ANNUAL REPORT
COMPREHENSIVE RESEARCH ON RICE
January 1, 2014– December 31, 2014

PROJECT TITLE:
Development of Infrared Rotary-Drum Dryer for Rough Rice

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LEVEL OF 2014 FUNDING: $ 35,000

OBJECTIVES AND EXPERIMENTS CONDUCTED, BY LOCATION, TO ACCOMPLISH OBJECTIVES:

Objectives:

Infrared (IR) drying as a novel technology has a promising potential to improve the drying efficiency and milling quality, achieve effective disinfestation and disinfection of rough rice, and effective stabilization for rice bran without affecting the quality of rice bran oil. We have systematically investigated and proved the technical feasibility of using IR heating as energy efficient technology for rice drying. Also, IR heating can be used as an effective method to improve the storage stability of rice. For commercial application, however, the IR drying technology should have a drier design which is simple and easy to operate, and can achieve thin layer drying effect with uniform heating and high energy efficiency while reducing the dryer footprint. Therefore, the objective of this research project is to design and test infrared rotary-drum dryer and optimize its operating parameters to achieve an efficient drying for rough rice. To achieve the objective, the following specific objectives have been chosen:

1. Design and develop a prototype IR rotary-dryer consisting of IR emitters and features for controlling and monitoring the drying process.

2. Optimize the operating parameters of IR rotary-dryer.

3. Evaluate the milling quality of rough rice under optimized operating parameters and provide recommendations for optimal design of the IR rotary-dryer for scale up.

Experimental Procedures

<u>Design and develop a prototype IR-rotary dryer consisting of IR emitters and features for controlling and monitoring the drying process</u>

A lab scale of IR-rotary drum dryer developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis was modified for conducting this research project. The dryer was facilitated with devices to achieve high and uniform heating and efficient mixing for rough rice. Also, the dryer was equipped with the tools to control the power of IR emitters, rotating speed and rice sample loading and unloading.

Samples and drying test

Freshly harvested medium grain rice, M206, obtained from Farmers' Rice Cooperative (West Sacramento, CA) was used for conducting this research. The initial moisture content (MC) (wet basis) of rough rice sample was 19.13±0.21% (w.b.) at harvest. The MC was determined by the air oven method (130°C for 24 h) (ASAE, 1995). The rice samples were heated using IR rotary-drum dryer under different resident times, emitter powers, masses and rotating speeds. The time to heat the rough rice to 60°C, moisture removal during IR heating and tempering were determined. The temperature of heated rice was determined using a Thermometer (Fluke, 568), with an accuracy of ±1 °C. The weight loss during heating and the initial MC was used to calculate the moisture removal during the heating period. The moisture removal was calculated as the difference between the initial MC and the MC after treatment and reported as percentage points. The heated samples were held for 4 hours as tempering treatment. After the tempering treatment, the samples were cooled using natural cooling at room temperature (24±1 °C) and then dried with ambient air (24±1 °C, speed of 0.1 m/s and relative humidity of 43±3%) to final moisture content of 13.5% ± 0.3. Three replicates were conducted for each condition.

Optimize operating parameters of IR rotary-drum dryer

A single factor drying experiments were designed to investigate effects of operating parameters (emitter power, sample mass, rotating speed) of IR dryer on the drying performance. The factorial experiment was used to evaluate the relationship between resident time and rice temperature under different levels of emitter power, sample mass, rotating speed. The rice samples were dried at power levels of 1440, 1620, 1800, 1980 and 2160 W, sample mass of 200, 400, 600 and 800 g and rotating speeds of 5, 7.5, 10, 12.5 and 15 rpm. The limits of the emitter power, sample mass, and rotating speed were determined based on the preliminary tests. The effect of power level on rice temperature was tested under sample mass of 400 g and rotating speed of 10 rpm. While, the effect of sample mass on rice temperature was tested under power level of 1800 W and rotating speed of 10 rpm. Finally, the effect of rotating speed on rice temperature was tested under power level of 1800 W and sample mass of 400g. After determining the operating parameter limits, the response surface methodology (Table 1) was applied to optimize the operating parameters of the IR dryer to achieve high heating rate, high moisture removal, good milling quality and low energy consumption.

Table 1. Levels of variables for experimental design of response surface methodology.

