire frame box so that it just barely extends beyond the sides of the box, it might look like this, in three dimensions. Notice where the balloon first touches the wire frame; this is where the points are selected to create the design. Therefore, the points are still on the surface of a ball, but the points are never further out than the low and high in any direction. In addition, there would be multiple center points as before. In this type of design you do not need as many center points (prefer to 3 center points) because points on the outside are closer to the middle. The number of center points are chosen so that the variance of is about the same in the middle of the design as it is on the outside of the design.

1943

Response surface methods usually involve the following steps:



Appendix Figure C2 Response surface methodology

Step 1: Selecting the appropriate experimental design of RSD including the regression model.

Concerning about the important factors and level of factors to select the appropriate RSD, this step includes

Step 1a: Defining the response variables

The step is to define the response variables that will be recorded each time that the experimental run is performed.

Step 1b: Defining the experimental factors

This step is to define the experiment factors including the levels of factors that will be varied during the experiment.

How to know the optimal ranges of the response?

Of course, the researchers need to refer to previous materials to scope down the operating range and then needs to conduct the experiments to move from the present operating conditions to the vicinity of the operating conditions where the response is optimum. This is done using the *method of steepest ascent* in the case of maximizing the response and the *method of steepest descent* in case of minimizing the response. This is checked to find whether it is better, the first, quadratic, or cubic model is fitted or not. (not applied in this study).

Once the vicinity of the operating conditions has been identified, the next step is to determine the setting ranges for these factors that the optimum response will be fell in those.

Step 1c: Defining the model to be fit to the data.

The statistical model upon which the analysis of response surface designs is based expresses the response variable Y as a linear function of the experimental factors, interactions between the factors, quadratic terms, and an error term. There are two types of models that are generally fit, illustrated below for 3 experimental factors:

First-order model – contains terms representing main effects only.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \quad (1)$$

Second-order model– contains terms representing main effects, second-order interactions, and quadratic effects.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \varepsilon \quad (2)$$

The experimental error ε is assumed to be randomly drawn from a normal distribution with a mean of 0 and a standard deviation equal to ε .

Note that for Response Surface Models in case of Box-Behnken design, quadratic types is simple model that provide an accurately estimated model parameters. However, with current Box-Behnken design, it is impossible to check the interaction between three factors because its design characteristic. The reduction in experimental runs leads to not sufficient data to check the third order model in terms of three factor interactions.

Step 2: Running experiment of RSM design

Appendix Table C1 Experimental runs (code values) of 3 factors for Box-Behnken design.

Run	X ₁	X ₂	X ₃
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

Each set of 4 consecutive runs is a 2-level experimental design involving a selected pair of factors. Roughly, 3-5 center-point at (0,0,0) should be added to the design. The repeated center point runs allow for a more uniform estimate of the prediction variance over the entire design space. The last three observations are the center points. The other points, you will note, all include one zero for one of the factors and then a plus or minus combination for the other two factors.

Step 3: Analyzing the results by constructing a statistical model for each response variable before optimizing for multi responses

The predictive models were obtained by multiple regression analysis. Each term in the models was checked its significance on the model prediction for each response. The p-value above a critical value associated with testing the null hypothesis that the coefficient for a selected effect equals 0, implying that the effect is not present. The p-values below a critical level (such as 0.05 if operating at the 5% significance level) indicate that the corresponding effect is statistically significant at that significance level. These parameters were used to interpret the main factor effects or the interaction between factors.

To check the adequacy of model, coefficient of determination and lack of fit test are applied.

The lack of fit test was designed to determine whether the selected model is adequate to describe the observed data, or whether a more complicated model should be used. The test is performed by comparing the variability of the current model residuals to the variability between observations at replicate settings of the factors. A statistically significant lack-of-fit F -statistic implies that the terms in the model do not account for all of the assignable cause variation in the response variable. Because the pure error mean square, $MSEP$, measures the variation associated with replicate observations, a large F -ratio indicates that the $MSLOF$ is a measure of the variation that exceeds the variation due to pure (replication) error. When a large F -ratio occurs, alternative model specifications should be considered. The p-value for lack-of-fit in the ANOVA table is greater or equal to 0.05, which means that the model appears to be adequate for the observed data at the 95.0% confidence level. Therefore, the statistical model of quadratic type with 10 coefficients for each of response was analyzed respectively. Briefly, the terms in the model with p-values below 0.05 indicate that their effect on the model is significant at the 5.0% significance level. The high value of R-squared statistic shows the smaller of variation percentage in the response explaining the better of fitted model.

