Governor

INFRARED DRYING OF RICE TO IMPROVE ENERGY EFFICIENCY AND DISINFESTATION

PIER FINAL PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

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Preface

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Executive Summary

This comprehensive research project was carried out to study the applications of the infrared (IR) drying/heating technology for processing rice and onions, which are two large food commodities of California. The objectives of research were (1) to improve the processing and energy efficiencies and the quality of the finished products, and (2) to achieve the disinfestations and reduction of microbial counts in the dried rice and onion. Two infrared heating/drying technologies, catalytic infrared (CIR) and electric vacuum infrared (EVIR), were compared with the conventional heated air heating/drying with respect to the processing characteristics, product quality and safety and energy use. The results showed that IR rice drying could significantly reduce drying time, especially with single-layer drying, improve milling quality and achieve simultaneous drying and disinfestation compared to heated air drying. The CIR heating can also be used for disinfestation of storage rice. Based on the results of processing efficiency and product quality, IR drying/heating is preferred over current processing methods. When CIR was used for drying onions, it showed high drying rate before onions reached low moisture levels and the product had significantly lower yeast and mold counts than those dried by heated air. It is suggested that CIR be used in the early stages of onion drying. It is also recommended that large scale IR dryers need to be tested for accurately quantifying their energy consumption and efficiency. The detailed research results are summarized in the following four sections.

Comparison of rough rice drying in thick-layer using CIR and heated air dryers

The study compared the drying characteristics, milling quality and energy consumption of three different drying methods, vibro-bed (thick-layer) CIR drying, laboratory scale heated air (CHA) drying, and commercial heated air drying. The rough rice samples were dried using single and multiple passes at 36^{o}C and 45^{o}C temperatures with different moisture removals from 1.5% to 4% in each drying pass. Following each drying pass, rice was tempered at drying temperature for four hours. The rice samples were dried to about 17% (w.b.) moisture using heat before they were further dried to a final moisture content of 13.5% (w.b.) using ambient air. Drying and rice quality data were also collected for the same rice dried using a commercial scale cross-flow dryer at 40^{o}C to 55^{o}C air temperature to remove about 2% moisture in a drying pass and compared with the results from CIR and CHA drying.

In general, CIR dried rice had higher milling quality compared to both laboratory and industrial scale CHA drying. The average HRY of CIR dried rice was 1.2 and up to 4% higher than laboratory and commercial CHA drying with similar TRY and whiteness. The highest head rice yield of 63.65 was observed for rice dried at 45^{o}C under CIR drying. The maximum HRY was 61.55 and 58% for laboratory and commercial CHA drying, respectively, at 45^{o}C drying temperature. The low drying temperature generally resulted in slightly higher milling quality than the high drying temperature in the tested range even though the difference was not statistically significant. No significant effect was observed with the number of drying passes on milling quality. Based on all the results related to milling quality, it can be concluded that CIR is preferred over CHA drying. The CIR reduced the required drying time and improved the milling quality. The minimum natural gas energy use of vibro-bed CIR laboratory scale prototype dryer was 12,135 kJ/kg of water removal at 1.9% moisture removal and 17,285 kJ/kg water removal at 1.3% moisture removal, which were achieved at 45^{o}C and 36^{o}C drying temperatures, respectively. High drying temperature had less energy consumption for CIR drying. However, the measured energy consumption based on the laboratory prototype CIR dryer was higher than industrial CHA dryer, which could be due to the too small size of the CIR dryer. In order to obtain accurate estimate of the energy consumption of CIR drying, a large scale CIR dryer needs to be studied.

Effectiveness of CIR heating for simultaneous drying and disinfestation of rough rice

The objective of this study was to investigate the drying characteristics, milling quality, and disinfestation effectiveness of rough rice under infrared (IR) radiation heating. Freshly harvested medium grain rice (M202) samples with low (20.6%) and high (25.0%) moisture contents (MC) were used for this study. Single-layer rough rice samples (non-infested and infested with the adults and eggs of lesser grain borers (*Rhizopertha dominica*) and angoumois grain moths (*Sitotroga cerealella*) were heated for various durations using a catalytic infrared emitter. The effects of tempering treatment and natural and forced air cooling methods on moisture removal, milling quality and disinfestation were determined. High heating rate and corresponding high moisture removal were achieved by using the IR heating. After heating, tempering increased moisture removal during cooling and improved milling quality of the rice samples. For example, 60 s IR heating of the rice with 20.6% MC resulted in 61.2°C rice temperature, 1.7% MC removal during the heating period and additional 1.4% MC removal after tempering and natural cooling. The rice also had 1.9% higher head rice yield than the control sample dried with ambient air. The heating and tempering treatment also completely killed the tested insects. It is concluded that simultaneous drying and disinfestation with high rice milling quality can be achieved by using the catalytic IR to heat rough rice to 60°C followed by tempering and slow cooling.

Effectiveness of CIR heating for disinfestation of storage rice

The objective of this study was to develop rapid, non-chemical, safe alternative methods for eliminating insect pests from storage paddy rice while retaining high rice quality. The IR heating was evaluated for its effectiveness in eliminating insects. The tests were conducted with two different approaches (thick-layer heating and single-layer heating) using the CIR dryers. Medium grain rice M202 was used for the tests. After the CIR thermal treatments the survived insects in different forms were examined by counting the survived and emerged adult insects during storage after the treatments. The moisture loss caused by infrared heating and the milling quality of treated rice samples were measured.

For thick-layer heating, Angoumois grain moth (*Sitotroga cerealella*) was tested. The rice samples were heated with CIR to different temperatures from 45 to 70°C and held for various time periods, from 1 to 10 min. The required temperature and holding time to achieve complete disinfestation were found to be 50°C and 1 min. Under such treatments, rice milling quality was notaffected, but infrared heating caused about 1% moisture loss.

For single-layer heating, before the disinfestation treatment, the rice samples were infested with lesser grain borers (beetles) (*Rhizopertha dominica)*, and angoumois grain moths (*Sitotroga cerealella)*. In order to reduce the moisture loss during infrared disinfestation treatment, the drying bed was pre-heated and rice was heated as single-layer. The single-layer heating method resulted in rapid heating of the rice with reduced moisture loss. For example, it took only 20 s to heat the rice sample to 60°C with 0.53% moisture loss compared to about 1%

loss obtained with thick-layer heating. The infrared heating did not cause any significant changes in rice milling quality. The minimum required disinfestation conditions were determined to be 20 min holding at 53°C for moths and 20 min holding at 60°C for beetles.

In conclusion, infrared heating treatment can be used for disinfestation of storage rice without lowering the milling quality, but could cause up to 0.53% moisture loss of the rice.

Electric vacuum infrared drying of rough rice

Freshly harvested medium grain rice (M-202) obtained from a commercial rice drying facility in Davis, California was dried in an infrared vacuum drier at 52, 45 and 36°C. The dryer was operated at -27 in Hg gauge pressure. Rough rice was circulated and mixed in the dryer with augers. The removed water was condensed in vacuum chamber using evaporator pipes of a heat pump. The dryer was batch type with a capacity of 29.5 kg rice.

Rough rice was dried for up to 45 min and samples were taken at predetermined time intervals for moisture content and milling quality evaluations. The required time to reduce MC by 2% was determined to be 12, 13.5 and 14 min for 52, 45 and 36^{o}C drying temperatures, respectively. There was a trend that TRY and HRY increased with up to 8 min of drying time. It was confirmed that vacuum IR drying can be used to remove more than 2% of moisture in a single drying pass without causing a significant loss in TRY and HRY. For example, the rice dried at 45^{o}C for 45 min with 5.7% moisture removal did not show significant TRY and HRY decreases compared to the rice dried with ambient air. It was observed that the whiteness increased with the increase of drying time. For the pilot scale vacuum IR dryer, the energy used to evaporate 1 kg water at 2% moisture removal was about 8000 kJ for all drying temperatures. High drying temperature showed higher energy efficiency than low drying temperature.

Onion drying

This study compared the drying and quality characteristics of onion dried with catalytic infrared (CIR) heating and forced air convection (FAC) heating. Sliced high solids onions were dehydrated under nine conditions: the CIR heating with and without air recirculation, and the FAC heating each operated at 60, 70 and 80 °C. In general, CIR heating, with or without air recirculation, had higher maximum drying rates, shorter drying times, and greater drying constants than the FAC heating at moisture contents greater than 50% (d.b.). Dried onion quality, which was measured as pungency degradation, was similar for both the drying methods at 60 °C and 70 °C. The color analysis showed better product color (more white and less yellow) at lower temperatures for the CIR heating and higher temperatures for the FAC heating. The browning could have been caused by the higher surface heat flux of the CIR heating and longer process times of the FAC heating. Aerobic plate counts and coliform counts were not significantly different for either product from the CIR or FAC heating. However, samples dried by the CIR heating had significantly lower yeast and mold counts than those dried by the FAC heating. It is recommended that the CIR heating be used in the early stages of onion drying.

Key words: Infrared; drying; heating; energy; efficiency; environment; safety; food; agricultural products; grain disinfestations; microorganism; productivity; quality.

1 Introduction

California produces about 43 billion pounds of rice and 75% of dehydrated onion products in the United States annually. All the rice and onion products are dried with conventional convection (column and tunnel) drying technologies which have low processing and energy efficiencies, which result in high production cost and low product quality. Since agricultural and food industry is facing the pressure of losing the use of methyl bromide, farmers and processors have also been seeking environmentally sound alternative methods for disinfestations of rice and reduction of microbial counts in food products. Based on the information that has been reported, infrared drying/heating technology may provide promising potentials in improving processing and energy efficiencies, product quality, and in disinfestations and reduction of microbial counts in dried food and agricultural products.

This research project focused on applications of the infrared drying/heating technology for processing two large food commodities of California, rice and onions, with the aim at improving the processing and energy efficiency and the quality of the finished products as well as achieving the disinfestations and reduction of microbial counts in the dried rice and onion. The ultimate goal of the research project was to investigate and quantify the advantages of infrared drying/heating technology in improving processing efficiency and energy consumption of drying and product quality and safety of dried rice and onions. The research investigated the drying and quality characteristics and potential benefits of using two types of innovative infrared dryers, catalytic infrared (CIR) and electric vacuum infrared (EVIR), for drying, disinfestations and reduction of microbial counts of rice and onions.

2 Drying and Heating Equipment

2.1 Catalytic Infrared Dryers

Two catalytic infrared (CIR) dryers have been used in this project. A vibro-bed CIR dryer was used for rice drying and disinfestation with thick-layer rice bed (Figure 2-1 (a)). The dryer was provided by Catalytic Industrial Group Inc. (Independence, KS). It is equipped with a CIR emitter (BUREST MODEL 12-24, 12,000 Btu input) along with an adjustable speed vibrating bed for mixing rice during heating/drying. The emitter generated IR radiation energy by catalyzing natural gas to produce heat along with small amounts of water vapor and carbon dioxide as by-products. When it was used for rice drying and disinfestation, the IR emitter was 0.265 m above the rice bed. Flexible bottom (0.8 m x 0.4 m) of the CIR dryer, made out of Teflon coated fabric material, was being vibrated in four sections. Wave-like vibration was created by rotating Teflon rollers arranged under the flexible bottom. Vibrating frequency was set at 450 cycles/min for the tests. Amplitude of the vibration was 2.5 cm in vertical direction.

Exhaust turbo blower (DAYTON 4C940) fixed at the top of the dryer exhausts the burnt gas and moist air inside the dryer at a rate of 138 m^3/h. Recirculation of air was created by two blowers (DYTON 2C9175) sucking air from the top of the dryer and blowing on to the rice bed along the two sides of the rice bed. Each blower has a flow rate of 312 m^3/h. Gas flow rate to the CIR dryer was measured using a flow meter (EQUIMETER MR-5). A computer based data acquisition and control (DAC) system was used to record temperature and gas flow data and to control solenoid valve (UNIVERSAL MODEL36C03) of the gas supply. CIR emitter temperature was measured using pre-installed eight J type thermocouples on the surface of the catalytic layer of the CIR emitter.

This CIR dryer was also used for onion drying after modification. The detailed description of dryer set-up for onion drying is presented in onion drying section in this report.

The second CIR device was used for rice drying and disinfestation with single-layer rice bed (Figure 2-2). An aluminum box with dimension of 65 cm (length) x 37 cm (width) x 45 cm (height) was installed around the emitter as wave guide to achieve a uniform IR intensity at the rice bed surface. The rice bed was set at 5 cm below the bottom edge of the wave guide. The average IR intensity at the rough rice bed surface was 5348 W/m^2, which was measured by using Ophir FL205A Thermal Excimer Absorber Head (Ophir, Washington, MA). The drying bed was made with a 3 mm thick aluminum plate for minimizing the radiation energy loss through the drying bed due to its high reflectively. The reflected radiation energy could also be used to heat the bottom side of rice kernels. A piece of plywood was installed beneath the aluminum plate for reducing the energy loss through conduction.

2.2 Conventional Heated Air Dryer

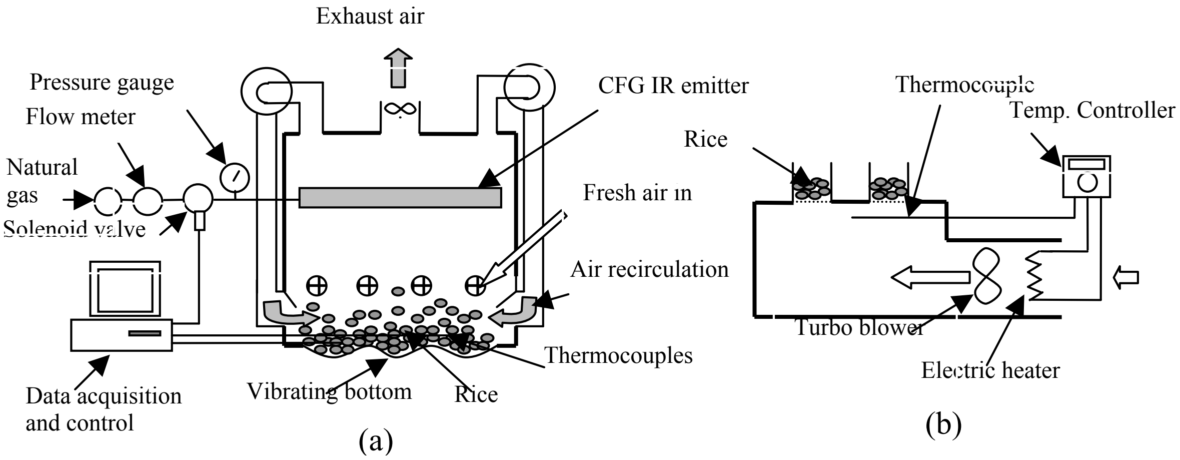
A laboratory scale electrically heated convectional air dryer (Figure 2-1 (b)) was also used for this project. Electric heaters of the dryer were controlled by a microcontroller (OMEGA-E CN132) to keep the air temperature at set temperature. The heated air temperature was considered as the drying temperature for conventional heated air (CHA) drying.

2.3 Electric Vacuum Infrared Dryer

An electric vacuum infrared (EVIR) dryer provided by Advance Light Technology LLC. (Chico, CA) was also used for rice drying tests (Figure 2-3). This dryer has two vacuum drying chambers with six electric IR emitters (1600W each) and two vacuum pumps. The continuously operated grain augurs in drying chambers are used to circulate and mix rice in the dryer. The capacity of the dryer is 29.5 kg of rice. Two condenser pipes running at the bottom (longitudinally) at each drying chamber are for condensing evaporated moisture from the rice and they are connected to 1 hp heat pump.

Table 1 shows the rated power of the instruments connected to the EVIR dryer. Six thermocouples inside the vacuum drying chamber under each electric IR emitter are used to measure the rice temperature. Microcontroller (OMRON) connected to the power supply of IR emitters controls the rice temperature by switching the emitter power on and off based on the actual rice and pre-set rice temperature.