Variable	Name	Levels		
		-1	0	1
RT	Resident time (s)	45	60	75
P	Power (W)	1620	1800	1980
SM	Sample mass (g)	300	450	600
RS	Rotating speed (rpm)	7	10	13

Evaluate the milling quality of rough rice and energy efficiency under optimized operating parameters of the IR rotary-dryer

The milling quality of rough rice was evaluated under optimized operating conditions of IR rotary-dryer. The rice samples were heated to 60 °C. Then the heated rice samples were quickly collected into sealed containers that preheated to 60 °C and placed in an incubator set at temperature of 60 °C for 4 h as tempering treatment. After the tempering treatment, the samples were cooled using natural cooling at room temperature of 24±1 °C. After natural cooling the samples were dried with ambient air (24±1 °C, speed of 0.1 m/s and relative humidity of 43±3%)

to final moisture content of 13.5% ± 0.3. Then, 400 g of the dried rice samples were dehulled using Yamamoto rice husker (Model: FC-2K, Yamamoto, Japan) and milled into white rice (Model: VP-222N, Yamamoto, Japan). Three rounds of rice milling were conducted to obtain the well-milled white rice as defined by the Federal Grain Inspection Service (FGIS, 1982). The throughput and whitening levels were set at 1 and 4 in the first two milling passes while 1 and 5 in the last pass. TRY was calculated as the percentage of milled (white) rice weight divided by the total weight of rough rice. HRY was determined with Graincheck (Foss North America, Eden Prairie, MN) as the percentage of whole milled rice kernels weight divided by the total weight of rough rice. The WI was measured with a whiteness tester (C-300, Kett Electronic Laboratory, Tokyo, Japan). Three replicates were performed for each condition. The control samples were prepared by using ambient air drying (AAD) method. The samples were dried from their initial moisture content of 19.13±0.21 to 13.5% ± 0.2 using air at temperature of 24±1 °C, speed of 0.1 m/s and relative humidity of 43±3%. The specific energy consumption (SEC) in MJ/kg H_2O was calculated following this equation:
SEC=(power (W)*heating time(s))/(sample weight(g)*dry matter content(%)* moisture removal(%)*1000)

Major Accomplishments:

<u>Design and develop a prototype IR rotary-dryer consisting of IR emitters and the features for controlling and monitoring the drying process</u>

The dryer was made from stainless steel with 15.7 inch in diameter and 24.4 inch in length (Figs. 1 and 2). The interior surface of the drum was coated with Teflon materials to improve the heating efficiency and uniformity. The dryer was facilitated with two IR emitters (Infrared Salamander, 292 x 92 x 19 mm size, 230V, 1800 W) mounted lengthwise inside the drum with heating surface focused downward with angle of 20 degrees. One arc-shape stainless steel shield with length of 60 cm and width of 20 cm was fixed on the top of the emitters to avoid falling of rice kernels on emitter surface. The power of the emitters was varied and controlled through Payne controller (Model 18 TB-2-25, U.S.A) in the range of 100 to 1800 Watts. The drum was provided with a feeding chute at the center of the drum, which was closed tightly with a locking mechanism after loading the rough rice samples. The drum was operated by an electric motor (JVJ 56H17T2011AK, U.S.A). The speed of the drum was varied through an automation direct controller (Model: GS1-10P2, U.S.A). The speed of drum was adjusted to be in the range from 5 to 15 rpm.

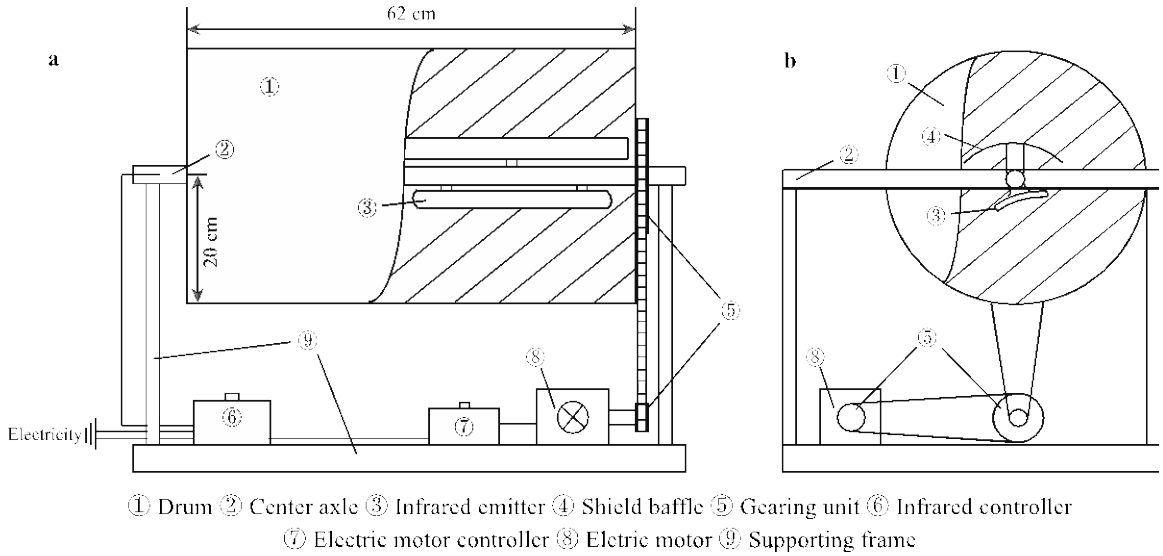


Fig.1. Schematic diagram representing structure of laboratory scale of IR rotary-drum dryer: (a) Front view, (b) Side view.