Step 4 Finding the setting of the experimental factors for optimizing the responses.

It is possible that in some cases, a number of responses have to be optimized at the same time. For example, a researcher may want to maximize the rehydration ratio, while keeping the hardness to be minimum. The optimum settings for each of the responses in such case may lead to conflicting settings for the factors. A balanced setting has to be determined in order to give the most appropriate values for all the responses. Overlay counter plot for multi-responses and desirability functions are useful in these cases (Derringer and Suich, 1980).

Once models have been constructed for each response, each response is optimized separately. Normally traditional graphical method, response surface, or contour plot are applied to see the optimal points. Once each response has been optimized separately, the multi responses are progressed by desirability function or overlay plot.

Overlaid contour plots are one of the traditional methods way to analyze and find the desired operating condition. This method is mainly useful when we have two or three controllable factors but in higher dimensions it loses its efficiency. This method simply consists of overlaying contour plot for each of the response, one over another in the controllable factors space and finding the area, which makes the best possible value for each of the response.

Another important procedure is the desirability function approach (Derringer and Suich, 1980). In this approach, the value of each response for a given combination of controllable factors is first translated to a number between 0 and 1 known as individual desirability.

Individual desirability functions are different for different objective types which might be maximization, minimization or target. If the objective type is maximum value, the desirability function is defined as

$$d_i(\hat{Y}_i) = \begin{cases} 0 & \text{if } \hat{Y}_i(x) < L_i \\ \left(\frac{\hat{Y}_i(x) - L_i}{T_i - L_i}\right)^s & \text{if } L_i < \hat{Y}_i(x) < T_i \\ 1 & \text{if } \hat{Y}_i(x) > T_i \end{cases} \quad (3)$$

When the objective type is a minimum value the, the individual desirability is defines as

$$d_i(\hat{Y}_i) = \begin{cases} 1 & \text{if } \hat{Y}_i(x) < T_i \\ \left(\frac{\hat{Y}_i(x) - U_i}{T_i - U_i}\right)^s & \text{if } T_i < \hat{Y}_i(x) < U_i \\ 0 & \text{if } \hat{Y}_i(x) > U_i \end{cases} \quad (4)$$

Finally the two-sided desirability function with target-the-best objective type is defined as