2.4 Appendix: Drying and Heating Equipment



(a)

(b)

Figure 2-1. Schematic diagrams and set-up of catalytic vibro-bed infrared dryer (a) and conventional heated air dryer (b) for rice drying

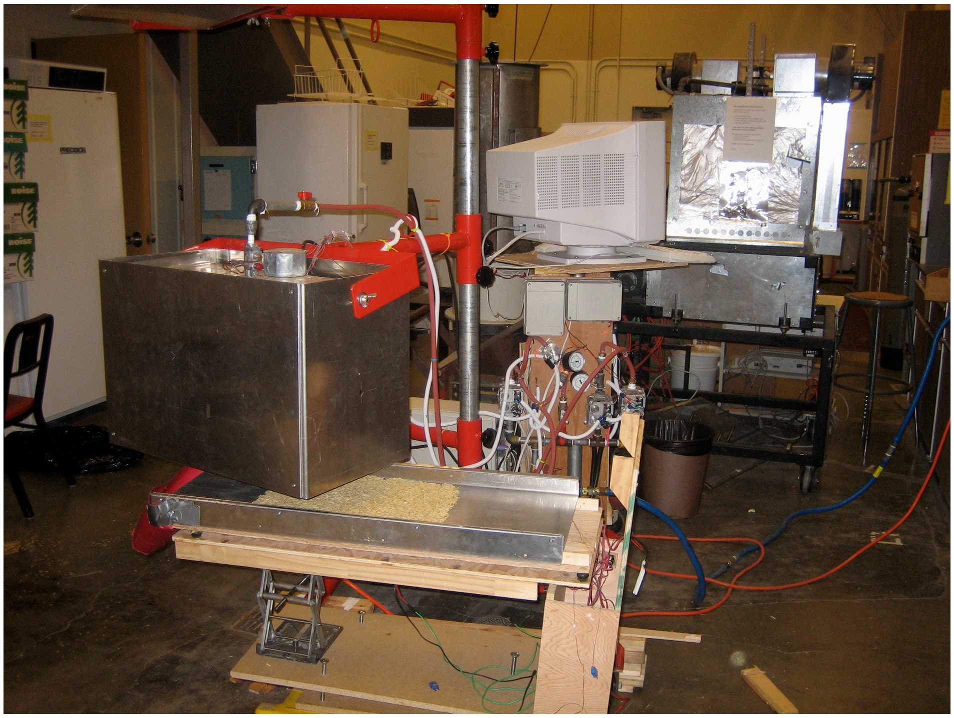


Figure 2-2. Infrared heating device set-up for single-layer drying and heating

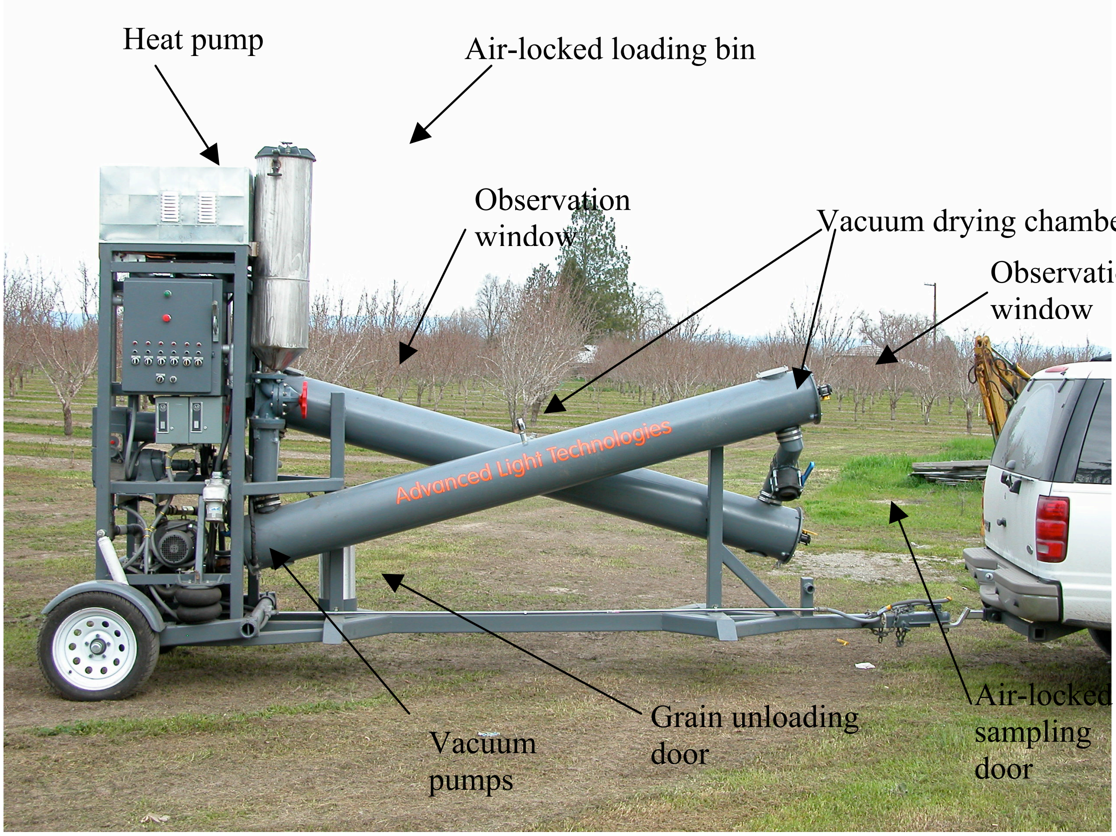


Figure 2-3. Electric vacuum infrared auger-type dryer

Table 2-1. Rated power of the components of electric vacuum infrared dryer

Component	Rated energy consumption
Vacuum pump -1	1.5 hp
Vacuum pump -2	1.5 hp
Motor for Augur	1 hp
Heat pump	1 hp
IR emitters (6)	1600 x 6 W

3 Comparison of Rough Rice Drying in Thick-layer Using Catalytic Infrared and Heated Air Dryers

3.1 Summary

The objective of this study was to compare the drying process characteristics and quality of rough rice dried with a vibro-bed infrared dryer, laboratory scale heated air dryer, and commercial heated air dyer and their energy consumption. Freshly harvested medium grain rice (M-202) samples obtained from a commercial rice drying facility in Arbuckle, California were dried in a vibro-bed catalytic infrared (CIR) dryer at an average IR radiation intensity of 2750 W/m^2. The rough rice samples were dried using single and multiple passes at 36^{o}C and 45^{o}C temperatures with different moisture removals from 1.5% to 4% in each drying pass. Following each drying pass, rice was tempered at drying temperature for four hours. The rice samples were dried to about 17% (w.b.) moisture using IR heating before they were further dried to a final moisture content of 13.5% (w.b.) using ambient air. The rough rice also dried using a laboratory convectional heated air (CHA) dryer at similar conditions as CIR drying. Drying and rice quality data of the same rice dried using a commercial scale cross-flow dryer at 40^{o}C to 55^{o}C air temperature to remove about 2% moisture in a drying pass, were also collected and compared with the results from CIR and CHA drying.

In general, CIR dried rice had higher milling quality compared to both laboratory and industrial scale CHA drying. The average HRY of CIR dried rice was 1.2 and up to 4 percentage points higher than laboratory and industrial CHA drying with similar TRY and whiteness. Highest head rice yield of 63.65 was observed for rice dried at 45^{o}C under CIR drying. Whereas the achieved maximum HRY for laboratory CHA drying was 61.55 at 45^{o}C drying temperature and commercially dried rice had even lower HRY, 58%. The low drying temperature resulted in slightly better milling quality than the high drying temperature in the tested range even though the difference was not statistically significant. No significant effect of the number of drying passes on milling quality was observed. By comparing all milling quality results, it can be concluded that CIR is preferred over CHA drying. Minimum natural gas energy use of vibro-bed CIR laboratory scale prototype dryer was 12,135 kJ/kg of water removal at 1.9% moisture removal and 17,285 kJ/kg water removal at 1.3% moisture removal at 45^{o}C and 36^{o}C drying temperatures, respectively. High drying temperature had less energy consumption for CIR drying. However, the measured energy consumption based on the laboratory prototype CIR dryer was much higher than industrial CHA dryer, which could be due the too small size of the CIR dryer. To achieve accurate estimate of energy consumption of CIR drying, a large scale CIR dryer is needed.

3.2 Objectives

The objective of this study was to compare the drying process characteristics and quality of rough rice dried with a vibro-bed infrared dryer, laboratory scale heated air dryer, and commercial heated air dyer and their energy consumption.

3.3 Materials and Methods

Samples of M-202 rough rice were first collected from 33 incoming trucks at the California Family Foods, Arbuckle, California. After sampling, the rice in the trucks was unloaded and then loaded in to a single silo. Collected rice samples were mixed thoroughly by passing it through a Boerner-Sampler (Seed Trade Reporting Bureau, Chicago, IL) divider 6 times. Samples were then sealed in polyethylene bags and stored in a laboratory at ambient temperature until the time for tests. The average initial moisture content of the samples was 21.3 ± 0.3% (w.b.). The rice samples were dried in the prototype vibro-bed catalytic infrared (CIR) dryer and the laboratory convectional heated air (CHA) dryer (Figure 2-1(b)) at 36°C and 45^{o}C (for CIR drying the temperature was rice temperature, for CHA drying the temperature was air temperature). Table 3-1 shows the experimental design of the drying tests. Samples were dried down to about 17% moisture using multiple passes or single pass at different moisture removals from 1.5% to 4%. Rice was tempered at drying temperature for four hours after each drying pass. The rice samples were then further dried to a final moisture content of 13.5% using ambient air.

The drying data of same rough dried with a commercial scale cross-flow dryer at 40^{o}C to 55^{o}C air temperature to remove about 2% moisture in each drying pass, were obtained from California Family Foods. The data were compared with laboratory tests of CIR and CHA drying. All moisture contents reported in the report are in wet weight basis and determined by the air oven method (130^{o}C for 24 hours).

3.3.1 Catalytic infrared drying

Infrared radiation directly heats the rice without heating the surrounding air. Therefore, the rice bed temperature was used as the drying temperature for CIR drying. Two thermocouples inserted in to the middle of the rice bed (Figure 1 (a)) were used to measure the average rice bed temperature. Gas supply to the IR emitter was controlled (switched on or off) by the DAC comparing the average bed temperature with the set temperature.

Sample size for CIR drying was 6 kg. This formed a 5 cm thick rice layer (thick-layer drying) on the vibrating bed. End point of drying was determined by drying time calculated based on the results of drying curve obtained under similar conditions. After reaching the desired moisture content the samples were taken out from the dryer and kept in sealed containers and stored inside an incubator (PRECISION 815, Winchester, VA) for tempering for 4 hours, at the same temperature as drying. Tempered rice was then dried again (for multiple pass drying) using CIR or dried down to about 13.5% moisture content (single pass drying) by ambient air (AA) drying depending on the moisture content.

3.3.2 Conventional heated air drying

A laboratory scale electrically heated convectional air dryer (Figure 2-1 (b)) was used for CHA drying. Sample size for CHA drying was 5 kg. Thickness of the rice layer was kept at 5 cm (similar to CIR drying bed thickness). The end point of drying was determined by measuring the weight loss during drying and initial moisture content. After drying using heated air, samples were tempered with the same procedures described as above. For multiple pass drying the samples were dried again followed by 4 hour tempering period before final drying.

3.3.3 Final drying and quality evaluation

Final rice drying was performed to reduce the moisture content of rice samples to the required 13.5% for milling test. Tempered rice samples dried by both CIR and CHA were removed from the incubator and allowed to cool down to room temperature (25°C) in the containers. The cooled rice was then further dried to the targeted MC of 13.5% by AA at 25°C and 37% relative humidity.

Head rice yield (HRY) and total rice yield (TRY) of the dried rice were determined according to the Federal Grain Inspection Services (FGIS), United State Department of Agriculture standards. Head rice yield (HRY) is the amount of whole kernels in the milled sample and total rice yield (TRY) is the amount of whole and broken kernels in the milled sample expressed as percent of the rough sample. Moisture contents of samples before the milling tests were 13.5 ± 0.5%. Two replicates of each rice sample were sent to the Federal Grain Inspection Services laboratory (FGIS) in Sacramento, California, for milling quality evaluation. The HRY, TRY, and the whiteness were measured. Whiteness was measured using KETT digital Whiteness Tester (Model C-300-3, Range 5-70, KETT electronic lab, Japan).

3.4 Results and Discussions

Targeted moisture contents after each drying pass were achieved with an average error of 0.28% with standard deviation 0.2% except experiment U, which was over dried by 2.7% (Table 3-2). The measured natural gas consumption of the CIR emitter operated at 190 mm H_2O pressure was 0.42464 m^3/h with average CIR panel temperature of 500°C. Assuming IR emitter as a black body the maximum wavelength is 3.7 μm, which is in the range of IR absorption peak of water. The average radiation energy intensity measured at the rice bed surface using OPHIR FL250A Thermal Excimer Absorber Head was 2750 W/m^2.

3.4.1 Rice Quality

Average TRY, HRY and Whiteness with standard deviation for each drying trial are listed in Table 3-3. All CIR dried rice had better milling quality (higher TRY and HRY) than CHA dried rice with similar whiteness under the same moisture removals. The average HRY of CIR dried rice was 1.2 percentage points higher that that of CHA dried rice. Four out of nine pairs of CIR and CHA drying tests, CIR dried rice showed significantly higher HRY. Three out of 9 pairs showed significant higher TRY for CIR drying. None of the CHA drying experiments had significantly higher TRY or HRY compared to CIR drying at 5% confident level. Four out of nine pairs showed higher whiteness in CIR drying and one showed higher whiteness for CHA drying. Highest head rice yield of 63.65 was observed for rice dried at 45°C under CIR drying. Whereas for CHA drying, the maximum HRY achieved was 61.55 at 45°C drying temperature.

In general, the low temperature drying resulted in slightly better milling quality than the high drying temperature even though the difference was not statistically significant (Table 3-4). No significant effect of the number of drying passes on milling quality was observed.

The HRY of commercially dried rice was much lower than all laboratory experiments (CHA and CIR drying) (Table 3-2 and 3-5). The improved HRY by CIR drying (up to 4 percentage points than industrial drying) would be a great economic interest in the rice industry. Since the HRY improvement by CIR drying was 1.2 percentage (average) compared to laboratory CHA drying, if assuming 2 percentage point improvement by adopting CIR drying in industry, the head rice yield will increase by 16229 kg in a single storage silo used in this study. This will return additional $ 8114.00 at $0.50/kg rice. The average TRY of commercial drying was similar to CIR and laboratory CHA drying.

By comparing all milling quality results, it can be concluded that CIR is preferred over CHA drying.

3.4.2 Rice temperature profile of CIR and CHA drying

The vibro-bed rice mixing mechanism was capable of maintaining uniform temperature in the thick rice bed. The maximum temperature difference was only 5°C between the surface and the average of rice bed temperatures. Figure 3-1 shows the rice bed temperature profile of CIR drying. To reach rice bed temperatures of 36°C and 45°C it took 4 and 8 min, respectively. The results also showed that the rice bed temperature was controlled within ± 2°C of the set temperature. A higher drying rate at 45°C was observed than at 36°C (Figure 3-2), which indicated that a slightly high drying temperature was desirable to reduce the needed drying time.

Figure 3-3 shows the measured rice temperature at bottom, middle and top of the 5 cm rice column at 45°C drying temperature. The velocity of air flow was 0.011 m/s. Maximum difference of 20°C was observed at 10 min drying at 45°C air temperature. Even after 30 min of drying there was a difference of 12.4°C between the top and bottom layers of rice in the same experiment. At 36°C drying, there was a maximum difference of 9.5°C at 10 min of drying, and after 30 min of drying the difference was 4.4°C. The results indicated that CIR has more uniform heating during drying due to the drying bed vibration.

3.4.3 Energy consumption of CIR drying

Tables 3-6 and 3-7 show the natural gas energy input to the IR emitter to evaporate 1 kg of water from the rice at different moisture removal levles. Minimum energy use was 12,136 kJ/kg of water removal at 1.9% moisture removal and 17,285 kJ/kg water removal at 1.3% moisture removal at 45°C and 36°C drying temperatures, respectively, for CIR drying. The high drying temperature had lower energy consumption and shorter drying time. This indicated that high drying temperature should be used if the rice milling quality permits. The 10 min CIR drying time was much shorter than the typical 20 to 30 min drying time in rice industry to remove about 2% moisture. To achieve high drying temperature thin or single-layer CIR drying should be considered.

The CIR drying energy consumption values were higher than commercial convectional heated air dryers which reportedly operate below 10,000 kJ/kg of water evaporated. Table 3-8 shows the energy consumption of an industrial cross flow dryer at California Family Foods, California. The 80 feet (24m) high industrial cross flow dryer, drying 811460 kg of rice from 19.9% w.b. moisture content to 18.5%, the energy use efficiency of natural gas was 7107 kJ/kg of water evaporated. Two blowers and the augurs in the dryer consumed electricity at a rate of 199kJ/kg of water evaporated. The total energy consumed was 7306 kJ/kg of water evaporated.

Unpublished data from Catalytic Industrial Group Inc. showed that CIR pilot dryer of the size 1.2 x 9 m, drying 850 kg of rice had energy consumption of 2900 to 4600 kJ/kg of water removal for removing 2.8% to 5.4% moisture content, which were much lower than the reustls obtained using the laboratory scale CIR in this study. Therefore, it must be emphasized that such energy estimate of a prototype laboratory scale IR dryer used in this study would not necessarily be accurate when applied to a workable large-scale infrared drier.

3.5 Conclusions

Freshly harvested rough rice samples were dried with three different drying methods, thick-layer drying using vibro-bed CIR dryer, laboratory CHA dryer and industrial CHA dryer. The resulted showed that CIR drying had higher drying rate and milling quality than heated air drying. High drying temperature had less energy consumption for CIR drying. But the measured energy consumption based on the laboratory prototype CIR dryer was much higher than industrial CHA dryer, which could be due the too small size of the CIR dryer. To achieve accurate estimate of energy consumption of CIR drying, a large scale CIR dryer is needed.

3.6 Appendix: Test results

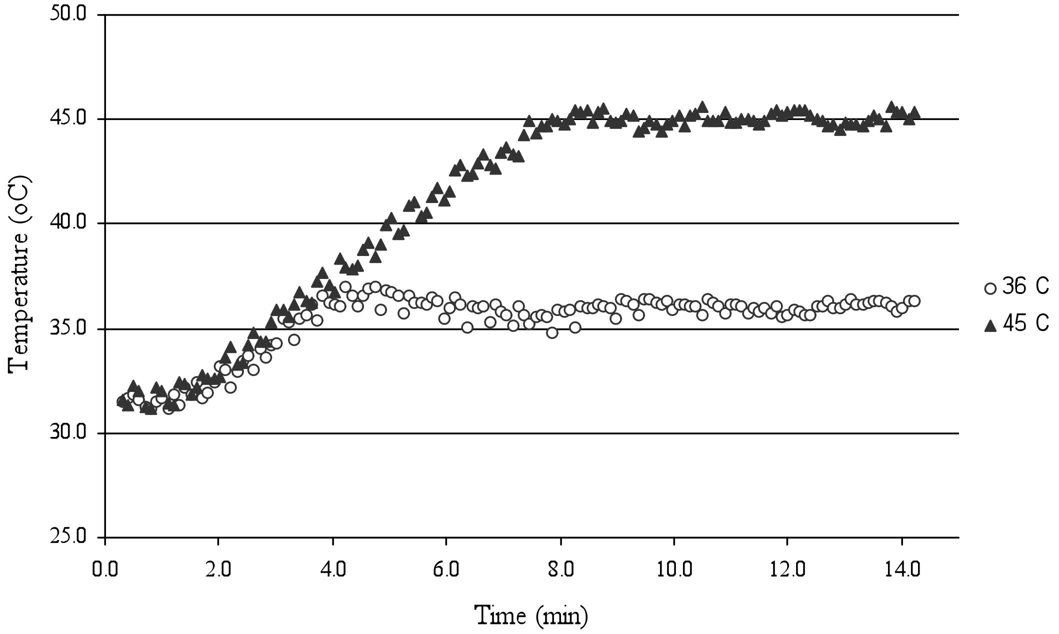


Figure 3-1. Rice temperature profiles at 36°C and 45°C drying temperature of infrared drying.