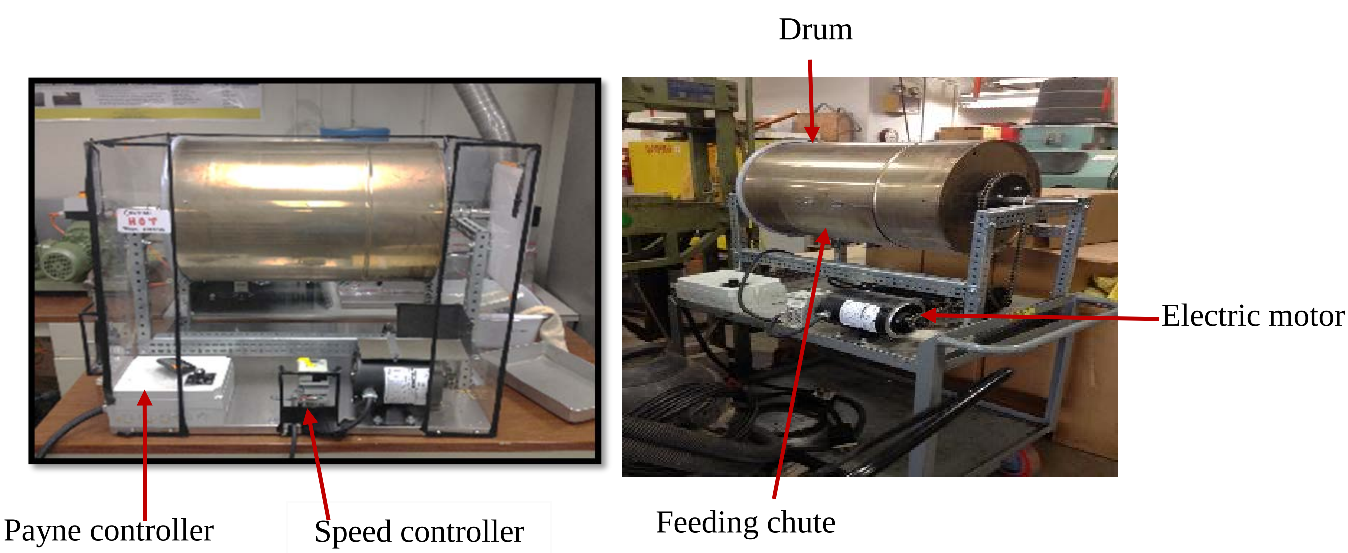
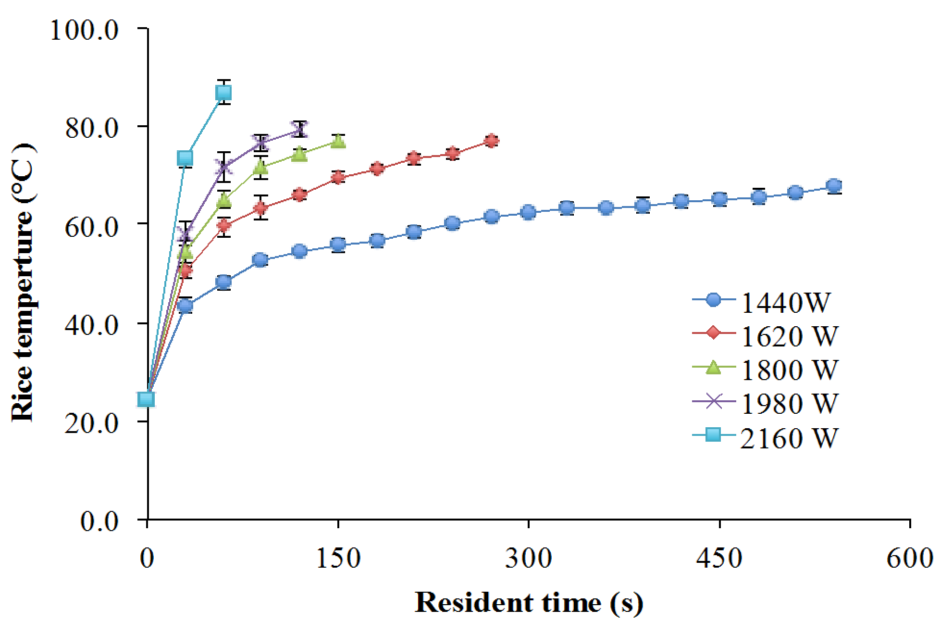


Fig.2. Infrared rotary-drum dryer for rough rice.