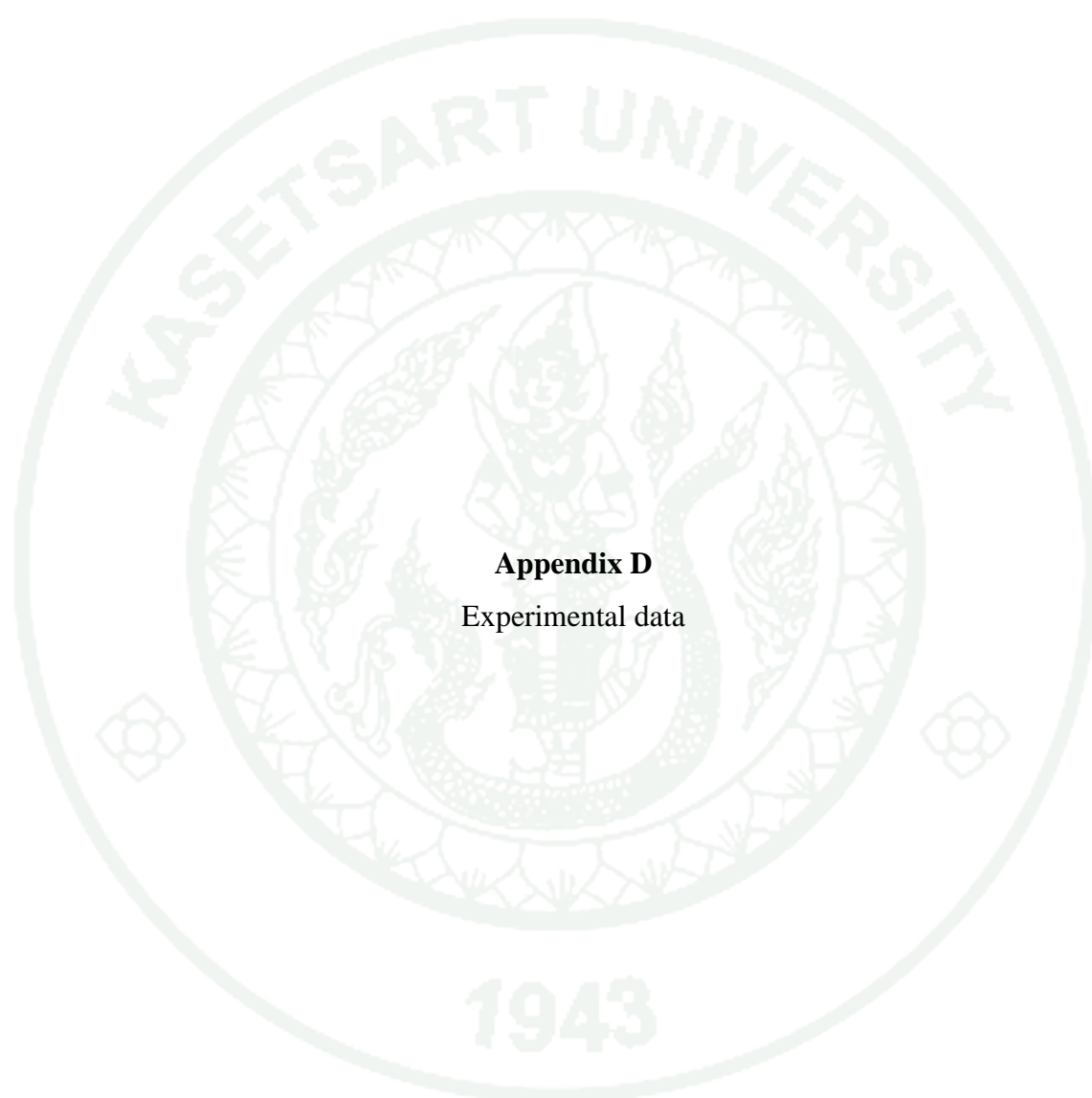
$$d_i(\hat{Y}_i) = \begin{cases} 0 & \text{if } \hat{Y}_i(x) < L_i \\ \left(\frac{\hat{Y}_i(x) - L_i}{T_i - L_i}\right)^s & \text{if } L_i < \hat{Y}_i(x) < T_i \\ \left(\frac{\hat{Y}_i(x) - U_i}{T_i - U_i}\right)^t & \text{if } T_i < \hat{Y}_i(x) < U_i \\ 0 & \text{if } \hat{Y}_i(x) > U_i \end{cases} \quad (5)$$

Where $\hat{Y}_i(x)$ = predicted value of the response for a particular combination of the experimental factors x .

L_i , U_i and T_i = the lower, upper, and target values, respectively, that are desired for response Y_i , with $L_i \leq T_i \leq U_i$. The s and t define the shape of the individual desirability function. The exponents s and t determining how important it is to hit the target value. For $s = t = 1$, the desirability function increases linearly towards T_i ; for $s < 1$, $t < 1$, the function is convex, and for $s > 1$, $t > 1$, the function is concave. Individual desirability is then used to calculate the overall desirability using the following formula:

$$D = \{d_1(\hat{Y}_1) \times d_2(\hat{Y}_2) \times d_3(\hat{Y}_3) \times d_4(\hat{Y}_4) \times \dots \times d_k(\hat{Y}_k)\}^{1/k} \quad (6)$$

where k is the number of responses.



Appendix D
Experimental data

Appendix Table D1 Results of the fitting experimental data into various thin-layer drying models for single-stage drying in HAO at 50, 70 and 90°C.