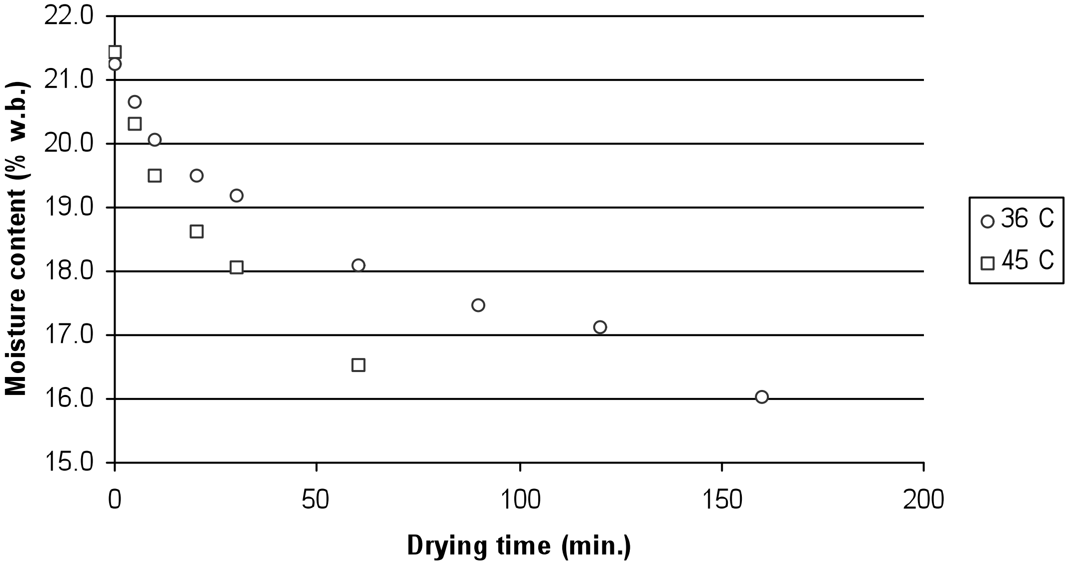


Figure 3-2. Drying curves of infrared drying at 36°C and 45°C

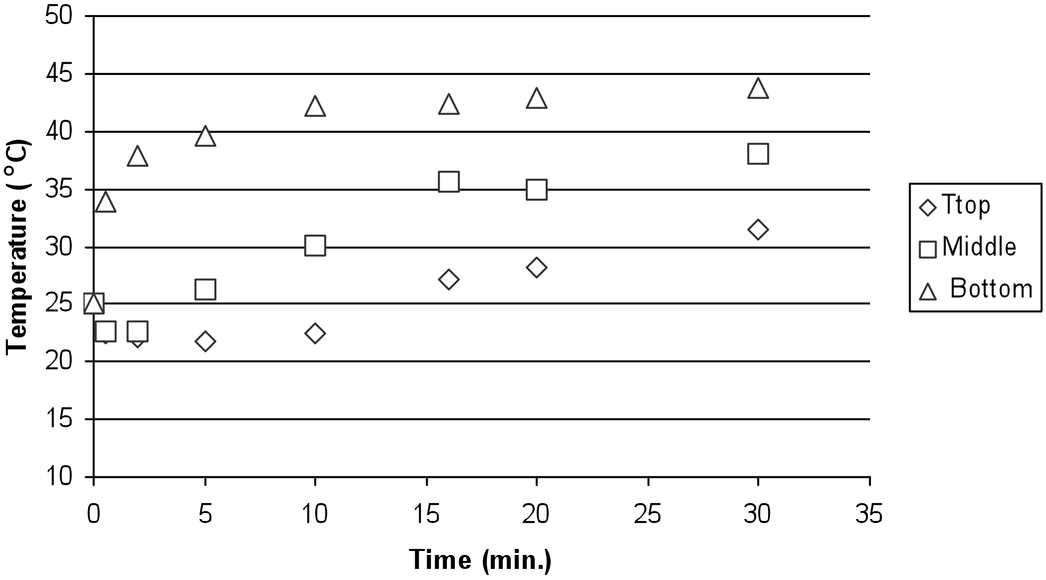


Figure 3-3. Temperature profile of CHA drying at 45 °C.

Table 3-1. Experimental design of rice drying*.

Drying Temperature (^oC)	Target moisture removal in each drying pass (%)	Drying conditions	Numbers of passes	Experiment Number
36	2	IR	SP	A
		IR	MP	B
		CHA	SP	C
		CHA	MP	D
	3	IR	SP	E
		CHA	SP	G
	4	IR	SP	I
		CHA	SP	K
45	1.5	IR	SP	M
		IR	MP	N
		CHA	SP	O
		CHA	MP	P
	2.5	IR	SP	Q
		IR	MP	R
		CHA	SP	S
		CHA	MP	T
	3.5	IR	SP	U
		CHA	SP	W

SP – Single pass drying
MP- Multiple Pass drying (two drying passes)
*For CIR drying the temperature was rice temperature and for CHA drying the temperature was air temperature

Table 3-2. Effect of drying conditions on rice milling quality

Drying Temp. (°C)	Target moisture removal (%)	MC removal after 1st drying pass (%)	MC removal after 2nd drying pass (%)	Drying condition (IR/CHA)	Number of passes	Exp. No.	TRY	HRY	Whiteness
36	2	2.3		IR	SP	A	70.50±0.28	62.95±0.07	40.58±0.32
		1.9	2.09	IR	MP	B	70.45±0.07	62.25±0.78	41.35±0.44
		1.6		CHA	SP	C	69.40±0.99	61.20±0.57	40.60±0.45
		1.6	2.65	CHA	MP	D	69.20±0.57	61.00±0.28	40.65±0.45
	3	2.7		IR	SP	E	70.15±0.35	62.55±0.64	41.05±0.33
		2.7		CHA	SP	G	69.35±0.21	61.80±0.28	40.97±0.61
	4	3.1		IR	SP	I	70.05±0.21	62.00±0.57	40.82±0.27
		3.9		CHA	SP	K	69.55±0.07	61.40±0.28	40.72±0.26
45	1.5	1.5		IR	SP	M	70.35±0.07	63.65±0.35	40.87±0.45
		2.0	2.19	IR	MP	N	70.10±0.28	61.60±0.14	40.85±0.35
		1.7		CHA	SP	O	69.65±0.07	60.95±0.07	40.22±0.52
		1.7	1.88	CHA	MP	P	69.95±0.21	61.55±0.21	40.07±0.43
	2.5	2.4		IR	SP	Q	70.20±0.57	62.30±1.13	40.70±0.62
		2.1	2.71	IR	MP	R	70.50±0.28	62.55±0.64	40.47±0.37
		2.8		CHA	SP	S	69.70±0.85	60.90±0.14	39.97±0.63
		2.8	2.94	CHA	MP	T	69.45±0.92	60.85±0.35	41.27±0.32
	3.5	6.2 *		IR	SP	U	69.90±0.14	61.45±0.21	40.40±0.39
		3.6		CHA	SP	W	69.65±0.21	60.60±0.0	40.22±0.46

SP – Single pass drying
MP- Multiple Pass drying (two drying passes)
*Over dried by 2.7%

Table 3-3. Statistical significance of mean quality parameters of CIR and CHA dried rice under different drying conditions.

Exp.		T (°C)	% MC loss/each pass	No. of Passes	Average HRY		Average TRY		Average Whiteness	
IR	CHA				IR	CHA	IR	CHA	IR	CHA
A	C	36	2	SP	62.95*	61.20	70.50	69.40	40.58	40.60
B	D	36	2	MP	62.25	61.00	70.45 *	69.20	41.35 *	40.65
E	G	36	4	SP	62.55	61.80	70.15	69.35	41.05	40.97
I	K	36	4	SP	62.00	61.40	70.05 *	69.55	40.82	40.72
M	O	45	1.5	SP	63.65 **	60.95	70.35 **	69.65	40.87 *	40.22
N	P	45	1.5	MP	61.60	61.55	70.10	69.95	40.85 **	40.07
Q	S	45	2.5	SP	62.30	60.90	70.20	69.70	40.70 *	39.97
R	T	45	2.5	MP	62.55 *	60.85	70.50	69.45	40.47	41.27 **
U	W	45	3.5	SP	61.45 *	60.60	69.90	69.65	40.40	40.22
Average					62.37	61.14	70.24	69.54	40.79	40.52

SP – Single pass
MP- Multiple pass (two drying passes)
* Significant at 5% confident level
** Significant at 1% confident level

Table 3-4. Effect of the number of drying passes on rice quality at different drying conditions.

Exp.		Tem. (°C)	% MC removal /pass	Drying Method	Average HRY		Average RTY		Average Whiteness	
SP	MP				SP	MP	SP	MP	SP	MP
A	B	36	2	IR	62.95	62.25	70.50	70.45	40.58	41.35 **
C	D	36	2	CHA	61.20	61.00	69.40	69.20	40.60	40.65
M	N	45	1.5	IR	63.65 **	61.60	70.35	70.10	40.87	40.85
O	P	45	1.5	CHA	60.95	61.55*	69.65	69.95	40.22	40.07
Q	R	45	2.5	IR	62.30	62.55	70.20	70.50	40.70	40.47
S	T	45	2.5	CHA	60.90	60.85	69.70	69.45	39.97	41.27 **
Average					61.99	61.63	69.97	69.94	40.49	40.78

SP – Single pass
MP- Multiple pass (two drying passes)
* Significant at 5% confident level
** Significant at 1% confident level

Table 3-5. Industrial cross flow drying data from California Family Foods

Parameter	Value
Initial Moisture content	22%
MC after 1st drying pass	20%
MC after second pass	18.5%
HRY	58%
TRY	70%

Table 3-6. Energy consumption of CIR drying at 36°C drying temperature

Drying time (min)	% MC reduction	Gas energy input (kJ/kg of water evaporated)	Electrical energy input (kJ/kg of water evaporated)	Total energy (kJ/kg of water evaporated)
5	0.7	23046.7	6059.6	29106.3
10	1.3	17285.2	6059.7	23344.9
20	1.9	18567.8	8241.1	26809.0
30	2.2	21005.6	10440.6	31446.3
60	3.3	26382.0	13974.3	40356.4
90	3.9	31445.9	17553.5	48999.4
120	4.3	38233.2	21507.8	59741.0
160	5.4	40795.3	23083.2	63878.5

Table 3-7. Energy consumption of CIR drying at 45°C drying temperature

Drying time (min)	% MC reduction	Gas energy input (kJ/kg of water evaporated)	Electrical energy input (kJ/kg of water evaporated)	Total energy (kJ/kg of water evaporated)
5	1.1	13702.31	3249.5	16951.8
10	1.9	12135.97	3812.5	15948.4
20	2.8	13410.59	5232.1	18642.7
30	3.4	15664.06	6570.6	22234.6
60	4.9	19483.98	9241.2	28725.2

Table 3-8. Results of rice drying of a commercial rice dryer

Description	Quantity
Amount of rice dried	811446 kg at 13%MC
Drying time	8h
Initial moisture content	19.9% w.b.
MC after one drying pass	18.5% w.b.
Amount of gas used	1020 Therms (107,590,008 kJ)
Amount of Electricity used	838 kWh
Gas energy used	7107 kJ/kg of water evaporated
Electrical energy used	199 kJ/kg of water evaporated
Total energy efficiency	7306 kJ/kg of water evaporated

4 Effectiveness of Catalytic Infrared Heating for Simultaneous Drying and Disinfestation of Rough Rice

4.1 Summary

The objective of this study was to investigate the drying characteristics, milling quality, and disinfestation effectiveness of rough rice under infrared (IR) radiation heating. Freshly harvested medium grain rice (M202) samples with low (20.6%) and high (25.0%) moisture contents (MC) were used for this study. Single-layer rough rice samples (non-infested and infested with the adults and eggs of lesser grain borers (*Rhizopertha dominica*) and angoumois grain moths (*Sitotroga cerealella*) were heated for various durations using a catalytic infrared emitter. The effects of tempering treatment and natural and forced air cooling methods on moisture removal, milling quality and disinfestation were determined. High heating rate and corresponding high moisture removal were achieved by using the IR heating. After heating, tempering increased moisture removal during cooling and improved milling quality of the rice samples. For example, 60 s of IR heating of 20.6% MC rice resulted in 61.2°C rice temperature, 1.7 percentage MC removal during the heating period and additional 1.4% MC removal after tempering and natural cooling. The rice also had 1.9 percentage points higher head rice yield than control sample dried with ambient air. The heating and tempering treatment also completely killed the tested insects. It is concluded that simultaneous drying and disinfestation with high rice milling quality can be achieved by using the catalytic IR to heat rough rice to 60°C followed by tempering and slow cooling.

4.2 Objectives

The objectives of this research were to (1) study the drying and milling characteristics of rice with high and low harvest MC under single-layer heating using catalytic IR followed by tempering and cooling treatments; and (2) determine the effective IR heating conditions for disinfestation and technical feasibility of simultaneous drying and disinfestation.

4.3 Materials and Methods

4.3.1 Rough rice and infestation methods

Freshly harvested medium grain rice, M202, obtained from Farmers' Rice Cooperative (West Sacramento, CA) was used for conducting the IR drying and disinfestation tests. The moisture content of rough rice was 25.0±0.3% (high MC) at the harvest. The rice sample with the high MC was equally divided into two portions. One of the portions was slowly dried to 20.6±0.2% (low MC) with room temperature from 17°C to 20°C on the floor in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The thickness of rice bed on the floor was less than 5 cm. During the slowing drying the rice was mixed frequently to ensure uniform drying. It took about three days to reach the 20.6% MC. Then the rice samples with both low and high MC were kept in polyethylene bags and sealed to ensure no moisture loss before they were used for the IR drying and disinfestation tests. The rice samples were further divided into 250 g samples with a sample divider at the test time. The drying and disinfestation tests were separately conducted using non-infested and infested samples. All reported moisture contents are on wet weight basis and determined by the air oven method (130°C for 24 h) (ASAE, 1995).

Four days before the disinfestation tests, each 250 g rice sample was infested with 100 adult lesser grain borers (*Rhizopertha dominica*), and 50 adult angoumois grain moths (*Sitotroga cerealella*), the most common insects in rough rice. These insects were emerged at the Entomology Laboratory, Department of Entomology, University of California, Davis after they were collected from naturally infested rough rice. The rice samples contained both adult insects and their eggs at the time of disinfestation treatment using infrared heating.

4.3.2 Infrared heating treatment

A catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as infrared radiation source (Figure 2-2). The emitter generated IR radiation energy by catalyzing natural gas to produce heat along with small amounts of water vapor and carbon dioxide as by-products. The dimension of the emitter was 30 x 60 cm with surface temperature at about 730°C and corresponding peak wavelength of 3.6 μm assuming a blackbody. An aluminum box with dimension of 65 cm (length) x 37 cm (width) x 45 cm (height) was installed around the emitter as wave guide to achieve a uniform IR intensity at the rice bed surface. The rice bed was set at 5 cm below the bottom edge of the wave guide. The average IR intensity at the rough rice bed surface was 5348 W/m^2, which was measured by using Ophir FL205A Thermal Excimer Absorber Head (Ophir, Washington, MA). The drying bed was made with a 3 mm thick aluminum plate for minimizing the radiation energy loss through the drying bed due to its high reflectively. The reflected radiation energy could also be used to heat the bottom side of rice kernels. A piece of plywood was installed beneath the aluminum plate for reducing the energy loss through conduction. In the drying and disinfestation tests, a 250 g rice sample was placed on the drying bed as a single layer with corresponding calculated loading rate of 2 kg/m^2.

Both high and low MC rough rice samples were used for the drying and disinfestation tests. For measuring the drying characteristics and milling quality, sixteen non-infested rice samples were heated for each of the four time durations, 15, 40, 60 or 90 s with initial drying bed surface temperature of 35°C. The rice sample weights were measured with a balance with two-decimal accuracy before and after heating. The weight loss during heating and the original moisture content were used to calculate the moisture removal during the heating periods. The moisture removal was calculated as the difference between the original MC and the MC after treatment and reported as percentage points. For disinfestation tests, because the rice temperature under 15 s heating was too low to kill the insects, eight infested rice samples were heated for each of the durations of 25, 40, 60 and 90 s. The grain temperature with 25 s heating was also determined. Control samples for milling quality comparison were produced by drying the high and low MC rough rice samples using room air to 13.6% from the original moisture contents.

4.3.3 Tempering and cooling treatments

In order to study the effects of tempering on moisture loss during cooling, disinfestation, and milling quality, both tempered and non-tempered samples were prepared. Half numbers of the heated rice samples (8 non-infested and 4 infested samples) were tempered and the rest of the samples were cooled without tempering in the laboratory. The tempering was conducted by keeping rice samples in closed containers placed in an incubator with a temperature as same as the heated rice for 4 h immediately following the heating. For non-infested rice samples, four samples were each cooled using natural cooling (slow cooling) or forced air cooling at room temperature of 20°C to 24°C as a thin layer (about 1 cm thick). For natural cooling, the thin layer of rice was placed on a laboratory bench for about 30 min. For forced air cooling, the samples were placed on mesh trays and cooled by blowing room air through the bed with air velocity of 0.1 m/s. All forced air cooling samples were cooled for 5 min. After the natural and forced air cooling processes, the temperatures of rice samples were close to the room air temperature. The sample weight changes caused by the cooling treatments were recorded at the end of cooling and used to calculate the moisture removal based on the moisture contents after corresponding IR heating treatments. The cooled samples were stored in polyethylene bags before they were further dried to 13.3±0.2% MC using room air. Two samples of each original weight of 250 g under each treatment were combined into one sample with a total weight more than 400 g for milling quality and disinfestation evaluation, which resulted in two samples under each treatment for the tests. The samples were stored in Ziplock bags at room temperature for about one month before milling. In order to avoid losing insects during handling, in the disinfestation tests the infested rough rice samples were only cooled with natural cooling after heating or tempering.

4.3.4 Milling quality and evaluation

The most important rice milling quality indicators are total rice yield (TRY), head rice yield (HRY) and degree of milling. To evaluate the effect of different treatments, the non-infested rice samples of 400 g each were dehulled and milled by using Yamamoto Husker (FC-2K) and Yamamoto Rice Mill (VP-222N, Yamamoto Co. Ltd., Japan). The rice samples were milled three times to achieve the well milled rice as defined by the Federal Grain Inspection Service (USDA FGIS, 1994). For the first two times, the settings of Throughput and Whitening were 1 and 4, respectively. For the third time, the settings were 1 and 5. The evaluated milling quality indicators included TRY, HRY, and Whiteness Index (WI). The HRY was determined with Graincheck (Foss North America, Eden Prairie, MN). The WI was used to evaluate the whiteness (degree of milling) of milled rice and determined with the Whiteness Tester, C-300, (Kett Electronic Laboratory, Tokyo, Japan). High index number indicates whiter milled rice. All quality evaluations were conducted at Farmers' Rice Cooperative (West Sacramento, CA).

4.3.5 Effectiveness of disinfestation treatments

After the IR heating or tempering treatments, all naturally cooled, infested rice samples were transferred to glass jars with screened lids to maintain sample moisture and oxygen supply to allow surviving insects and eggs to emerge. All jars were kept in incubators at 28°±2°C with 64±3% relative humidity (RH) to allow development of surviving insects and eggs (Kirkpatrick, 1975). The populations of the surviving and emerged live adult insects were visually counted one day after the treatment and then every several days for 35 days that covered more than one life cycle of the insects. All adult insects were removed from the rice samples after each examination. The average numbers of live adult insects in the two samples under each treatment at different storage times are reported. Because each sample was obtained by combing two original samples, the original numbers of insects were doubled in each incubated sample.