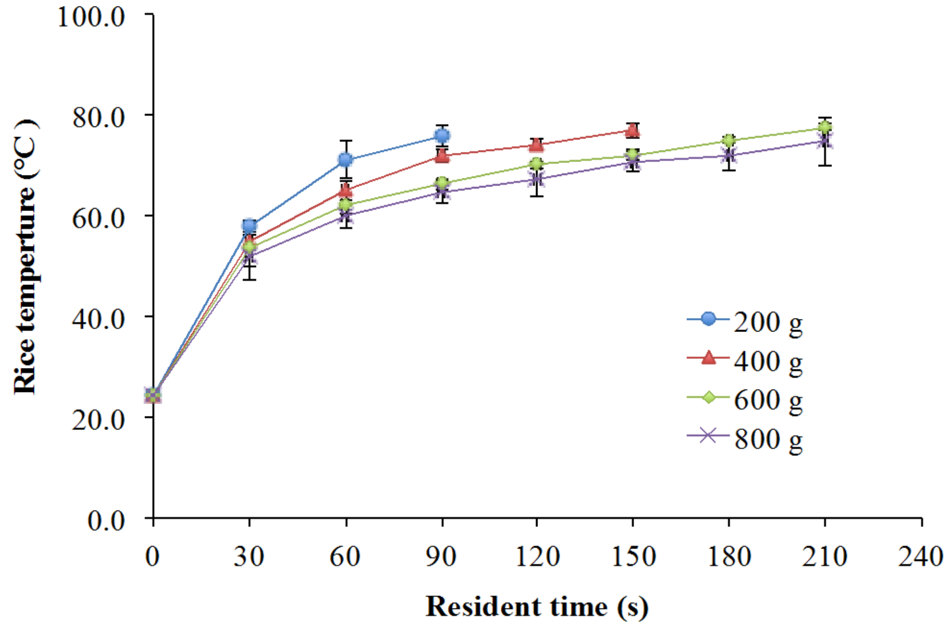
Optimize operating parameters of IR-rotary drum dryer

Determining the levels of operating parameters

The factorial experiment was used to determine the levels of operating parameters including, power of IR emitters, sample mass and rotating speed of the drum. Preliminary experiments established separate effects of operating parameters on the rice temperature. The relationships between resident time and rice temperature under different levels of the emitter power, sample mass and rotating speed are shown in Fig. 3. It can be seen that the needed time to heat the rice samples to 60 °C decreased by increasing the power level (Fig. 2a) under sample mass of 400g and rotating speed of 10 rpm. It took 5 min to heat the rice to temperature of 60 °C under power level of 1440 Watts. However, it took only 30 s to heat the rice to temperature of 70 °C under the power level of 2160 Watts. Obviously, the power level of 1440 Watts was too low and power level of 2160 Watts was too high. Also, the rice temperature under the same heating time decreased while the sample mass increased (Fig. 3b) under power level of 1800 Watts and rotating speed of 10 rpm. However, along with the increase of sample mass, the standard deviation of the rice temperature increased simultaneously. This means that the heating uniformity decreased while the sample mass increased. The rotating speed had no significant effect on the rice temperature (Fig. 3c) under power level of 1800 Watts and sample mass of 400g. The effects of the rotating speed of 7.5, 10 and 12.5 rpm on rice temperature showed a similar trend with minimum standard deviation and uniform mixing of rice kernels. Based on the results of the factorial experiment, the limits of operating parameters were selected to be from 45s to 75 s for resident time, from 1620 Watts to 1980 Watts for emitter power, 300 g to 600 g for sample mass and from 7 rpm to 13 rpm for rotating speed.



(a)



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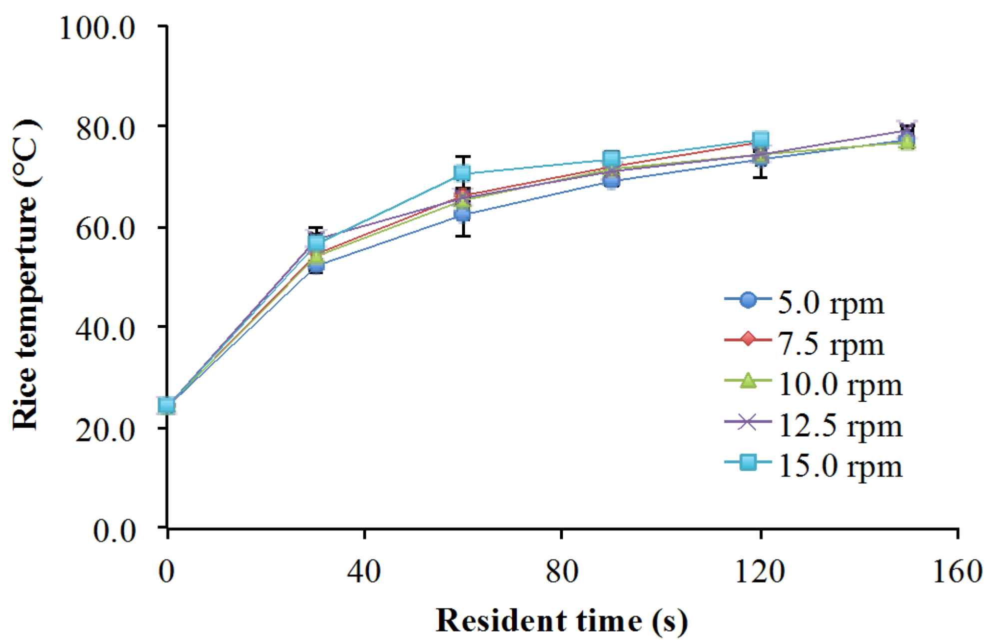