Model No	Model name	Drying conditions	Coefficients and constants				R ²	RMSE (% d.b)	PE (%)	
1	Page	50°C	K(min ⁻¹)	N			0.9946	4.20	10.86	
		70°C	0.000961	1.329127			0.9983	2.62	13.78	
		90°C	0.002388	1.267382			0.9996	1.29	5.01	
2	Hii et al.	50°C	B	K ₁ (min ⁻¹)	N	C	K ₂ (min ⁻¹)	0.9988	1.97	2.43
		70°C	1.02985	0.001025	1.280071	-0.05123	-0.00029	0.9983	2.57	8.91
		90°C	0.383893	0.002216	1.281863	0.608458	0.002197	0.9996	1.20	4.97
3	Midilli- Kucuk	50°C	A	K(min ⁻¹)	N	B		0.8282	23.61	17.28
		70°C	1.158007	0.592023	2.36461E-05	-0.00156		0.9986	2.33	10.64
		90°C	0.998392	0.002962	1.214556	-6.2E-05		0.9996	1.64	4.24
4	Hadenson and Papis	50°C	A	K(min ⁻¹)				0.9742	9.16	24.70
		70°C	1.066393	0.005816				0.9879	6.94	34.53
		90°C	1.052686	0.009314				0.9936	5.08	27.59

Appendix Table D1 (Continued)

Model No	Model name	Drying conditions	Coefficients and constants					R ²	RMSE (%d.b)	PE (%)
5	Verma	50°C	A	K ₁	K ₂			0.9851	2.20	6.51
		70°C	1.894016	0.002425	0.000242			0.9979	2.89	10.38
		90°C	4.908007	0.003512	0.002011			0.9990	2.02	12.60
3.723867	0.006498	0.003118								
6	Modified Page	50-90°C	K(min ⁻¹)	N	A			0.9962	3.77	9.96
			99.74483	1.298209	3686.118176					
7	Modified two compartment	50-90°C	A ₁	K1(min ⁻¹)	B	A ₂	K ₂ (min ⁻¹)	0.9927	5.79	18.80
			-6.57314	14.84308	2758.544097	7.60076	16.2547			

Appendix Table D2 Results of the fitting experimental data into various thin layer models for single-stage drying in MWO at power level of 425 W, 595 W and 850 W.

Model No	Model name	Power (W)	Coefficients and constants				R ²	RMSE (%d.b)	PE (%)
1	Page	425	K (min ⁻¹)	N			0.9963	3.37	5.16
		595	0.120849	1.063144			0.9938	4.57	11.09
		850	0.121354	1.083422			0.9958	3.67	11.23
			0.17481	1.050047					

Appendix Table D2 (Continued)

Model No	Model name	Power (W)						R ²	RMSE (%d.b)	PE (%)
2	Hii <i>et al.</i>		B	K ₁ (min ⁻¹)	N	C	K ₂ (min ⁻¹)			
		425	0.500444	0.121303	1.06182	0.500444	0.121303	0.9963	3.37	5.18
		595	0.487882	0.108019	1.126835	0.487882	0.108019	0.9942	4.37	10.10
		850	0.500642	0.175616	1.048245	0.500642	0.175616	0.9958	3.67	11.28
3	Midilli- Kucuk		A	K	N	B				
		425	1.005231	0.127818	1.023663	-0.00102		0.9964	3.30	4.82
		595	1.007583	0.184465	0.844268	-0.005686078		0.9960	6.50	6.60
		850	1.007571	0.188531	0.975008	-0.002859213		0.9965	3.37	6.07
4	Hadenson and Papis		A	K(min ⁻¹)						
		425	1.02023	0.140996				0.9956	3.66	7.77
		595	1.011611	0.145645				0.9918	5.21	15.23
		850	1.014743	0.194189			0.9954	3.86	13.53	
5	Verma		A	K ₁ (min ⁻¹)	K ₂ (min ⁻¹)					
		425	1.122271	0.118941	0.00291			0.9963	3.34	4.75
		595	0.711153	0.176254	-0.02119			0.9975	2.88	4.04
		850	0.84949	0.211876	-0.0119			0.9966	3.31	4.78
6	Modified Page	425-850	K(min ⁻¹)	N	A					
			0.091901	1.031085	-285.109			0.9939	5.19	10.11
7	Modified two compartment	425-850	A ₁	K ₁ (min ⁻¹)	B	A ₂	K ₂ (min ⁻¹)			
			0.503708	0.100005	-276.792	0.504854589	0.256861952	0.9937	5.40	11.23

Appendix Table D3 Results of the fitting experimental data into various thin-layer drying models for the second-stage drying in HAO at 50, 70 and 90°C.