4.4 Results and Discussions

4.4.1 Moisture removals under different heating durations

After the 20.6% and 25.0% MC rough rice samples were heated for 15, 40, 60, and 90 s, they reached corresponding temperatures of 42.8, 54.3, 61.2, 69.4°C, and 42.8, 55.5, 59.1, 68.0°C, respectively. The low MC rice samples had slightly higher temperatures than the high MC rice samples at 60 and 90 s heating, which could be due to less energy used for heating the water and a lower evaporative cooling effect in the low MC rice than the high MC rice under the constant radiation heat supply. The maximum difference in temperatures of the samples with different original MC under the same heating duration was 2.2°C, which was relatively small. Therefore, the average temperatures of low and high MC rice samples at different heating durations are presented in Figure 4-1. A high correlation between the average rice temperature and heating time was obtained with a power model. The model can be used to predict the temperature change for the rice with a known heating time under the tested moisture range and bed temperature. In our other experiments, the required heating time to reach a specific rice temperature was significantly reduced when the drying bed temperature increased by preheating to a higher temperature than the 35°C used in this study. If it is necessary to reduce the heating time, the method of preheating drying bed to a relatively high temperature could be considered. Further research is needed to study the effect of preheating temperature on the required heating time, moisture removal, and milling quality of rough rice.

The trend of high moisture removal for the high MC rice samples was clearly shown in Figure 4-2 even though the difference between the low and high moisture rice samples was relatively small. With 90 s heating (average temperature of 68.7°C), the moisture removal was 2.8 and 2.5 percentage points for the high and low MC rice samples. It is important to notice that the average drying rates of the rice samples with initial 25% and 20.5% MCs were 2.4, 1.8, 1.7, and 1.7 percentage points per minute at the moisture removal levels of 0.6, 1.2, 1.7, and 2.6 percentage points by each drying pass. The high drying rate at relative high moisture removal levels by each drying pass, for example of 1.7 percentage points per min at 1.7 and 2.6 percentage point MC removal, was much higher than that of current commercial, conventional heated air drying of 0.1 to 0.2 percentage points per min due to low heated air temperature used (Kunze and Calderwood, 1985). The high drying rate was achieved by using IR heating alone even without counting the moisture removal during cooling.

4.4.2 Moisture removals under different tempering and cooling treatments

The clear trends of tempering vs. non-tempering and natural cooling vs. forced air cooling are seen in Figures 4-3 and 4-4. For low MC rice, the moisture removals of tempered rice samples under natural cooling and forced air cooling were 0.6 to 1.3 and 1.1 to 1.9 percentage points, respectively, in the tested temperature range from 42.8°C to 69.4°C. In contrast, the non-tempering rice had 0.4 to 0.8 and 0.7 – 0.9 percentage point moisture removals under natural cooling and forced air cooling, respectively. The tempering resulted in 0.2 to 0.5 percentage point more MC removals than non-tempering, which showed that tempering treatment significantly improved the moisture removal during cooling compared to non-tempering samples. The forced air cooling also had more moisture removal up to 0.9 percentage points than natural cooling in the tested temperature range. However, at the high heating temperature of 69.4°C without tempering, similar moisture removals were achieved with both natural cooling and forced air cooling. This was due to the high moisture gradients after more than 2.5 percentage point moisture removal and moisture diffusion in the rice kernels became limited factor for further improving the drying rate by using increased drying force of forced air cooling.

The high MC rice had similar moisture removal trends as the low MC rice during cooling even though more moisture was removed compared to the low moisture rice. The tempered rice had the moisture removals of 1.6 to 2.2 percentage points for forced air cooling and 0.8 to 1.5 percentage points for natural cooling compared to 1.1 to 1.3 percentage points for forced air cooling and 0.4 to 1.1 percentage points for natural cooling of non-tempered rice in the tested temperature range. The tempering treatment resulted 0.4 to 0.5 and 0.5 to 0.9 percentage points more moisture removals than the non-tempering treatment under natural cooling and forced air cooling, respectively. The results indicate that tempering is even more important for high MC rice than low MC rice to have high MC removal during cooling.

Based on the above results, the tempering process reduced the moisture gradient in rice kernels and allowed the moisture to equilibrate before the rice kernels were cooled. Without tempering, there was a significant moisture gradient in the rice kernels and low moisture content near the surface, which resulted in less moisture removal during cooling. In general, both reduced moisture gradient in the tempered rice kernels and forced air cooling increased the moisture removal during the cooling process. Therefore, the tempering process is a critical step to increase the moisture removal during cooling. In order to achieve high moisture removal during cooling, a combination of tempering and forced air cooling could be used even though the high moisture removal could cause rice fissures lowering rice milling quality which need to be considered.

The trend of total moisture removal at different temperatures with different tempering and cooling treatments was more or less parallel to the moisture removal caused by heating only (Figures 4-5 and 4-6). The highest total MC removals of rice were 1.7 to 4.4 and 2.2 to 4.8 percentage points for low and high MC rice samples, respectively, which were achieved with tempering and forced air cooling among the treatments. But the lowest total MC removals were generally occurred for rice experienced non-tempering and natural cooling treatment. For rice treated with tempering and natural cooling, the total moisture removals were 1.4, 2.4, 3.2 and 4.3 percentage points for the high MC rice and 1.3, 2.0, 2.7 and 3.8 percentage points for the low MC rice under the tested temperature range. The moisture removals were the second highest among the treatments when the temperatures were above 55°C. These numbers indicated that 2.7 to 3.2 percentage point moisture were removed with 1 min heating followed by tempering and natural cooling. The drying rates were much higher than the 2 to 3 percentage point moisture removal with 15 to 20 min heating of the current conventional hot air drying.

For the total moisture removal, the moisture removed due to sensible heat during cooling was a very significant portion. For example, 37% and 44% of total moisture removals occurred during cooling when the low and high MC rice samples were heated for 60 s (about 60°C) followed by tempering and natural cooling. Because no additional heating energy is needed during the cooling, the high moisture removal could further improve the energy efficiency of the IR drying process. The exact amounts of energy saving and consumption still need to be determined in future research.

4.4.3 Milled rice quality

In general, for both the high and low initial moisture rice samples, infrared dried rice with tempering followed by natural cooling had similar and higher TRY compared to the control (Figures 4-7 and 4-8). On average, the TRYs of low and high MC rice dried by using IR followed with natural cooling were 68.0% and 68.1%, respectively, which were 0.3 and 0.7 percentage points more than the controls. Especially, the rice dried at about 60°C with natural cooling had the highest TRYs of 68.4% for low moisture rice and 68.6% for high moisture rice compared to the controls of 67.7% and 67.4%, respectively. This meant that the TRYs of IR dried rough rice were 0.7 to 1.2 percentage points more than the control. However, the samples treated with other methods had much lower TRYs than the controls, especially for the rice with the low MC dried under the high temperature.

Similar trends were also observed for the HRYs (Figures 4-9 and 4-10). The low MC rice samples dried using IR with tempering and natural cooling had significantly higher HRY (0.6 to 1.9 percentage points) than the control and the highest HRY of 65.2% was obtained with 61.2°C of rice temperature. For the high moisture rice, the rice dried followed by tempering and natural cooling had the same HRY (63.6%) at 58.8°C as the control and slightly lower HRY at 42.8°C and 55.5°C than the control. All other post heating treatments resulted in much lower HRYs.

When the results of the WI of milled rice were examined, it can be seen that the IR dried rice generally had higher WI values than the controls, especially for the low MC rice, even though the differences between the controls and the some of the treated rice samples were not significant (Figures 4-11 and 4-12). This indicated that most of IR dried rice with tempering followed by natural cooling had a similar milling degree to the control. It seems that there is the trend that WI increased with the increase of the rice drying temperature for the non-tempering treatment, especially for the low MC rice. This could be due to the difference in the hardness of rice with different treatments and/or the contribution of broken kernels to the color, which needs to be further studied.

Based on the milling quality results, it can be concluded that rice can be dried by using IR followed by tempering and natural cooling to achieve superior rice milling quality. It is recommended that the rice temperature of IR heating is controlled at close or below 60°C. For the current rice drying practice, the drying temperature or heated air temperature is controlled away below the 60°C to avoid creating fissures lowering HRY. The reason that the high temperature of IR heating did not damage the rice quality could be due to the relative uniform heating in the rice kernel resulting from the IR penetration, which had less moisture gradient compared to conventional heated air drying. The results indicate rice milling quality may not be compromised with a relatively large amount of moisture removal in a single drying pass with high drying rate if the rice can be heated quickly and uniformly for minimizing the moisture gradient. When a large amount of moisture is removed during IR heating, tempering is very important to reestablish the moisture equilibrium in rice kernels.

This research also showed that the cooling method following the tempering was very important. The rapid cooling by using forced air can significantly lower the rice milling quality. Because a relative large amount of moisture was removed during forced air cooling, the cooling might regenerate significant moisture and temperature gradients causing fissures. Based on the glass transition hypothesis, the temperature and moisture at the rice surface were lowered first and starch reached glassy state during cooling. At the same time the center temperature and moisture of rice kernel were still relatively high and starch was remained at rubbery state. The differences in thermomechanical properties of starch at different stages would generate stress and fissure resulting in breakage in milling and lowered rice milling quality. Therefore, controlled slow cooling will be very important for high temperature rice drying. Since the natural cooling effectively preserved the quality, controlled slow cooling could be accomplished by low rates of air flow through a bin of rice to cause cooling.

4.4.4 Effectiveness in disinfestation

The disinfestation results clearly showed adult beetles were more heat resistant than the adult moths (Tables 4-1 and 4-2). The 60 and 90 s heating killed moths in all stages in the rice with both the initial MCs. Only a few of adult moths survived the at the low temperature treatments. It was also observed some adult moths developed from the eggs or 1st-stage larvae during the incubation for the low MC rice with 25 s heating treatment. For beetles, the 90 s heating regardless of tempering or non-tempering and 60s heating with tempering achieved near 100% kill even though total 4 inactive beetles were found in all samples under such treatments. With the low temperature treatments, significant numbers of live adult beetles were discovered during the first week of the incubation, which were believed to be the adult beetles survived the treatments. The obtained results agreed with the reported results that the death time of insects was less than 1 min if they are heated to temperature above 62°C (Banks & Fields 1995, Fields & Muir 1996). Based on the disinfestation results, it is recommended to heat rice to 60°C followed by tempering to achieve complete disinfestation of moths and beetles. Because the 60°C rice temperature followed by tempering also had high rice milling quality, it is concluded that IR heating can be used for simultaneous drying and disinfestation for freshly harvested rough rice.

It appeared that non-tempered samples, especially at low temperatures, had fewer insects developed during the incubation than the samples without tempering. This could be due to the cooling shock of the non-tempering reduced the surviving capability of the insects after the IR treatment, which needs to further studied.

4.5 Conclusions

The research showed high rice drying temperature can be achieved with a relatively short heating time by using catalytic IR emitter with single-layer of rough rice. The moisture removal during heating increased with an increase in rice temperature. It took only 60 s to achieved about 60°C rice temperature and removed 1.7 and 1.8 percentage point MC during IR heating alone for the low and high MC rice, respectively. The tempering process after the rapid IR heating and moisture removal is essential to achieve high rice milling quality and improve the amount of moisture removal during cooling. The natural cooling following the tempering treatment can be used to remove a significant amount of moisture with high rice milling quality. But the forced air cooling following heating or tempering could result in lowered rice milling quality, which is not recommended. The recommended conditions for simultaneous drying and disinfestation of freshly harvested rice were 60°C rice temperature followed by tempering and slow cooling.

4.6 References

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4.7 Appendix - Test Data and Results

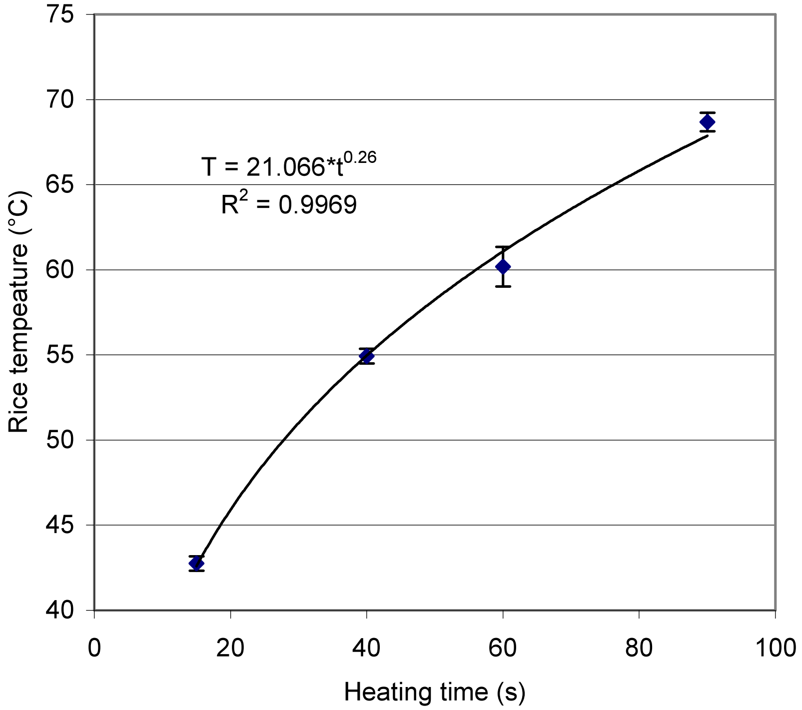

Figure 4-1. Relationship between rice temperature and heating time

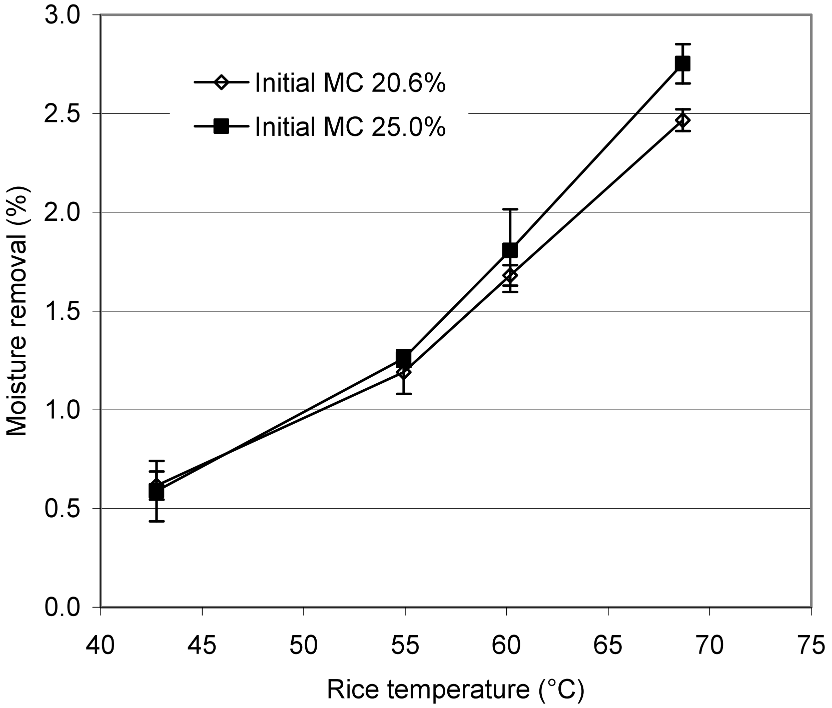

Figure 4-2. Moisture removals of rice samples with different initial moisture contents after heated to various temperatures

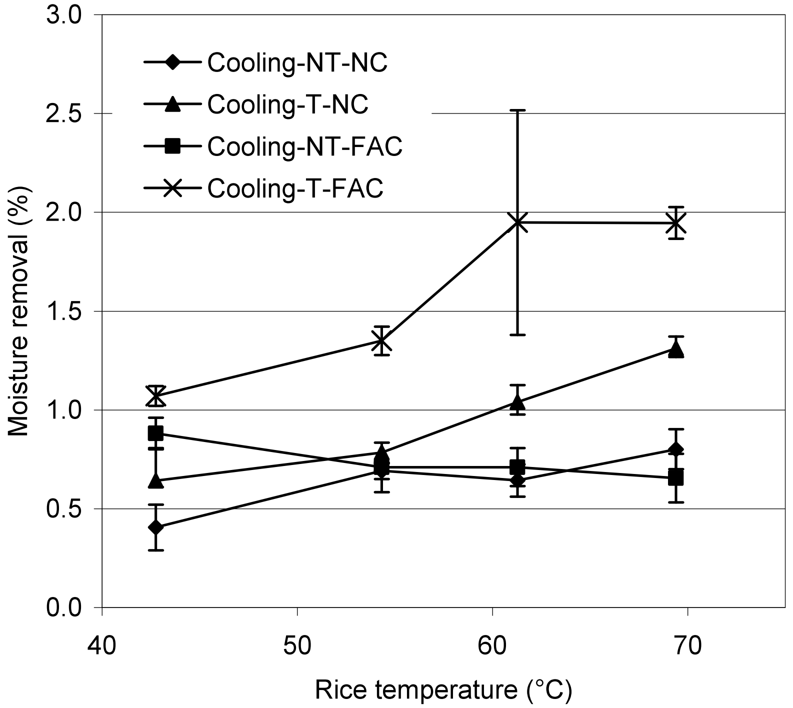

Figure 4-3. Moisture removal of rice with initial MC of 20.6% under different cooling methods with and without tempering

(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

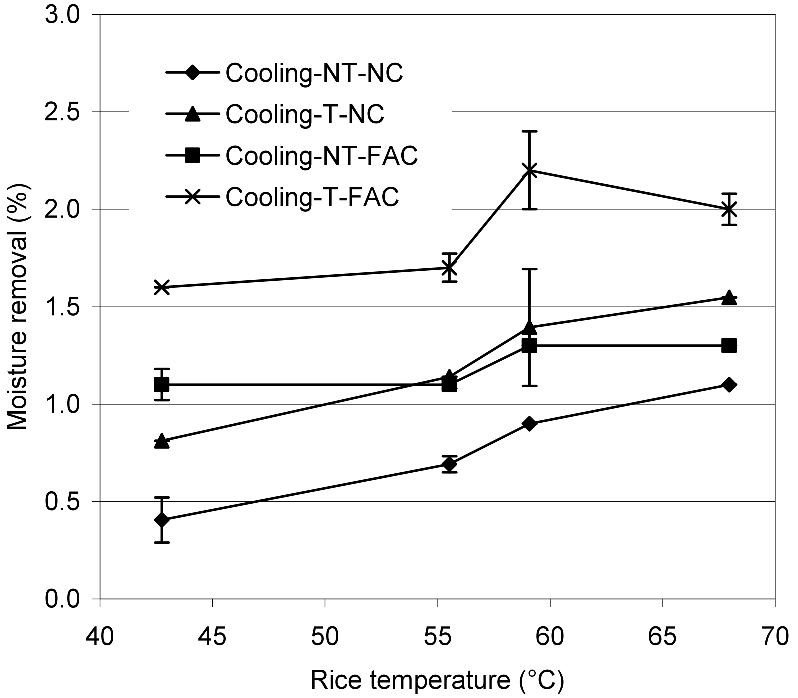

Figure 4-4. Moisture removal of rice with initial MC of 25.0% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