(c)

Fig.3. Relationship between resident time and rice temperature under different levels of operating parameters: (a) emitter power, (b) sample mass, (c) rotating speed.

Optimization of operating parameters

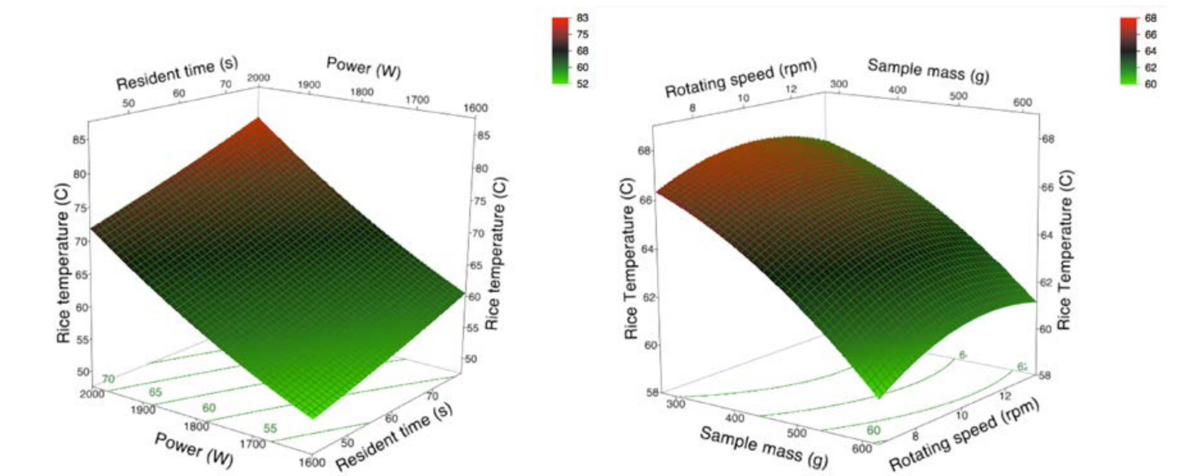
Response surface method (RSM) was used to determine the best combination of the operating parameters (resident time, emitter power, sample mass, rotating speed) that can maximize heating rate, moisture removal and milling quality and minimize specific energy consumption. Twenty eight combinations of coded values of four operating parameters used to obtain experimental data for optimization were tested randomly. Combinations of operating parameters and the results of all experiments are summarized in Table 2. Obtained data were analyzed using the multivariate regression (second-order polynomial expressions) to find the correlation between the operating parameters and rice temperature, moisture removal, and specific energy consumption. Response surfaces were built to represent the effect of resident time (RT), emitter power (P), and sample mass (SM) and rotating speed (RS) on rice temperature (T), moisture removal (MR), and specific energy consumption (SEC) (Fig.4). High correlations were found between rice temperature, moisture removal and specific energy consumption and operating parameters Figs. 4a, 4b, 4c, respectively. Based on the correlations, regression models were developed and are listed in Table 3. They were used to predict T, MR and SEC under tested conditions as dependent factor to operating parameters of RT, P, SM and RS.

For optimization, desirability functions of RSM were used. Then, the best values of operating parameters were found using the RSM as they are represented by shadow region in (Fig. 5). The best operating parameters values were determined to be resident time (RT) of 59.5±0.8 s; power of emitters (P) of 1694±10 Watts; sample mass (SM) of 450±20 g; rotating speed (RS) of 10.7±1.0 rpm. These optimum operating parameters would result in uniform heating, high heating rate, high moisture removal, minimum energy consumption and good milling quality.