Model No	Model name	T (°C)	Coefficients and constants				R ²	RMSE (%db)	PE (%)	
1	Page		K(min ⁻¹)	N			0.9941	0.46	3.07	
		50	0.025184	0.823145						
		70	0.095387	0.595405						
		90	0.093599	0.636354			0.9932	0.71	10.01	
2	Hii <i>et al.</i>		B	K ₁ (min ⁻¹)	N	C	K ₂ (min ⁻¹)	0.9989	0.20	1.14
		50	-1.22756	4.673814	0.44988	2.227563	0.250054			
		70	0.501318	0.096083	0.594244	0.501318	0.096083			
		90	0.212478	0.001185	1.255087	0.787675	0.0143	0.9999	0.07	1.01
3	Midilli-Kucuk		A	K	N	B	0.9968	0.34	2.33	
		50	1.004027	0.015878	0.948204	0.000251				
		70	1.001748	0.071286	0.67604	0.000157				
		90	1.001216	0.047411	0.825199	0.000296	0.9979	0.40	5.54	
4	Hadenson and Papis		A	K(min ⁻¹)		0.9848	0.73	6.08		
		50	0.969752	0.010668						
		70	0.935286	0.01497						
		90	0.968835	0.020069		0.9662	1.59	28.96		
5	Verma		A	K ₁ (min ⁻¹)	K ₂ (min ⁻¹)	0.9976	0.29	1.73		
		50	0.822711	0.015983	-0.00038					
		70	0.755546	0.033024	-0.00077					
		90	0.857418	0.031327	-0.000333	0.9994	0.21	2.08		

Appendix Table D3 (Continued)

Model No	Model name	T (°C)	Coefficients and constants				R ²	RMSE (%db)	PE (%)	
6	Modified Page	50-90	K(min ⁻¹) 3.171278	N 0.696276	A 1366.997		0.9893	0.71	7.53	
7	Modified two compartment	50-90	A ₁ 0.211065	K ₁ (min ⁻¹) 1.592722	B 2104.71	A ₂ 0.792292	K ₂ (min ⁻¹) 11.93713	0.9957	0.44	3.31

Appendix Table D4 Results of the fitting experimental data into various thin-layer drying models for second-stage drying in FDB at 160, 180 and 200°C.

Model No	Model name	T(°C)	Coefficients and constants				R ²	RMSE (%d.b)	PE (%)	
1	Page	160	K(min ⁻¹) 0.169324	N 0.535432			0.9752	1.06	10.05	
		180	0.17526	0.543789			0.9836	0.94	9.39	
		200	0.251266	0.45234			0.9928	0.55	3.09	
2	Hii <i>et al.</i>	160	B 0.674047	K ₁ (min ⁻¹) 0.108213	N 0.965092	C 0.324404	K ₂ (min ⁻¹) 0.006525	0.9991	0.21	1.59
		180	0.510002	0.185903	0.532255	0.510002	0.185903	0.9842	0.92	9.32
		200	0.503704	0.256086	0.448724	0.503704	0.256086	0.9929	0.55	4.66
3	Midilli- Kucuk	160	A 1.010818	K 0.124034541	N 0.691705	B 0.00132		0.9935	0.54	5.45
		180	1.010331	0.139200911	0.662213	0.00102		0.9949	0.53	4.96
		200	1.002767	0.213428	0.54173	0.0011		0.9981	0.29	2.42

Appendix Table D4 (Continued)

Model No	Model name	T(°C)	Coefficients and constants					R ²	RMSE (%d.b)	PE (%)
4	Hadenson and Papis	160	A	K(min ⁻¹)			0.8661	2.47	26.41	
		180	0.865387	0.033327		0.8864	2.48	27.76		
		200	0.869113	0.036994		0.8210	2.76	22.64		
5	Verma	160	A	K ₁ (min ⁻¹)	K ₂ (min ⁻¹)		0.9988	0.24	2.19	
		180	0.69617	0.098265	-0.00153		0.9990	0.24	2.47	
		200	0.692811	0.106861	-0.00191		0.9927	0.56	4.97	
6	Modified Page	160-200	K(min ⁻¹)	N	A		0.9809	0.95	8.37	
			1.065349	0.513261947	770.1526					
7	Modified two compartment	160-200	A ₁	K ₁ (min ⁻¹)	B	A ₂	K ₂ (min ⁻¹)	0.9956	0.46	3.30
			0.615725	3.883211216	1538.892	0.37673	0.2499			

Appendix Table D5 Results of the fitting experimental data into various thin layer models for second-stage drying in MWO at power level of 425 W, 595 W and 850 W.