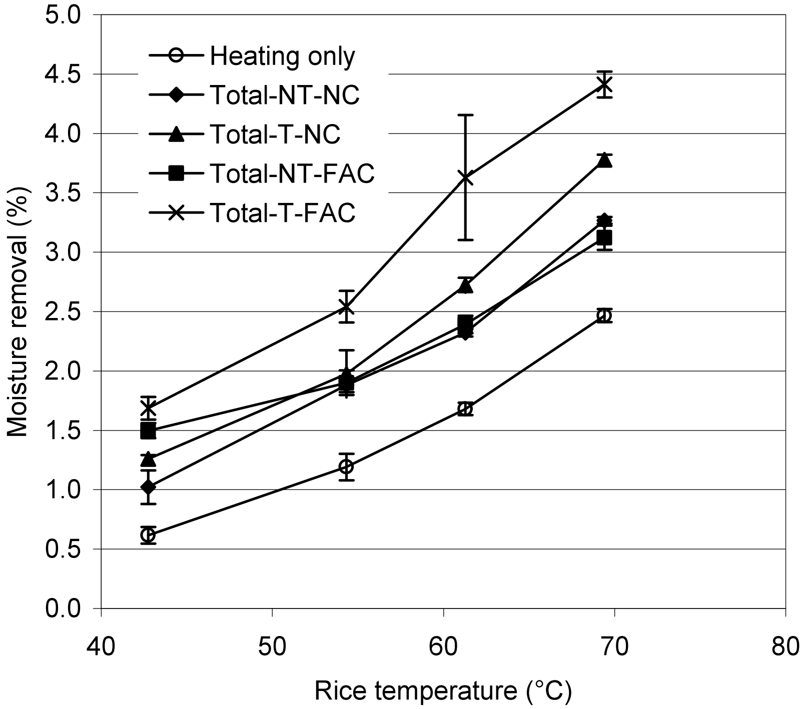

Figure 4-5. Total moisture removal of rice with initial MC of 20.6% under different cooling methods with and without tempering

(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

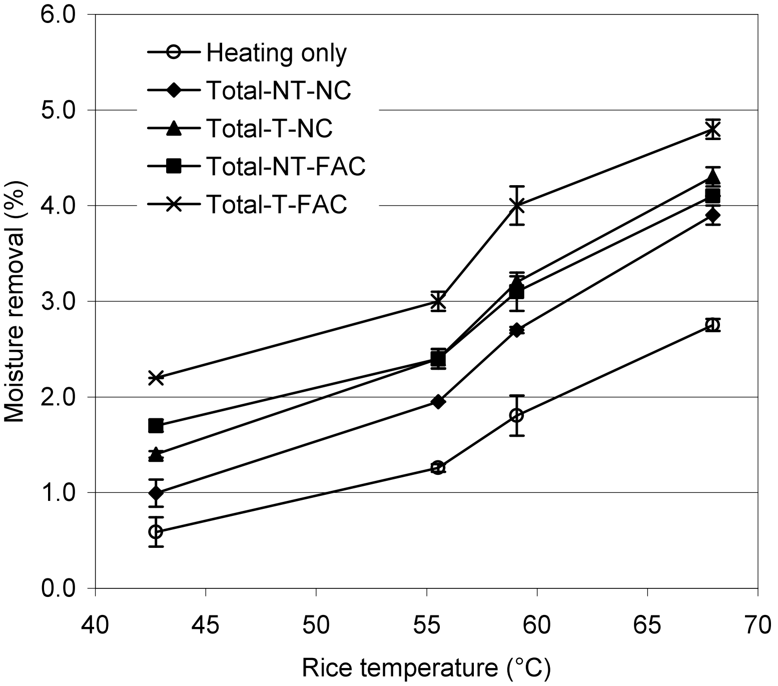

Figure 4-6. Total moisture removal of rice with initial MC of 25.0% under different cooling methods with and without tempering

(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

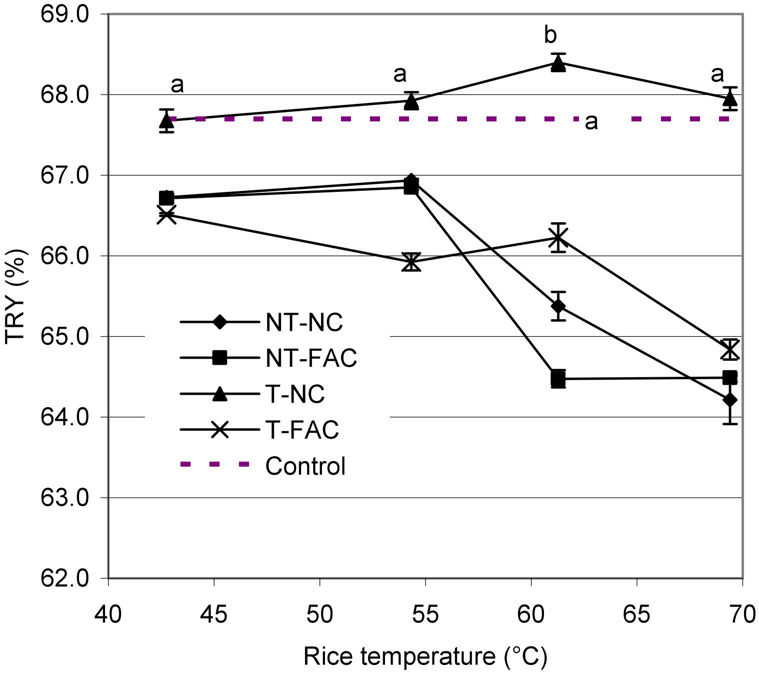

Figure 4-7. Total rice yields of rice with 20.6% initial moisture content and different drying treatments

(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

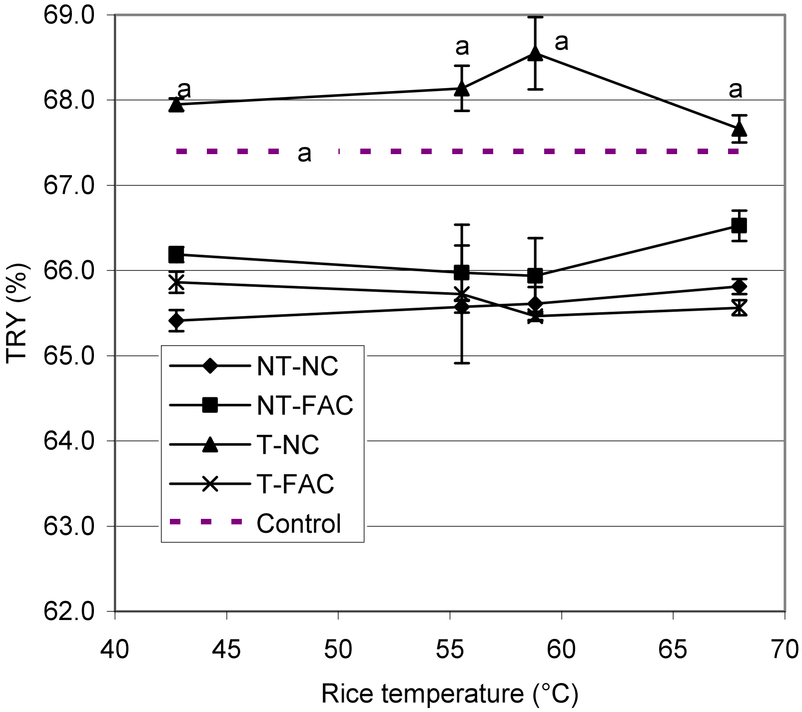

Figure 4-8. Total rice yields of rice with 25.0% initial moisture content and different drying treatments

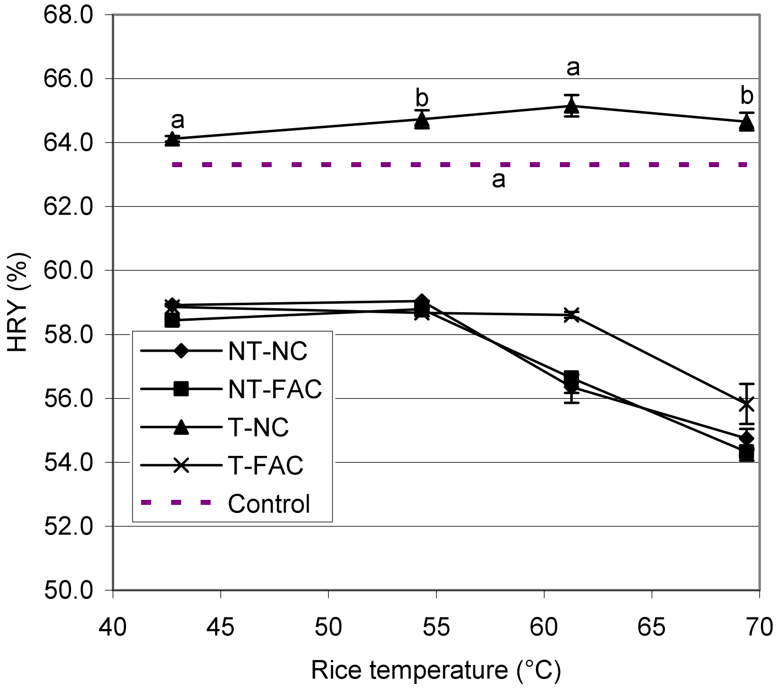

Figure 4-9. Head rice yields of rice with 20.6% initial moisture content and different drying treatments

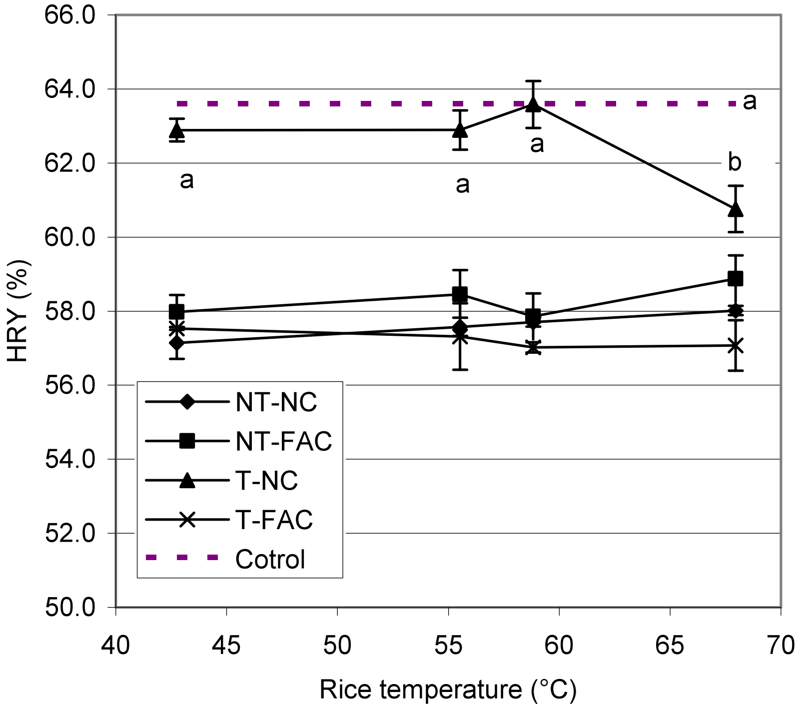

Figure 4-10. Head rice yields of rice with 25.0% initial moisture content and different drying treatments

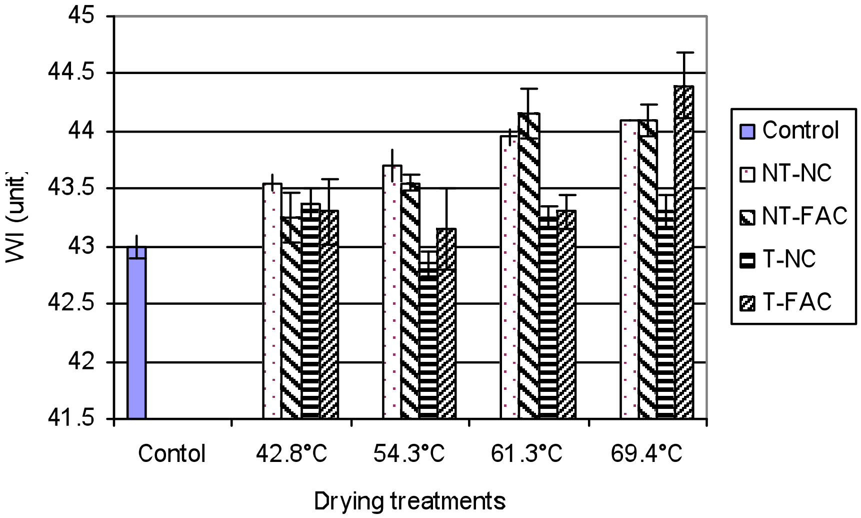

Figure 4-11. Whiteness of milling rice with 20.6% initial moisture content and different drying treatments

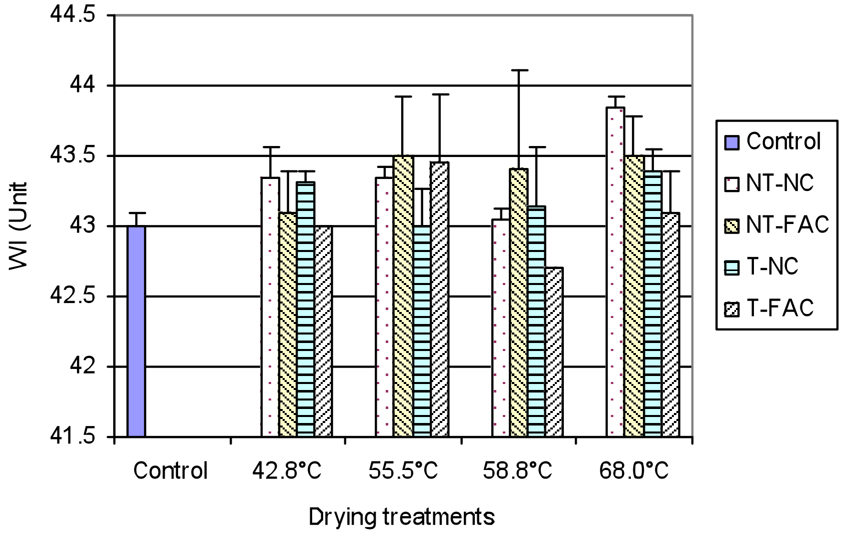

Figure 4-12. Whiteness of milling of rice with 25.0% initial moisture content and different drying treatments

Table 4-1. Numbers of live moths in the rice samples with different drying treatments[a]

Harvest MC (%)	Heating time (s)	Rice temperature (°C)	Tempering	Days of storage after treatment						
				1[b]	5	8	15	27	32	34
20.6%	90	69.4	Yes	0	0	0	0	0	0	0
	90	69.4	No	0	0	0	0	0	0	0
	60	61.3	Yes	0	0	0	0	0	0	0
	60	61.3	No	0	0	0	0	0	0	0
	40	54.3	Yes	0	0	0	0	0	8	2.5
	40	54.3	No	0.5	0	0	0	0	0	0
	25	49.0	Yes	0	0	0	0	0.5	17.5	3.5
	25	49.0	No	0	0	0	0	0	0.5	0
25.0%	90	68.0	Yes	0	0	0	0	0	0	0
	90	68.0	No	0	0	0	0	0	0	0
	60	59.1	Yes	0	0	0	0	0	0	0
	60	59.1	No	0	0	0	0	0	0	0
	40	55.5	Yes	0.5	0.5	0	0	0	0	0
	40	55.5	No	0	0	0	0	0	0	0
	25	49.0	Yes	1	1	0	0	0	0	0
	25	49.0	No	0	0	0	0	0	0	0

[a] Numbers are the average numbers of insects recovered from two samples at each treatment condition

[b] Numbers of insects that survived the thermal treatment

Table 4-2. Numbers of live beetles in rice samples with different drying treatments[a]

Harvest MC (%)	Heating time (s)	Rice temperature (°C)	Tempering	Days of storage after treatment						
				1[b]	5	8	15	27	32	34
20.6%	90	69.4	Yes	0	0	0.5	0	0.5	0	0
	90	69.4	No	0	1	0	0	0	0	0
	60	61.3	Yes	0	0	0	0	0	0	0
	60	61.3	No	0	0.5	0	0	0	0	0
	40	54.3	Yes	26	51	1	1	0	0.5	0
	40	54.3	No	0.5	0	0	0	0	0	0
	25	49.0	Yes	45.5	54.5	3.5	1.5	0.5	0	0
	25	49.0	No	50.0	44.5	2	0.5	0.5	0	0
25.0%	90	68.0	Yes	0	0	0	0	0	0	0
	90	68.0	No	0	0	0	0	0	0	0
	60	59.1	Yes	0	0	0	0	0	0	0
	60	59.1	No	2	4.5	0.5	0	0	0	0
	40	55.5	Yes	26	51	1	1.5	0	0.5	0
	40	55.5	No	0	0	0	0	0	0	0
	25	49.0	Yes	58.5	67.5	2.5	1.5	2	0	0
	25	49.0	No	29.5	48.5	0.5	1	1	0	1

[a] Numbers are the average numbers of insects recovered from two samples at each treatment condition

[b] Numbers of insects that survived the thermal treatment

5 Effectiveness of Catalytic Infrared Heating for Disinfestation of Storage Rice

5.1 Summary

The objective of this part of research was to develop rapid, non-chemical, safe alternative methods to eliminate insect pests from storage paddy rice with retaining high rice quality. IR heating was evaluated for its effectiveness in eliminating insects. The tests were conducted with two different approaches (thick-layer heating and single-layer heating) using the CIR dryers. Medium grain rice M202 was used for the tests. After the CIR thermal treatments the survived insects in different forms were examined by counting the survived and emerged adult insects during storage after the treatments. The moisture loss caused by infrared heating and milling quality of treated rice samples were measured.