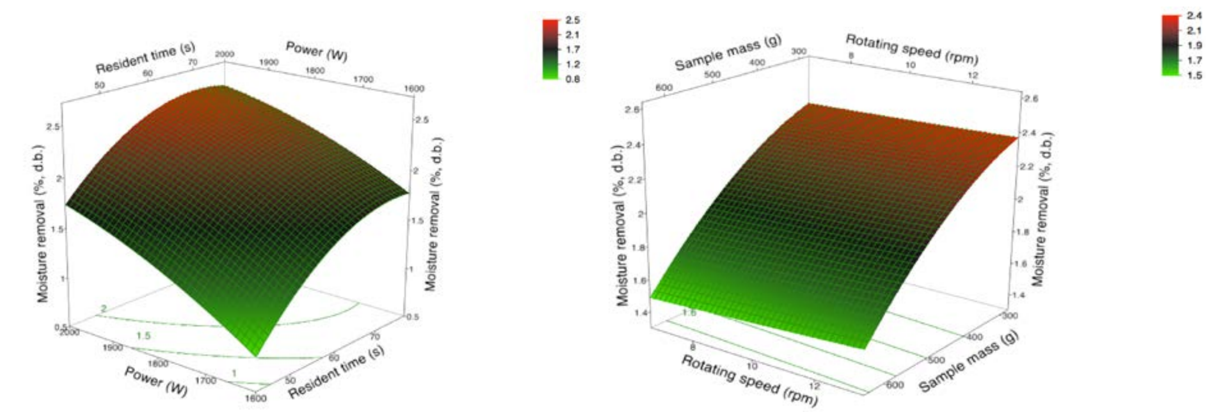
Table 2. Experimental design and data for the response surface analysis.

	Parameter levels				Responses (Y)			
	RT	P	SM	RS	TR (°C)	SD_{TR} (°C)	MR (%)	SEC ($MJ \cdot kg^{-1} H_2O$)
1	0	0	0	0	64.8	0.6	1.98	15.88
2	1	-1	1	-1	53.9	1.9	1.38	19.22
3	1	1	1	1	75.2	1.2	1.98	16.37
4	-1	1	-1	1	73.5	1.8	2.07	18.79
5	1	1	-1	1	81.3	1.2	2.94	22.05
6	0	0	1	0	63.5	1.5	1.58	14.92
7	1	1	1	-1	75.7	2.4	1.95	16.62
8	0	0	0	1	66.0	0.7	2.14	14.69
9	0	0	0	0	63.9	0.7	2.01	15.64
10	-1	1	-1	-1	75.3	2.4	2.33	16.7
11	-1	0	0	0	60.6	0.9	1.49	15.82
12	0	1	0	0	75.8	1.0	2.16	16.01
13	0	0	0	0	64.1	0.6	2.02	15.56
14	-1	1	1	1	64.8	2.6	1.44	13.51
15	-1	-1	-1	-1	51.9	0.8	1.01	31.51
16	0	0	0	0	63.7	0.6	2.05	15.33
17	0	0	-1	0	67.3	0.4	2.50	18.86
18	-1	-1	-1	1	55.0	0.7	1.11	28.67
19	-1	1	1	-1	67.5	0.7	1.34	14.51
20	1	-1	-1	1	62.7	1.0	2.04	26
21	1	-1	-1	-1	60.1	0.3	1.90	27.92
22	1	0	0	0	71.8	0.7	2.33	16.86
23	1	1	-1	-1	83.5	0.9	2.80	23.15
24	-1	-1	1	-1	50.6	1.3	0.82	19.41
25	0	0	0	1	64.6	0.8	2.10	14.97
26	1	-1	1	1	59.5	1.1	1.53	17.34
27	0	-1	0	0	58.3	0.8	1.93	14.66
28	-1	-1	1	1	52.4	1.0	0.78	20.4

TR, rice temperature; SD_{TR}, standard deviation between the measured rice temperatures of triplicates; MR, moisture removal; SEC, specific energy consumption.



(a)



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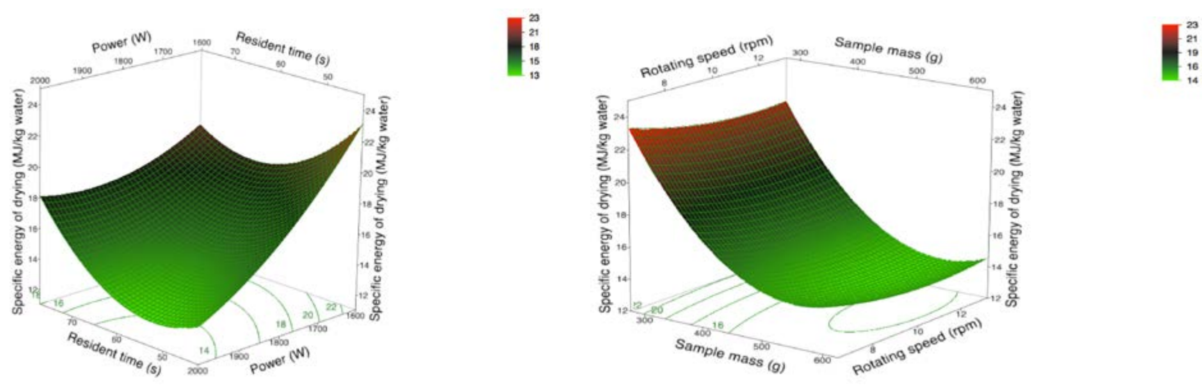

Fig.4. Response surfaces for effects of operating parameters of IR rotary-drum dryer on (a) rice temperature, (b) moisture removal and (c) specific energy consumption.