Model No	Model name	Power (W)	Coefficients and constants				R ²	RMSE (%d.b)	PE (%)
1	Page		K (min ⁻¹)	N					
		425	0.223368	0.870361		0.9955	0.61	5.02	
		595	0.225722	0.956968		0.9950	0.64	3.08	
		850	0.273074	1.080038		0.9992	0.40	3.52	

Appendix Table D5 (Continued)

Model No	Model name	Power (W)	Coefficients and constants					R ²	RMSE (%d.b)	PE (%)
2	Hii <i>et al.</i>		B	K ₁ (min ⁻¹)	N	C	K ₂ (min ⁻¹)			
		425	0.498932	0.221575	0.873844	0.498932	0.221575	0.9951	0.61	5.03
		595	0.497492	0.221186	0.967341	0.497492	0.221186	0.9942	0.67	3.12
		850	0.5002	0.273419	1.079357	0.5002	0.273419	0.9992	0.40	3.51
3	Midilli- Kucuk		A	K	N	B				
		425	1.001341	0.211833	0.6906	-0.0232		0.9970	0.52	4.10
		595	1.000031	0.144176	0.379386	-0.08747		0.9991	0.53	2.52
		850	0.999162	0.276058	1.131582	0.007035		0.9994	0.38	3.20
4	Hadenson and Papis		A	K(min ⁻¹)						
		425	0.974024	0.17801				0.9915	0.63	4.12
		595	0.990566	0.211234				0.9948	0.68	2.90
		850	1.011086	0.302239				0.9980	0.55	3.46
5	Verma		A	K ₁ (min ⁻¹)	K ₂ (min ⁻¹)					
		425	0.363013	0.641314	-0.09967			0.9986	0.48	3.63
		595	0.285213	0.861965	-0.17301			0.9990	0.53	2.61
		850	12.41538	0.122043	0.099963			0.9991	0.44	3.60
6	Modified Page	425-850	K(min ⁻¹)	N	A					
			0.4673	0.9594	383.4811			0.9884	0.75	4.36
7	Modified two compartment	425-850	A ₁	K ₁ (min ⁻¹)	B	A ₂	K ₂ (min ⁻¹)	0.9882	0.75	4.47
				0.4957	0.4465	392.3206	0.4957			

Appendix Table D6 Results of fitting the experimental data into various models for predicting the moisture diffusivity as a function of moisture content.

Drying methods	Drying condition	a ($\times 10^{-10}$)	P-value	b ($\times 10^{-10}$)	P-value	c ($\times 10^{-10}$)	P-value	d ($\times 10^{-10}$)	P-value	R ²	RMSE ($\times 10^{-10}$ m ² /s)	PE (%)
Single stage drying in HAO	50°C	4.938983	0.0761	2308.712	0.0000	-32360.5	0.0043	306909.5	0.0008	0.9970	2.18	6.15
	70°C	27.34996	0.0001	1674.805	0.0005	-17928.2	0.0058	59819.68	0.0169	0.9123	4.70	7.78
	90°C	65.23964	0.0004	1519.447	0.0099	-9952.0697	0.0344	19123.29	0.0604	0.8972	8.40	6.79
Single stage drying in MWO	425 W	577.4758	0.0000	6827.409	0.0000	-54253.07	0.0000	232827.2	0.0000	0.9998	1.25	0.14
	595 W	511.5404	0.0000	14047.82	0.0000	8461.861	0.2379	-56526	0.2903	0.9999	2.04	0.11
	850 W	892.8114	0.0000	1090.254	0.4095	134931.77	0.0006	-628792	0.0029	0.9972	13.81	1.00
Second stage drying in HAO	50°C	-70.2694	0.2207	6228.977	0.0314	-85305.6	0.0283	334486.3	0.0356	0.9365	4.23	5.98
	70°C	195.805	0.0185	-892.812	0.6683	-5269.44	0.7880	26549.94	0.6375	0.9365	11.80	16.72
	90°C	139.6282	0.0062	1119.257	0.2164	-14470.3	0.0425	31919.34	0.0282	0.9640	10.87	22.0