For thick-layer heating, Angoumois grain moth (*Sitotroga cerealella*) was tested. The rice samples were heated with CIR to different temperatures from 45 to 70°C and held for various times, from 1 to 10 min. The research results indicated that infrared heating could be used to disinfest storage rough rice. The required temperature and holding time were 50°C for 1 min. Under such treatments, no rice milling quality was affected, but infrared heating caused about 1 percentage point moisture loss.

For single-layer heating, before the disinfestation treatment, the rice samples were infested with lesser grain borers (beetles) (*Rhizopertha dominica)*, and angoumois grain moths (*Sitotroga cerealella)*. In order to reduce the moisture loss during infrared disinfestation treatment, the drying bed was pre-heated and rice was heated as single-layer. The single-layer heating method resulted in rapid heating of the rice with reduced moisture loss. For example, it took only 20 s to heat the rice sample to 60°C with 0.53% moisture loss compared to about 1.0% loss obtained with thick-layer heating. The infrared heating did not cause any significant changes in rice milling quality. The minimum required disinfestation conditions were 53°C with 20 min holding for moths and 60°C with 20 min holding for beetles.

In conclusion, infrared heating treatment can be used for disinfestation of storage rice without lowering the milling quality, but could cause about 0.53% moisture loss during heating.

5.2 Objectives

Ultimate goal of this part of research was to develop a rapid, non-chemical, safe alternative method to eliminate insect pests from storage rough rice. The specific objectives were:

1. Determine the effectiveness of infrared heating on disinfestations of storage rough rice with different infrared heating conditions.
2. Investigate the effects of the infrared heating treatments on rice milling quality and moisture loss.

5.3 Materials and Methods

5.3.1 Thick-layer heating treatment

5.3.1.1 Rough rice, moisture determination and milling quality evaluation

Two different storage California medium grain M202 samples were used for this study. A naturally infested rice sample with Angoumois grain moth (*Sitotroga cerealella*) and 12.9% moisture content from the Food Processing Lab at UC Davis was used for disinfestation tests. The moisture losses of the rice samples under different infrared treatments were determined by using oven method at 130°C for 24 h. A rice sample with 13.5% MC used for milling quality evaluation was obtained from Farmer's Rice Co-operatives in Sacramento. Under selected conditions of infrared heating treatments, the moisture losses and milling quality of treated rice samples were determined. The moisture content and milling quality were determined using standard FGIS method at the CDFA lab in Sacramento, CA. The evaluated quality indicators included total rice yield (TRY), head rice yield (HRY), and Whiteness Index (WI). The WI was used to evaluate the whiteness of milled rice determined with the Whiteness Tester, C-300, (Kett Electronic Laboratory, Tokyo, Japan). A higher index number indicates whiter milled rice.

5.3.1.2 Infrared heating treatment

The catalytic heating device (Fig. 2-1) was used for the tests. Since the infrared radiation directly heated the rice without heating the surrounding air, air temperature inside the heating chamber was much lower than the rice temperature. Therefore, the rice bed temperature was used as control temperature. Rice temperature was measured using two thermocouples that were inserted into the middle of the rice bed. The average of thermocouple readings was used to control the natural gas supply to the IR emitter. Gas supply to the IR emitter was controlled (switched on or off) by the DAC comparing the average bed temperature with the set point temperature. The heating times needed to reach the set point temperatures were recorded. Then the samples were kept in the heating chamber for the desired time periods.

Sample size for the disinfestation treatments was 2 kg for each batch, which was corresponded to about 2 cm thickness of rice bed. After reaching the desired treatment time, the samples were taken out from the heating chamber and saved for moisture and disinfestation evaluation. The experimental design was shown in the Table 5-1. Based on the results of disinfestation evaluation, only four treatment conditions, 50°C for 1 and 5 min and 60°C for 1 and 5 min, were used to obtain rice samples for milling quality evaluation.

5.3.1.3 Evaluation of effectiveness in disinfestation

After infrared heating treatment, all rice samples were transferred to plastic containers or glass jars with screen on lids to maintain sample moisture and oxygen supply to allow for surviving insects, larvae or eggs to grow. All these containers were kept inside an incubator of 80% relative humidity (RH) and 28°C for infrared treated samples during an observation period of up to about 42 days.

Insect populations at each observation period were determined by counting the number of emerging adults in each rice sample (both treated and control) every 2-3 days, during the entire observation period. Cumulative numbers of emerging adults as a function of time were then calculated and reported. The results showed the disinfestation effectiveness of the treatments on storage rice infested with Angoumois grain moth. If no live adult insects were observed after 1 or two insect life cycles (about 21 days for each cycle), the treatment conditions were considered as effective. After each observation and counting all adult insects were removed.

5.3.2 Single-layer heating treatment

5.3.2.1 Rough rice and infestation methods

Storage rough rice, medium grain rice, M202, with moisture content of 11.0% was used for this part of study. The rice sample was obtained from Pacific International Rice Mills, Inc. (Woodland, CA). The moisture contents of all rice samples used for this study were determined by using an oven method at 130°C for 24 h.

Each 250 g rice sample was infested with 100 adult lesser grain borers (beetles), *Rhizopertha dominica*, and 50 adult angoumois grain moths, *Sitotroga cerealella,* at 18 and 6 days before the thermal treatment to produce larvae and eggs of the insects in the samples. At the 18 days before the infrared treatment, the adult insects were mixed with the rice samples and kept for 2 days and then manually removed by sifting and hand picking. It was expected that the eggs laid by the adult insects during the two days would become larvae at the time of thermal treatment. At the 6 days before the treatment, the same numbers of adult insects were put into the infested rice samples and kept until the infrared treatment. The eggs from the adult insects should be produced and adult insects were remained in the samples. For radio frequency treatment, a large sample of storage rough rice was infested by mixing both adult beetles and moths at about a month before the disinfestation treatment. The infested rice was kept in an incubator at 28-30ºC and 35-40 % relative humidity to emerge more insects.

5.3.2.2 Infrared treatment and disinfestation and milling quality evaluation

In order to reduce the moisture loss during disinfestation treatment, the infested storage rice samples were heated as single-layer using a CIR emitter with the radiation intensity of 5300 W/m^2 and five exposure times from 10 to 30 s (Figure 2-2). The rice loading-rate was 2 kg/m^2. To reduce the heating time, the drying bed was preheated to the temperatures closed to targeted rice temperatures before the rice sample was placed. The final temperatures of heated rice were in the range of 46°C to 67°C, which was measured using an infrared temperature sensor after the heating. After the heating treatments, the samples were held at the heated temperature for various times, up to 3 h, and then cooled gradually in a closed container to the room temperature, about 23°C. The detailed experimental design is shown in Table 5-2. The disinfestation evaluation method was the same as the method used for thick-layer heating.

The moisture losses of the rice samples caused by the heating were calculated based on the weight losses during the treatment and original moisture content. Based on the disinfestation results, only uninfested rice samples with temperatures of 46°C, 53°C and 60°C were separately produced for milling quality evaluation. All quality evaluations were conducted at Pacific International Rice Mills, Inc. (Woodland, CA) and Farmer's Rice Cooperative (Sacramento, CA) based on the methods used for the thick-layer rice heating treatment.

5.3.3 Results and discussions

5.3.3.1 Thick-layer treatment - disinfestation effectiveness and milling quality

When the rice sample was heated in the heating chamber, it took about 2, 3, 4 and 5 min to reach 45, 50, 60 and 70°C, respectively. The heating was quite rapid and could be further improved if a thinner layer is used, which may reduce the moisture loss during the treatment (Table 5-3). The moisture losses were in range of 0.59 to 2.86% under the tested conditions. When the treatment was 50°C and 1 min, the moisture loss was about 1%.

The disinfestation results showed that only control and treated samples at 45°C had emerging adult insects (Figure 5-1). No insects were found in the rest of samples after two insect life cycles. The results clearly indicated that using 50°C or above temperature treatment could effectively kill all forms of Angoumois grain moth (Sitotroga cerealella). The minimum treatment under the test conditions was 50°C and 1 min. The total time including heating was about 4 min with about 1% moisture loss.

The milling quality of rice samples treated with infrared at 50°C for 1 and 5 min was not affected compared with the control sample (Table 5-4). Also, no difference in whiteness was observed between milled rice samples treated at 50°C and the control. However, significant quality loss occurred for the rice samples treated at 60°C. Therefore, it can be concluded that the infrared could be an effective method for storage rice disinfestation without quality loss. Through optimization of the treatment conditions, the moisture loss could be minimized.

5.3.3.2 Single-layer treatment - disinfestation effectiveness and milling quality

Since the single-layer heating was used, the required heating time to reach certain temperature was significantly reduced compared to the results from thick-lay treatment. It took only 20 s to reach 60°C, which meant that the heating rate was very high (Figure 5-2). Due to the reduced heating time, the moisture loss was also significantly reduced compared the results mentioned above. For example, the moisture loss was only 0.53% when the rice sample was heated to the temperature of 60°C. In the tested temperature range, 46°-67°C, the moisture losses were in the range of 0.28% to 0.76%. The results meant that single-layer heating was better method for reducing the moisture loss caused by infrared disinfestation treatment compared with the thick-layer heating.

The disinfestation results of storage rice are shown in Tables 5-5 and 5-6. No live adult moths were found in all treated samples during the first 14 days. For storage time of 21 days or longer, live moths appeared for all treatments with 46°C and 53°C with no holding and 5 min holding, which may indicate that some insect eggs survived the thermal treatments at those conditions. For beetles, it was clear that treatment temperatures at 53°C or below could not completely kill the adult beetles. It seems that 60°C treatment was effective even though the treatment of 60°C with 5 min holding had two unhealthy live beetles in the three samples were recovered following the thermal treatment. Very few live beetles from the 46°C treated samples were recovered during incubation. Such results may indicate that adult beetles were more heat resistant than the insect in other forms, such as eggs and larvae, which was different from the moths. The disinfestation results also showed that the beetles were more heat resistant than the moths, which has also been observed during the tests.

The milling qualities of rice samples treated with the temperatures from 46°C to 60°C without holding and 3 h holding are shown in Figures 5-3 to 5-5. The infrared treatments reduced the total rice yield from 0.2 to 1.0 percentage points, but the head rice yields slightly increased except for the treatment of 60°C without holding. Since the WI of treated rice samples were 0.5-0.7 unit higher than the control, the total rice yields of treated samples and control could be very similar if the samples were milled to the similar whiteness. Therefore, it is reasonable to believe that the infrared disinfestation treatments did not significantly affect the rice milling quality except for the treatment of 60°C without holding. For high temperature treatment of 60°C, the holding was necessary to reduce the quality loss caused by the disinfestation treatment.

5.3.4 Conclusions

The research results indicated that infrared heating could be used to disinfest storage rough rice. For thick-layer treatment, the required temperature and time for kill all moths were 50°C for 1 min. Under such treatments, no rice milling quality was affected, but infrared caused about 1% moisture loss. For single-layer treatment, the minimum required treatments were 53°C with 20 min holding for moths and 60°C with 20 min holding for beetles. For the storage rice, the infrared disinfestation could cause about 0.53% moisture loss. The 60°C temperature of single-layer storage rice can be achieved with 20 s heating when the drying bed was pre-heated to the targeted temperature. The infrared treated storage rice had similar milling qualities compared with the corresponding control samples.

5.3.5 Appendix: Test results

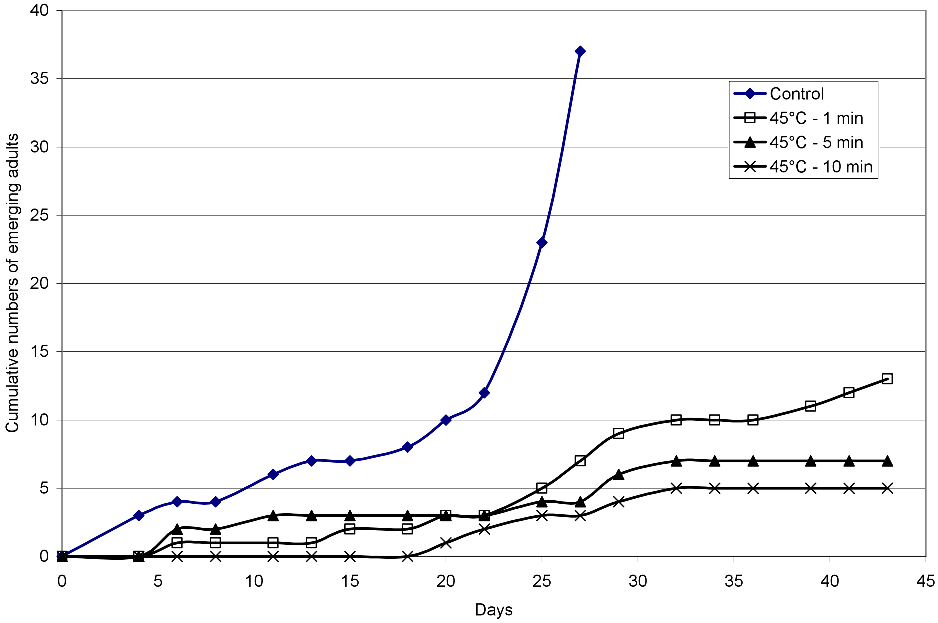

Figure 5-1. Emerging adult insects in infrared treated thick-layer samples (no insects found for the samples treated at 50°C or above)

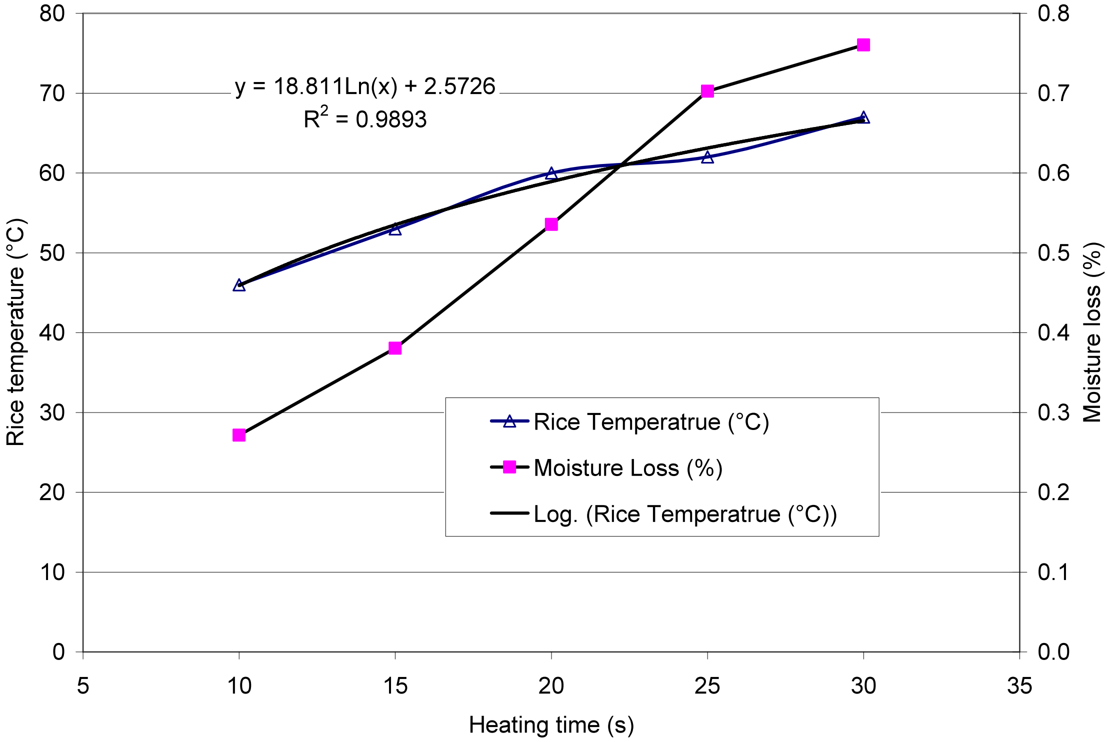

Figure 5-2. Storage rice temperature and moisture loss after infrared single-layer heating treatment

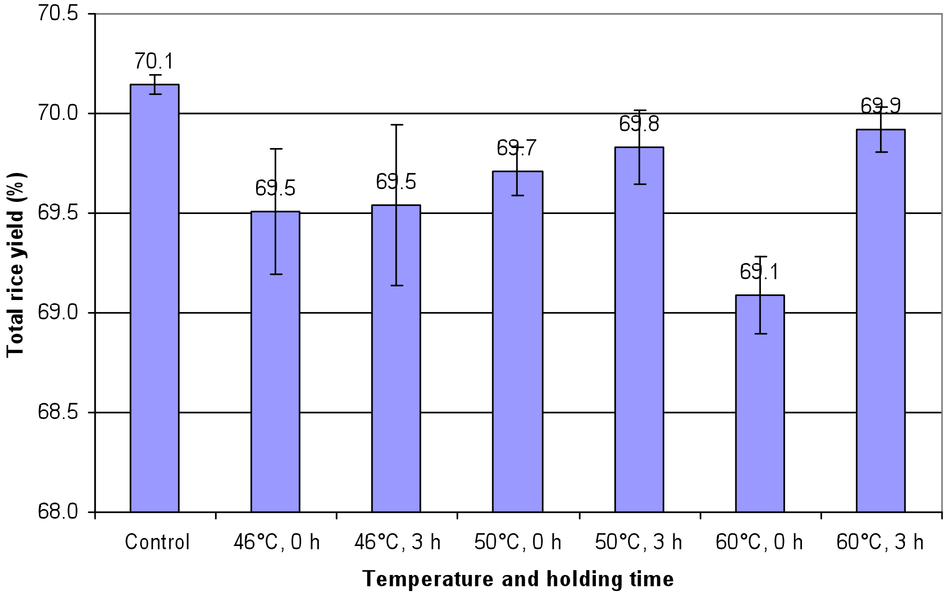

Figure 5-3. Total rice yields of single-layer rice treated at different temperatures with and without holding