Table 3. Regression models for operating and response parameters for optimization.

Response parameters for optimization	Model	R^2	RSME
Temperature (T)	T=65.237+4.006RT+9.344P-2.639SM+0.406RS+0.519RT×P-0.181RT×SM-1.069P×SM+0.319RT×RS-1.269P×RS+0.156SM×RS+0.222RT^2+1.072P2-0.578SM^2-0.678RS^2	0.988	1.402
Moisture removal (MR)	MR=2.077+0.359RT+0.362P-0.328SM+0.022RS-0.04RT×P-0.044RT×SM-0.118P×SM-0.035RT×RS-0.021P×RS+0.008SM×RS-0.208RT^2-0.073P^2-0.078SM^2+0.002RS^2	0.967	0.142
Specific energy consumption (SEC)	SEC=14.877+0.345RT-2.634P-3.408SM-0.344RS+1.512RT×P-0.108RT×SM+1.128P×SM-0.274RT×RS+0.337P×RS+0.102SM×RS +1.947RT^2+0.942P^2+2.497SM^2+0.437RS^2	0.929	1.829

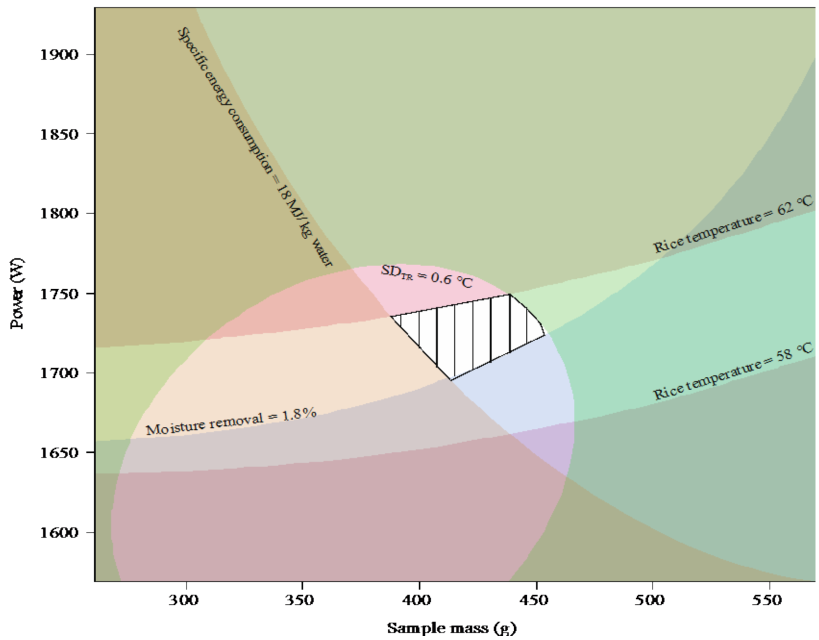

Fig.5. Optimum region for operating parameters of IR-rotary drum dryer.

Evaluate the milling quality of rough rice under optimized operating parameters

The milling quality of rough rice was evaluated under optimized operating conditions as mentioned in the previous section for the IR rotary-drum dryer. The results revealed that the infrared dried rice (IRD) had similar total rice yield (TRY) and Head rice yield (HRY) compared to those dried with ambient air drying (AAD). On average, the TRY values were 68.1±1.2 and 67.9±1.2 percent for rough rice dried with IRD and AAD, respectively. The corresponding values of HRY were 57.8±0.9 and 58.0±1.2 percent (Table 4). The results showed that there was no significant difference ($P<0.05$) among the WI values of rice dried with IRD and AAD. The obtained results clearly demonstrated that good milling quality can be achieved by heating the rice to about 60 ºC using IR followed by tempering and natural cooling. These results are in agreement with earlier reports (Pan et al., 2008 and 2011; Khir et al., 2011 and 2012).

The obtained resulted clearly revealed that high and uniform heating, high drying rate and good milling quality can be achieved by using IR rotary-drum dryer to heat rough rice to about 60 ºC followed by tempering and natural cooling. It took only about one minute to heat the rice to temperature of 60 ºC with corresponding moisture removal of 1.8% points, and additional moisture removal of 1.1 % points was removed during the natural cooling without energy consumption. Moreover, the results obtained from this research demonstrated that the feasibility of using IR rotary-dryer to perform continuous drying for rough rice with no adverse effect on rice milling quality.