Appendix Table D6 (Continued)

Drying methods	Drying condition	a ($\times 10^{-10}$)	P-value	b ($\times 10^{-10}$)	P-value	c ($\times 10^{-10}$)	P-value	d ($\times 10^{-10}$)	P-value	R ²	RMSE ($\times 10^{-10}$ m ² /s)	PE (%)
Second stage drying in FDB	160°C	530.3257	0.0000	-5367.21	0.0004	15077.23	0.1021	-4894.35	0.8230	0.9942	8.55	5.81
	180°C	595.52	0.0000	-7098.98	0.0000	28661.44	0.0040	-36566.7	0.0565	0.9903	11.63	6.75
	200°C	1804.883	0.0014	-36101.2	0.0089	234799.8	0.0262	-478220	0.0511	0.8330	100.8	39.31
Second stage drying in MWO	425 W	1029.309	0.2528	-11767.5	0.7469	-4074.1	0.9933	635466.09	0.7533	0.7716	38.45	3.62
	595 W	2765.456	0.2506	-101085	0.3612	1436366	0.3953	-6287253.5	0.4352	0.5876	76.20	10.84
	850 W	1407.268	0.0648	-33553.3	0.1551	518473.4	0.0987	-2162174	0.0742	0.9398	67.80	13.00

P-value < 0.05 is significant at $\alpha = 0.05$.

Appendix Table D7 Results of fitting the experimental data for empirical model of instant brown rice drying.

Drying methods	Drying conditions	a ₀	P-value	a ₁	P-value	a ₂	P-value	a ₃	P-value	R ²	RMSE	PE (%)
Single stage drying in HAO	50°C	0.8581	0.0000	-0.0023	0.0000	-29.7414	0.2135	117.6357	0.5832	0.9455	0.0247	3.64
	70°C	0.8929	0.0000	-0.0030	0.0000	-27.7831	0.0021	109.3149	0.0118	0.9489	0.0264	3.08
	90°C	0.7599	0.0000	-0.0021	0.0002	-9.34078	0.0346	27.5961	0.0784	0.9519	0.0222	1.82
Single stage drying in MWO	425W	0.8020	0.0000	-0.0022	0.0000	29.4072	0.2588	108.6180	0.7534	0.9790	0.0164	2.47
	595W	0.7402	0.0000	-0.0020	0.0000	25.3288	0.1113	-295.9094	0.0298	0.9779	0.0166	2.08
	850W	0.7205	0.0000	-0.0018	0.0000	14.7326	0.6263	-282.1495	0.4786	0.9803	0.0000	2.26
Second stage drying in HAO	50°C	0.4143	0.0000	0.0250	0.0052	-0.0006	0.0150			0.8520	0.0148	1.83
	70°C	0.4842	0.0000	0.0221	0.0001	-0.0006	0.0003			0.9345	0.0091	1.10
	90°C	0.6029	0.0000	0.0061	0.0410	-0.0001	0.1445			0.8627	0.0086	1.19

Appendix Table D7 (Continued)

Drying methods	Drying conditions	a ₀	P-value	a ₁	P-value	a ₂	P-value	a ₃	P-value	R ²	RMSE	PE (%)
Second stage drying in FDB	160°C	0.4893	0.0000	0.0138	0.0005	-0.0003	0.0126			0.9271	0.0115	1.36
	180°C	0.4522	0.0000	0.0176	0.0001	-0.0004	0.0010			0.9309	0.0127	1.63
	200°C	0.4365	0.0000	0.0215	0.0002	-0.0005	0.0014			0.9345	0.0132	1.60
Second stage drying in MWO	425W	0.4393	0.0001	0.0223	0.0038	-0.0004	0.0135			0.9409	0.0112	1.46
	595W	0.382137	0.0029	0.024698	0.0139	-0.0004	0.0347			0.9740	0.0083	1.01
	850W	0.498997	0.0000	0.017712	0.0008	-0.0003	0.0024			0.9953	0.0032	0.39

P-value < 0.05 is significant at $\alpha = 0.05$.