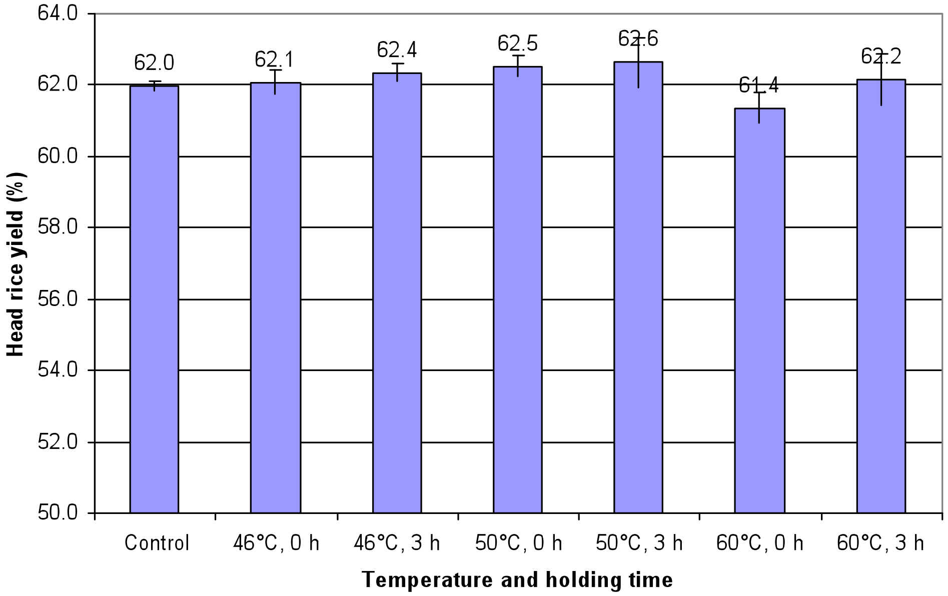

Figure 5-4. Head rice yields of single-layer rice treated at different temperatures with and without holding

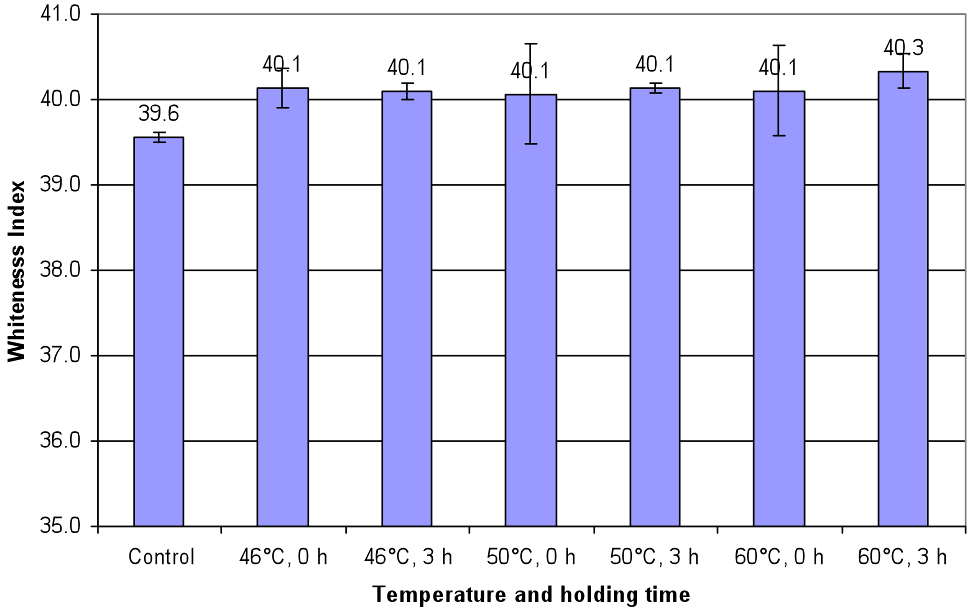

Figure 5-5. Whiteness index of single-layer rice treated at different temperatures with and without holding

Table 5-1 Experimental design of infrared treatment of thick-layer rice

Temperature (°C)	Heating time (min)		
45	1	5	10
50	1	5	10
60	1	5	10
70	1	5	10

Table 5-2. Experimental design of infrared heating treatment of single-layer rice

Heating time (s)	Rice temperature (°C)	Holding time (min)
10	46	0, 5, 20, 60,180
15	53	0, 5, 20, 60,180
20	60	0, 5, 20, 60,180
25	62	0, 5, 20
30	67	0

Table 5-3. Moisture content of thick-layer rice sample treated with infrared at different conditions (% wb)

Temperature (°C)	Treatment time (min)			
	0	1	5	10
Control	12.92			
45		12.33	11.87	11.78
50		11.87	11.75	11.45
60		11.71	11.24	10.79
70		10.91	10.87	10.06

Table 5-4. Moisture change and milling quality of infrared treated thick-layer rice samples

	MC (%)	TRY (%)	HRY (%)	WI
Control	13.5±0.1	68.5±0.4	54.1±0.7	44.4±0.3
50°C - 1 min	12.3±0.0	69.2±0.4	53.8±0.6	45.1±0.3
50°C - 5 min	12.0±0.0	69.5±0.2	54.6±0.1	44.7±0.3
60°C - 1 min	11.9±0.1	69.8±0.4	52.4±0.0	45.1±0.4
60°C - 5 min	11.4±0.1	70.3±0.4	44.9±0.4	44.5±0.2

Table 5-5. Numbers of live moths in single-layer rice samples treated with infrared heating*

Rice temperature (°C)	Holding time (min)	Days of storage after treatment					
		1**	14	21	27	31	35
67	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0
62	5	0	0	0	0	0	0
62	20	0	0	0	0	0	0
60	0	0	0	0	0	0	0
60	5	0	0	0	0	0	0
60	20	0	0	0	0	0	0
60	60	0	0	0	0	0	0
60	180	0	0	0	0	0	0
53	0	0	0	0	0	0.3	0
53	5	0	0	0	0	0.3	0
53	20	0	0	0	0	0	0
53	60	0	0	0	0	0	0
53	180	0	0	0	0	0	0
46	0	0	0	0.3	0	1.3	13.0
46	5	0	0	0.0	0.3	8.0	9.3
46	20	0	0	0.7	4.3	4.3	2.7
46	60	0	0	2.0	6.7	4.7	4.3
46	180	0	0	0.3	3.0	1.7	1.0

*Numbers are the average numbers of insects recovered from three samples at each treatment condition

** Numbers of insects that survived the thermal treatment

Table 5-6. Numbers of live beetles in single-layer rice samples treated with infrared heating*

Rice temperature (°C)	Holding time (min)	Days of storage after treatment					
		1**	14	21	27	31	35
67	0	0	0.3	0	0	0	0
62	0	0	0	0	0	0	0.3
62	5	0	0	0	0	0	0
62	20	0	0	0	0	0	0
60	0	0	0	0	0	0	0
60	5	0.7	0	0	0	0	0
60	20	0	0	0	0	0	0
60	60	0	0	0	0	0	0
60	180	0	0	0	0	0	0
53	0	2.3	0	0	0	0.3	0
53	5	2	0	0	0	0	0
53	20	3.7	0	0	0	0	0
53	60	0	0.7	0	0	0	0
53	180	2	0	0	0	0	0
46	0	67.0	0.7	0.3	0	0.0	0.0
46	5	64.7	1.3	2.0	0.3	0.0	0.0
46	20	52.7	2.0	1.0	0.0	0.7	0.7
46	60	60.0	3.7	1.7	0.3	0.3	0.0
46	180	69.3	4.0	0.0	0	0.0	0.7

*Numbers are the average numbers of insects recovered from three samples at each treatment condition

** Numbers of insects that survived the thermal treatment

6 Electric Vacuum Infrared Drying of Rough Rice

6.1 Summary

Freshly harvested medium grain rice (M-202) obtained from a commercial rice drying facility in Davis, California was dried in an infrared vacuum drier at 52, 45 and 36°C. The dryer was operated at -27 in Hg gauge pressure. Rough rice was circulated and mixed in the dryer with augurs. The removed water was condensed in vacuum chamber using evaporator pipes of a heat pump. Dryer was batch type with a capacity of 29.5 kg of rice.

Rough rice was dried for up to 45 min and samples were taken at predetermined time intervals for moisture content and milling quality evaluations. Time taken to reduce MC by 2% was 12, 13.5 and 14 min for 52, 45 and 36^{o}C drying temperatures, respectively. There was a trend of increasing TRY and HRY up to 8 min of drying time. Further it was confirmed that IR vacuum drying can be used to remove more than 2% of moisture in a single drying pass without a significant loss in TRY and HRY. As an example rice dried at 45^{o}C for 45 min removing 5.7% moisture did not show significant TRY and HRY decrease at $p=0.05$ compared to ambient air drying. Increasing whiteness was observed with increasing drying time. For the pilot scale vacuum IR dryer, the energy used to evaporate 1 kg of water to remove 2% moisture content was about 8000 kJ for all drying temperatures. High drying temperature showed higher energy efficiency than low drying temperature.

6.2 Objective

The objective of the study was to study drying rate and milling quality of rough rice dried with an electric vacuum infrared dryer and energy efficiency.

6.3 Materials and Methods

Freshly harvested rough rice samples of M-202 variety were obtained from a rice drying and storage facility in Davis, California. Rice was stored in 45 gallon (198 L) cans at 5^{o}C until time for drying tests. The vacuum dryer provided by Advance Light Technologies LLC, Chico, CA) used for the study (Figure 2-3).

Rice drying experiments were conducted at rice temperatures of 36, 45 and 52^{o}C with two replicates at each temperature. Rice was brought to the room temperature before the drying tests. The dryer was pre-heated to the pre-set temperature by drying one load of rice (29.5 kg) before formal test runs. After loading 29.5 kg of rice in to the air locked loading bin, vacuum pump (booster pump) was switched on until the gauge pressure inside the drying chambers reached -20 in Hg. Then the second vacuum pump was switch on and the rice was loaded into the drying chamber by opening the valve between the airlock loading bin and the vacuum chambers. Heaters were switched on after 3 min of loading (it takes 3 min to fill the drying chambers with rice). Samples of rice (≈ 600 g) were drawn at 3, 8, 15, 35 and 45 min of drying and used for measuring moisture content and milling quality. Moisture contents of the samples were measured by air oven method (130°C for 20h). All moisture contents reported are in wet weigh basis. Samples were dried down to 13% ± 0.5% by ambient air after IR drying. For rice milling quality evaluation, 500g of rice was used. Rice was hulled using Testing Husker (Model FC-2K, YAMAMOTO, Japan) and then the total rice yield (TRY) was determined. TRY is the amount of whole and broken kernels in the milled sample expressed as weight percentage of the rough sample. The hulled rice was passed through RICEPAL-32 rice mill for three times (YAMAMOTO, Japan). Representative sample from the polished rice was obtained by passing through Boerner-Sampler (Seed Trade Reporting Bureau, Chicago, Ill) divider 3 times for head rice yield (HRY) determination. Head rice yield (HRY) and the whiteness were assessed at Federal Grain Inspection Serves (FGIS) laboratory at Sacramento, California. Head rice yield (HRY) is the amount of whole kernels in the milled sample expressed as weight percentage of the rough sample. Whiteness was measured using KETT digital Whiteness Tester (Model C-300-3, Range 5-70, KETT electronic lab, Japan).

Energy consumption was measured by recording the current of each phase of three phase current supply. Total power associated with inductive loads (augur, vacuum pumps and heat pump) is 4430 W. The electric IR heaters consumed 8432 W. Therefore, it has been considered that 34% of the total power is associated with inductive power. It was assumed that the power factor for inductive component was 0.8. Energy efficiency of vacuum IR drying was calculated as the consumed energy for evaporating one kilogram of water. Cumulative amount of water evaporated was calculated at each time. For different drying period, energy efficiency was calculated by dividing the cumulative energy used by the cumulative amount of water evaporated at each drying time.

6.4 Results and Discussions

6.4.1 Drying curve

Drying curves present the average moisture contents of rice dried at 36, 45 and 52°C drying temperatures for various time periods (Figure 6-1.). Figure 6-2 shows the percentage MC reduction with various drying conditions. Table 6-1 shows the corresponding data. Increasing rice temperature increased the rate of drying. Required time to reduce MC by 2 percentage point was 12 min for 52°C and 14 min for 36°C. After 2 percentage point of moisture removal the required time for further MC removal increased more rapidly for 36°C compared to 52°C of drying temperature. As an example, for 4% moisture reduction, 22.5, 30 and 39 min were taken for rice dried at 52, 45 and 36°C respectively.

6.4.2 Rice quality

Figure 6-3 and 6-4 show the TRY and HRY variations with MC removal levels. The corresponding data are shown in Table 6-3 and 6-4. At all temperatures used (52, 45 and 36°C), there was a trend of increasing TRY and HRY up to 2% MC removal. Total rice yields (TRY) with drying time were compared with the ambient air dried rice. Rice dried at 52°C showed significant TRY decrease for 45 min drying at 5% significant level. Rice dried at 45 and 36°C did not show significant TRY reduction even for 45 min drying. Significant HRY increase ($p<0.05$) was observed for rice dried at 36°C for 8 min compared to ambient air drying. HRY also showed the same trend of increasing HRY up to 8 min as TRY. At 36°C and 52°C the HRYs were lower ($p<0.05$) than the ambient air drying after 45 min drying. The rice dried at 45°C did not show significant difference in HRY at 8, 15, 25 and 45 min of drying. Increased whiteness was observed with increasing drying time (Figure 6-5 and Table 6-5).

6.4.3 Rice temperature profile of vacuum IR drying

A slight drop in rice temperature was observed at the beginning of drying due to evaporative cooling under reduced pressure (Fig. 6-6). It took about 27, 18 and 12 min to reach 52, 45 and 36°C rice set-temperatures, respectively. More IR emitters may be added if a high heating rate is desirable. After reaching 52°C set temperature, the rice temperature variation was ±3°C. At 45°C, the temperature controller was able to keep rice bed temperature with an accuracy of ±2°C. At 36°C the temperature controlling accuracy was ±1.5°C.

6.4.4 Energy efficiency of IR vacuum drying

Energy efficiency of drying was calculated based on energy used for evaporating one kilogram of water from rice. Figure 6-7 shows the total energy used at different moisture removal levels under different drying temperatures. A higher energy consumption was observed for low temperature drying than the high temperature drying with the same amount of moisture removal. For all drying temperatures used, the energy used to evaporate 1 kg of water at 2% moisture removal level was about 8000 kJ (Figure 6-8). At 52°C drying, the energy use efficiency did not exceed 14000 kJ/kg of water evaporated even with 7% MC removal.

IR vacuum dryer operating at 52°C was able to remove 1.5 % moisture, from 24.2 to 22.7 %w.b. at an energy efficiency of 6582 kJ/kg of water evaporated. At 36°C it was capable of removing 1.4% moisture from 24.3% moisture content at an efficiency of 6900 kJ/kg of water evaporated. The energy efficiency depends of several factors like initial moisture content, maturity and grain history. Therefore it is difficult to compare energy efficiencies of two different drying systems (IR vacuum drying and industrial hot air drying). According to the available data, it can be concluded that IR vacuum dryer's energy efficiency is comparable or better to commercial rice drying, which had energy efficiency of 7107 kJ/kg of water removal at 1.4% moisture removal level.

6.5 Conclusion

Electric vacuum IR drying had a trend of increasing TRY and HRY up to 2% MC removal. Further it confirmed that IR vacuum drying can use to remove more than 2% of moisture without a significant loss in TRY and HRY in a single drying pass. As an example rice dried at 45°C for 45 min removing 5.7% moisture did not show significant decrease in TRY and HRY ($p < 0.05$) compared to ambient air drying. Whiteness tends to increase with moisture removal, which is also considered as desirable. Energy efficiency of vacuum IR drying at 2% moisture removal level was about 8000 kJ/kg of water removal.

According to the observations, IR vacuum drying showed possibility of removing higher amount of moisture from rice in a single drying pass without reducing the TRY and HRY. Higher energy efficiency at 52°C is an additional advantage as higher temperature reduces drying time considerably.

6.6 Appendix: Test Results

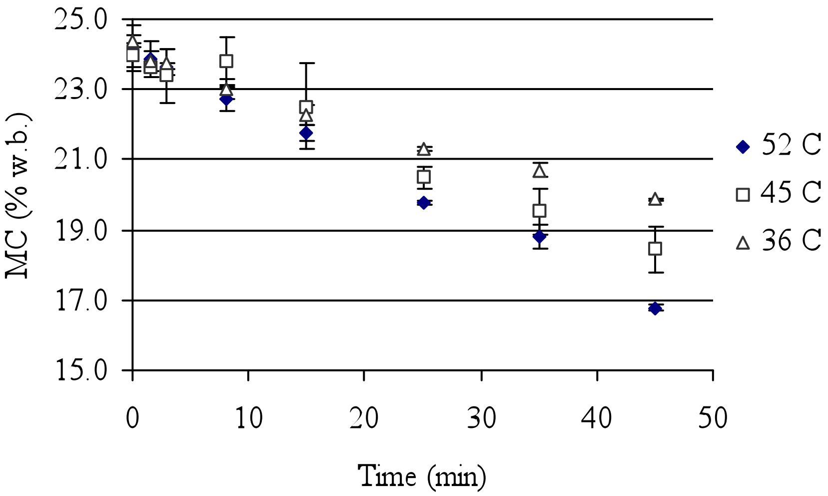

Figure 6-1. Drying curves of rice dried in vacuum dryer at different temperatures.