Table 4. Milling quality of rough rice dried under optimized operating conditions of IR-rotary drum dryer

Rough rice	TRY (%)	HRY (%)	WI (unit)
IR dried rice	68.1±1.2	57.8±0.9	39.4±0.3
Control (AAD)	67.9±1.2	58.0±1.2	39.1±0.1

TRY: Total rice yield; HRY: Head rice yield; WI: Whiteness index;
AAD: ambient air drying

Conclusions and recommendations

The research revealed that high heating and drying rates and good milling quality can be achieved by using IR rotary-drum dryer. High correlations were found between rice temperature (T), moisture removal (MR) and specific energy consumption (SEC) and operating parameters including, resident time (RT), power level (P), sample mass (SM) and rotating speed (RS). Based on the correlations, regression models were developed. They could be used to predict T, MR and SEC as dependent factor to operating parameters (RT, P, SM and RS) under tested conditions.

Also, response surface methodology was effective in determining the optimum operating parameters of IR rotary-drum dryer.

The best operating parameters values were determined using response surface methodology to be resident time of 59.5 s; power of IR emitters of 1694 Watts; sample mass of 450 g; rotating speed of 10.7 rpm. These optimum operating parameters would result in rice temperature of 60.2 ℃, moisture removal of 1.83 % during IR heating only, and specific energy consumption of 16.65 MJ/kg H_2O. It is important to notice that the aforementioned energy consumption was calculated for the lab scale of the IR dryer. For the commercial scale, the energy efficiency can be much higher than that of the lab scale dryer.

PUBLICATIONS OR REPORTS

N/A

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CONCISE GENERAL SUMMARY OF CURRENT YEAR'S RESEARCH

The objective of this research project was to design and test infrared rotary-dryer and optimize its operating parameters to achieve an efficient drying for rough rice. A lab scale of IR rotary-drum dryer developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis was modified for conducting the research project. The dryer was made from stainless steel with 15.7 inch in diameter and 24.4 inch in length. The interior surface of the drum was coated with Teflon materials to improve the heating efficiency and uniformity. The dryer was facilitated with two IR emitters mounted lengthwise inside the drum with heating surface focused downward with angle of 20 degrees. One arc-shape stainless steel shield with length of 60 cm and width of 20 cm was fixed on the top of the emitters to avoid ±falling of rice kernels on emitter surface. The power of the emitters was varied and controlled through Payne controller in the range of 100 to 1800 Watts. The drum was equipped with a feeding chute at the center of the drum, which was closed tightly with a locking mechanism after loading the rough rice samples. The drum was operated by an electric motor. The speed of the drum was varied through an automation direct controller. The speed of drum was adjusted to be in the range from 5 to 15 rpm. Freshly harvested medium grain rice, M206, was used for conducting the drying tests.

A single factor drying experiments were designed to investigate effects of operating parameters (emitter power (P), sample mass (SM), rotating speed (RS)) of IR dryer on the drying performance of rough rice. The factorial experiment was used to evaluate the relationship between resident time (RT) and rice temperature (T) under different levels of emitter power, sample mass, rotating speed. The rice samples were dried at power levels of 1440, 1620, 1800, 1980 and 2160 W, sample masses of 200, 400, 600 and 800 g and rotating speeds of 5, 7.5, 10, 12.5 and 15 rpm. The limits of the emitter power, sample mass, and rotating speed were determined based on the results of preliminary tests. After determining the operating parameter limits, the response surface methodology was applied to optimize the operating parameters of the IR dryer to achieve high heating rate, high moisture removal, good milling quality and low energy consumption. The milling quality of rough rice and specific energy consumption (SEC) were evaluated under optimized operating conditions of IR rotary-dryer.

The research clearly revealed that high correlations were found between rice temperature, moisture removal and specific energy consumption and operating parameters. Based on the correlations, regression models were developed. They could be used to predict T, MR and SEC as dependent factor to operating parameters including RT, P, SM and RS under tested conditions. Also, response surface methodology was effective in determining the optimum operating parameters of IR rotary-drum dryer.

The best operating parameters values were determined using response surface methodology to be resident time of 59.5±0.8 s; power of IR emitters of 1694±10 Watts; sample mass of 450±20 g; rotating speed of 10.7±1.0 rpm. These optimal operating parameters would result in high heating uniformity and rate, high moisture removal, minimum energy consumption and good milling quality. The results obtained from this research project can lead to design an IR dryer for rough rice which is simple and easy to operate, and achieve continuous thin layer drying with uniform heating and high energy efficiency while reducing the dryer footprint.

ACKNOWLEDGEMENT
The investigators would like to express their appreciation for the great support received from the following personnel and organization.

Chao Ding
UC Davis
USDA-ARS-WRRC
California Rice Research Board
Farmer's Rice Cooperative