Appendix Table D8 Controlled values and optimization goals for texture and physical properties of instant brown rice

Name	Units	Analyze	Goal	Target	Impact	Sensitivity	Low	High
Ratio of rehydration	%	Mean	Maximize		3.0	Medium	122.0	146.0
Lightness		Mean	Maximize		3.0	Medium	60.0	62.0
color intensity		Mean	Minimize		3.0	Medium	198.0	220.0
Hardness	N	Mean	Minimize		3.0	Medium	91.0	110.0
Stickiness	N	Mean	Hit target	14.0	3.0	Medium	9.0	18.0

Remark: Controlled sample was freshly cooked brown rice.

The low and high value is of freshly cooked brown rice.

Appendix Table D9 Texture and physical properties of optimal operating process conditions and freshly cooked brown rice

Factor	Setting values		Rehydration ratio (%)	Lightness	Color intensity	Hardness(N)	Stickiness(N)
	Low	High					
Ratio of water to rice	1.3	1.7	1.69997	1.68399	1.7	1.55228	1.3
Microwave power levels	255.0	595.0	595.0	593.727	591.182	595.0	594.341
Hot air temperature	50.0	90.0	50.0	89.998	90.0	75.5395	89.9214
Optimum value for response			148.303	64.8816	187.336	83.9807	11.2924
Freshly cooked brown rice			122-146*	60-62	198-220	91-110	9-18

*These values were obtained for the sample that has the moisture content closer to that of freshly cooked brown rice.

Appendix Table D10 Correlation coefficients between textural and physical properties of instant brown rice.

	Bulk density	Dried color intensity	Hardness	Dried Lightness	Ratio of rehydration	Stickiness
Bulk density		0.3079 (51)	0.4140 (51)	-0.3815 (51)	-0.5103 (51)	-0.2527 (51)
color intensity	0.3079 (51)		0.0025 (51)	0.0057 (51)	0.0001 (51)	0.0737 (51)
Hardness	0.0280 (51)	0.0280 (51)		0.2161 (51)	0.1048 (51)	0.0283 (51)
Lightness	0.4140 (51)	0.0845 (51)	0.5554 (51)		-0.1605 (51)	-0.3072 (51)
Ratio of rehydration	0.0025 (51)	0.5554 (51)	0.2607 (51)	0.2607 (51)		0.0283 (51)
Stickiness	-0.3815 (51)	-0.1762 (51)	-0.1605 (51)	0.3777 (51)	0.3777 (51)	0.3806 (51)
	0.0057 (51)	0.2161 (51)	0.2607 (51)	0.0063 (51)	0.0063 (51)	0.0059 (51)
	-0.5103 (51)	-0.2298 (51)	-0.3072 (51)	0.3777 (51)	0.3777 (51)	0.0704 (51)
	0.0001 (51)	0.1048 (51)	0.0283 (51)	0.0063 (51)	0.0063 (51)	0.6233 (51)
	-0.2527 (51)	-0.3072 (51)	-0.0161 (51)	0.3806 (51)	0.0704 (51)	0.0704 (51)
	0.0737 (51)	0.0283 (51)	0.9110 (51)	0.0059 (51)	0.6233 (51)	0.6233 (51)

Remark: Pearson correlations

P-value < 0.05 and 0.01 is significant at $\alpha = 0.05$ and 0.01 respectively.

The number in the 1st row is correlation coefficients.

The number in the parentheses of the 2nd row is pairs of data values used to compute each coefficient.

The number in the 3rd row is p value.

CURRICULUM VITAE

NAME : Mr. Tuan Quoc Le
BIRTH DATE : September 15, 1986
BIRTH PLACE : Soc Trang, Viet Nam

EDUCATION	: <u>YEAR</u>	<u>INSTITUTE</u>	<u>DEGREE/DIPLOMA</u>
	2009	Can Tho University	B.Sc (Food Technology)

WORK : 2009 Vuon Trai Cuu Long foreign private company
POSITION/TITLE : Supervisor of coffee production

SCHOLARSHIP : Department of Food science and Technology, Kasetsart University; Research Fund by Center of Advanced Studies for Agriculture and Food, Institute for Advanced Studies, Kasetsart University.

PRESENTATION : Oral presentation “Drying kinetics of cooked jasmine brown rice during various drying methods” at the 22nd graduation conference, November 7-9, 2011, Kasetsart University, Bangkok, Thailand.