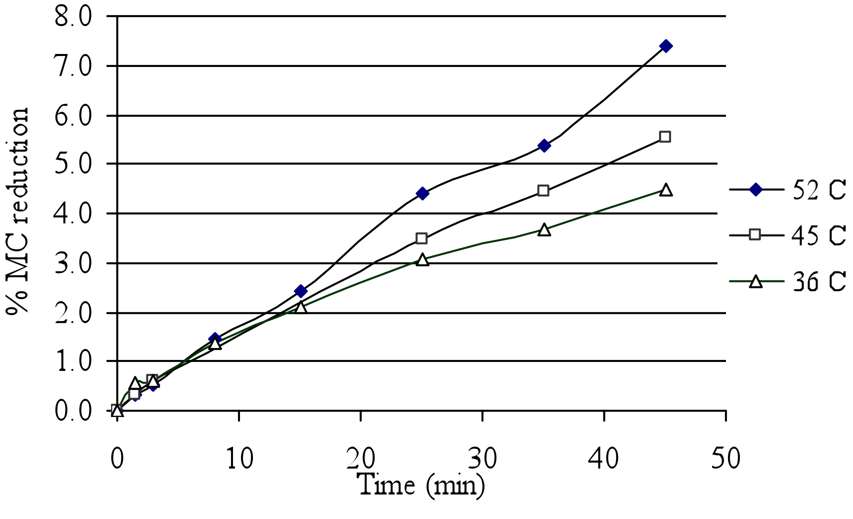

Figure 6-2. Percent moisture removal at different time under various temperatures

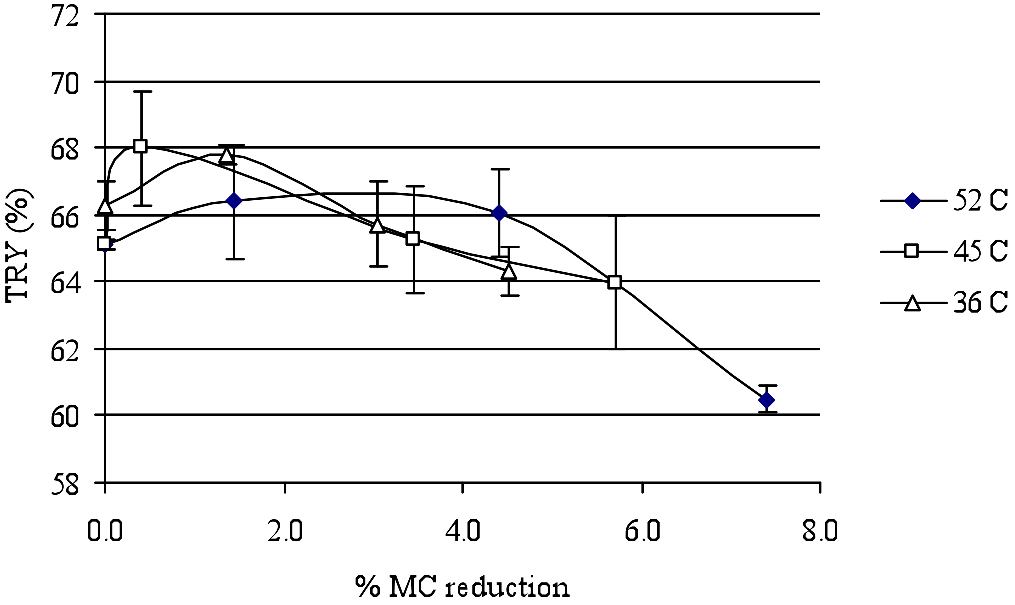

Figure 6-3. Total rice yield (TRY) of rice dried using vacuum IR with different moisture reduction levels and temperatures

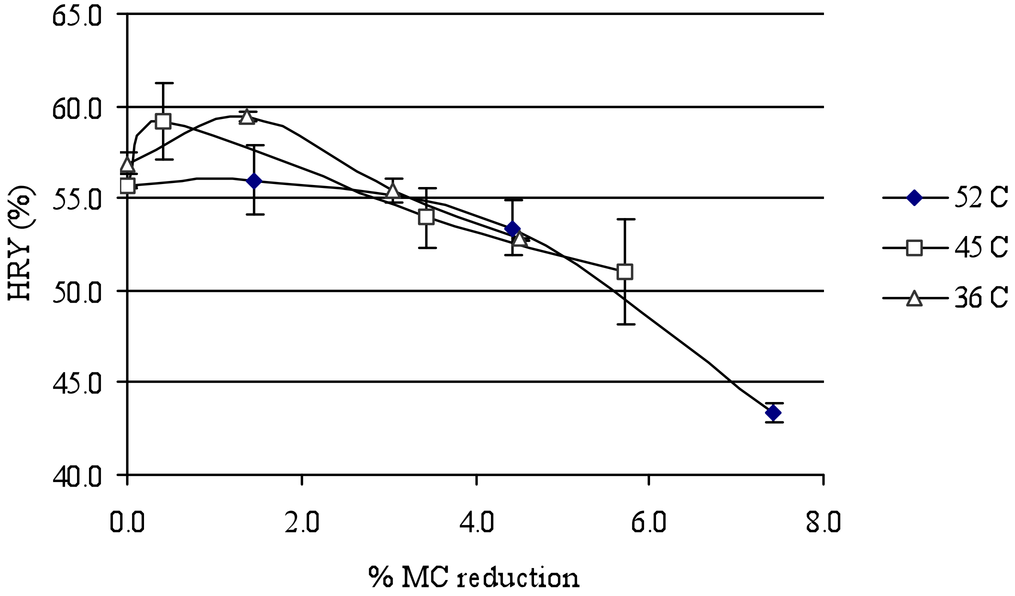

Figure 6-4. Head rice yield (HRY) of rice dried using vacuum IR with different moisture reduction levels and temperatures.

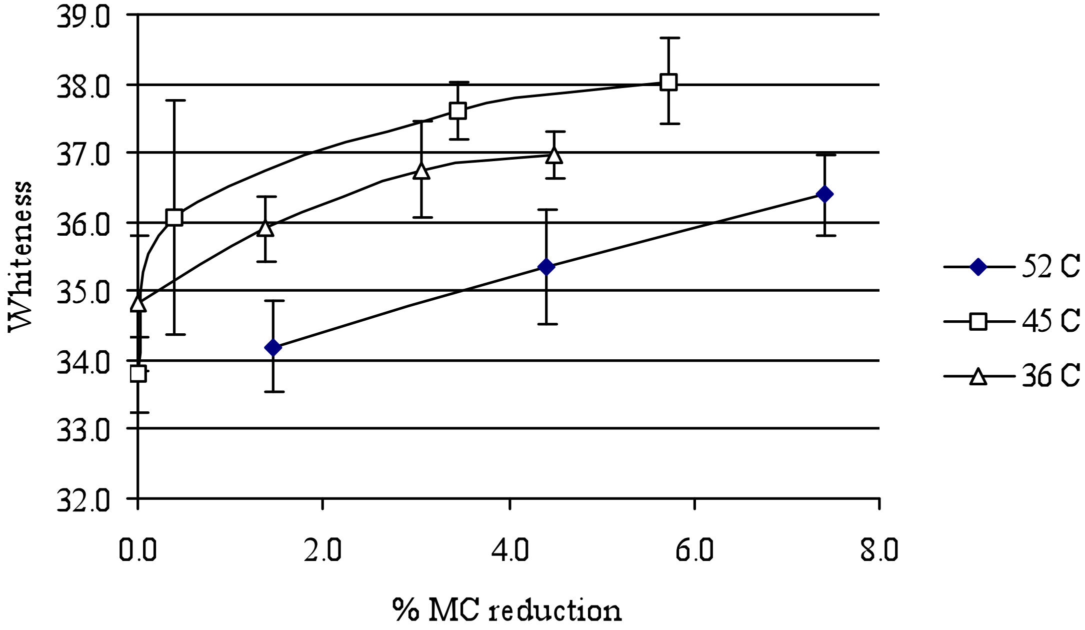

Figure 6-5. Variation of whiteness of the milled rice dried using vacuum IR with different moisture reduction levels and temperatures.

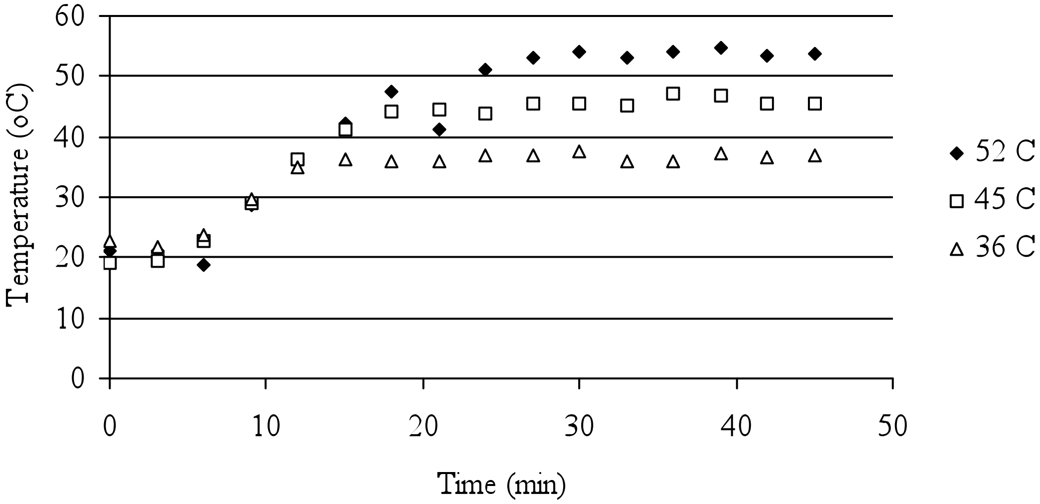

Figure 6-6. Rice temperature profiles during vacuum IR drying

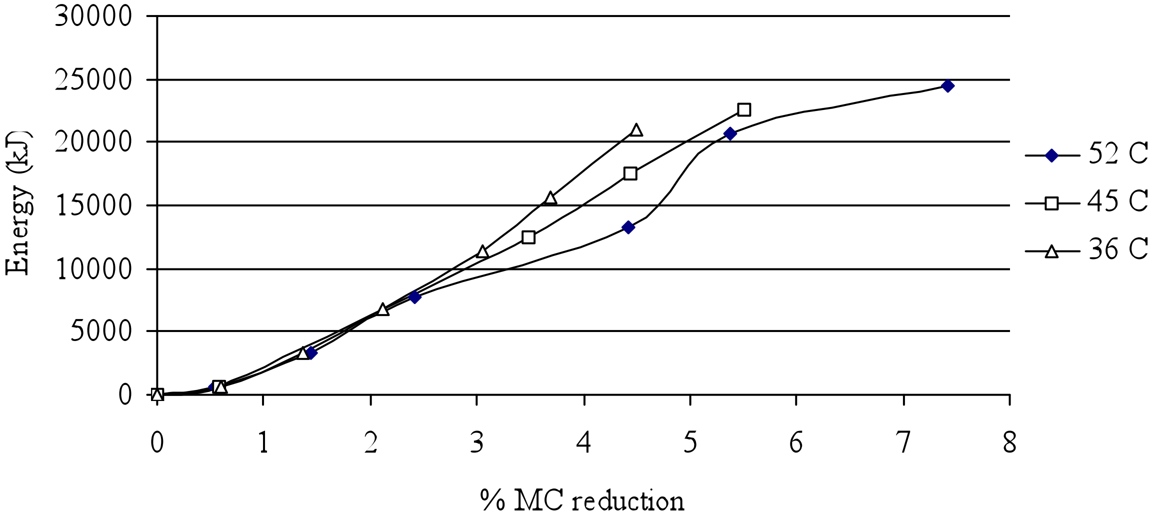

Figure 6-7. Energy consumption of vacuum IR drying with different moisture removal levels and temperatures

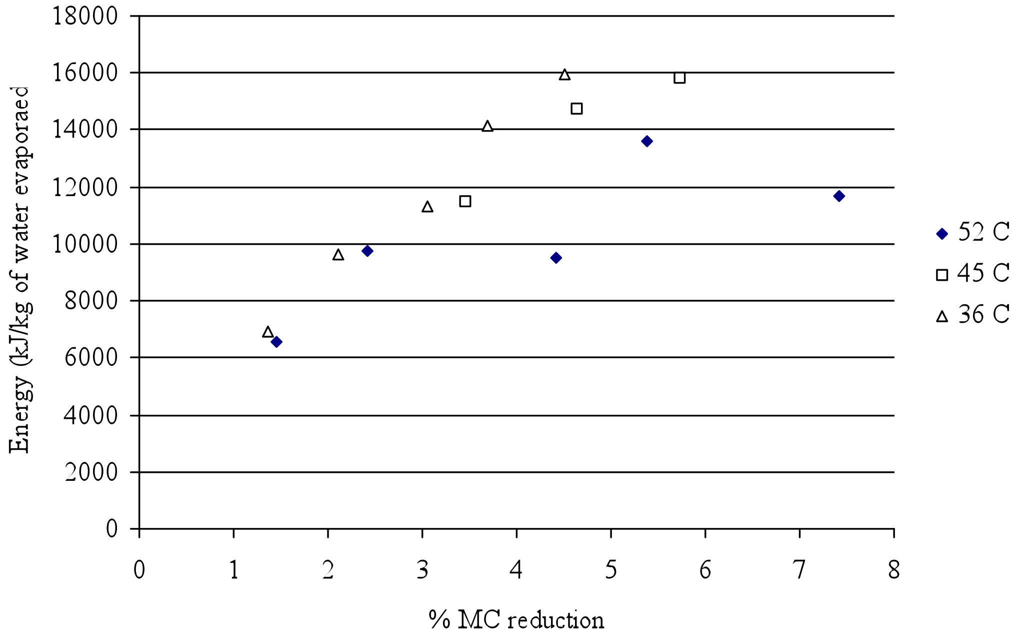

Figure 6-8. Energy efficiency of IR vacuum drying with different moisture removal levels and drying temperatures.

Table 6-1. Moisture content of rice dried using vacuum IR with various drying durations and temperatures

Time (min)	Moisture contents % (W.B.)		
	52°C	45°C	36°C
0	24.2	23.7	24.4
1.5 *	23.9	23.6	23.8
3 *	23.7	23.9	23.8
8	22.7	23.3	23.0
15	21.8	21.6	22.3
25	19.8	20.3	21.3
35	18.8	19.1	20.7
45	16.8	18.0	19.9

* Vacuum only. IR emitters were off.

Table 6-2. Average total rice yield (TRY) and standard deviation of rice dried with various conditions

Time	Temperature					
	52°C		45°C		36°C	
	MC %	TRY %	MC %	TRY %	MC %	TRY %
0	24.2	65.1±0.14	23.7	65.1±0.14	24.4	66.3±0.72
8	22.7	66.4±1.70	23.3	68.0±1.69	23.0	67.8±0.28
25	19.8	66.1±1.32	20.3	65.3±1.60	21.3	65.7±1.24
45	16.8	60.5±0.42 *	18.0	63.9±2.0	19.9	64.3±0.71

* Significantly lower ($p<0.05$) than ambient air drying.

Table 6-3. Average head rice yield (HRY) and standard deviations of rice dried with various conditions

Drying Time (min)	Temperature					
	52°C		45°C		36°C	
	MC %	HRY %	MC %	HRY%	MC %	HRY%
0	24.2	55.7±0.06	23.7	55.7±0.06	24.4	56.9±0.62
8	22.7	56.0±1.90	23.3	59.2±2.10	23.0	59.4±0.25 **
25	19.8	53.4±1.53	20.3	53.93±1.64	21.3	55.4±0.63
45	16.8	43.4±0.52 *	18.0	60.0±2.86	19.9	52.8±0.03*

* Significantly lower ($p<0.05$) than ambient air drying.

** Significantly higher ($p<0.05$) than ambient air drying.

Table 6-4. Average whiteness with standard deviation of rice dried with various conditions

Drying Time (min)	Temperature					
	52°C		45°C		36°C	
	MC %	Whiteness	MC %	Whiteness	MC %	Whiteness
0	24.2	36.0±3.46	23.7	33.8±0.55	24.4	34.8±0.99
8	22.7	34.2±0.82	23.3	36.1±1.68	23.0	35.9±0.46
25	19.8	35.4±0.58	20.3	37.6±0.42	21.3	36.8±0.70
45	16.8	36.4±0.50	18.0	38.0±0.61	19.9	37.0±0.36

7 Catalytic Infrared Drying of Onion

7.1 Summary

This study compared the drying and quality characteristics of onion dried with catalytic infrared (CIR) heating and forced air convection (FAC) heating. Sliced high solids onions were dehydrated under nine conditions: CIR heating with and without air recirculation, and FAC each operated at 60, 70 and 80 °C. In general, CIR both with and without air recirculation had higher maximum drying rates, shorter drying times, and greater drying constants than FAC at moisture contents greater than 50% (d.b.). Dried onion quality, measured as pungency degradation, was similar for both the drying methods at 60 °C and 70 °C. The color analysis showed better product color (whiter and less yellow) at lower temperatures for CIR and higher temperatures for FAC. The browning could have been caused by the higher surface heat flux of the CIR heating and longer process times of FAC drying. Aerobic plate counts and coliform counts were not significantly different for either product from the CIR or FAC drying. However, samples dried by the CIR had significantly lower yeast and mold counts than those dried by the FAC. It is recommended that CIR be used in the early stages of onion drying.

7.2 Objectives

The objective of this research was to compare the drying characteristics of thin-layer onion dehydration using CIR drying and forced air convection (FAC) drying with various drying conditions. The studied drying characteristics included the drying rate, drying time, drying constant, and quality of dried onion product. The measured quality characteristics included pungency degradation, color changes and microbial load reductions.

7.3 Materials and Methods

7.3.1 Materials

Southport White Globe onions were supplied by Gilroy Foods Inc. (Gilroy, Calif., U.S.A.) and were representative of onions used in their commercial operation for the 2003 and 2004 seasons. The onions had diameter of 40-70 mm and solids content ranged between 24.3 to 29.3%. Moisture content of onion samples was measured according to the American Dehydrated Onion and Garlic Association (ADOGA) Official Standards and Methods (1997) (70°C for 6 h at 26.1 mmHg vacuum). Moisture measurements were performed in duplicate and reported as average on a dry basis unless otherwise mentioned. Onions were cleaned by removing the tops and bottoms along with the outer dry layers and the first fleshy layer, which accounted for about 20% of each onion. Onions were sliced perpendicular to the axis into 2.5 ± 0.2 mm thick pieces using an industrial food slicer.

7.3.2 CIR dryer setup

The catalytic infrared (CIR) dryer arrangement (Fig. 7-1) consisted of a drying chamber (95 x 65 x 65 cm) with an CIR emitter (Catalytic Drying Technologies LLC., Independence, Kans., U.S.A.) mounted from the top of the chamber. The sample was placed on a drying tray (84 x 53 cm) which consisted of a fine mesh aluminum screen stretched across a strip steel frame. At the product surface, IR intensity decreased away from the center of the drying tray. When the drying tray was positioned 20 cm below the emitter the intensity at the tray's center was 4818 W/m^2. Average intensity at 15 points across the tray at this distance was 2226 W/m^2 measured using an Ophir FL205A Thermal Excimer Absorber Head (Ophir Optronics Inc., Wilmington, Mass., U.S.A.). An aluminum wave guide (48 x 30 cm, upper rim; 42 x 22 cm, base perimeter), used to achieve a uniform heating of the entire product, rested on top of the drying tray and surrounded the product. A balance (Ohaus Adventurer Pro; 8 kg capacity, 0.1 g accuracy) was placed beneath the drying tray and measured product weight during drying. A 1/100 HP exhaust fan (Dayton Electric Mnfg., Niles, Ill., U.S.A.) was located on the top of the drying chamber for ventilation. Two 1/10 HP fans (Dayton Electric Mnfg., Niles, Ill., U.S.A.) mounted on each side of the dryer were used to recirculate part of the warm air in the drying chamber. These fans pulled air from the top of the drying chamber and fed it back into the chamber through slits running the entire length of the drying chamber.

The CIR emitter was preheated by an electric element located inside the emitter. The natural gas intake was regulated by a gas control valve controlled by a computer system. Two Type-T thermocouples (response time 0.15 s) were used to measure the product temperature. Each thermocouple was placed inside the flesh of an onion slice which was placed within the innermost 10 cm^2 of the onion bed. The average temperature was used as input to control the product temperature by turning the emitter on or off which was achieved by opening and closing the gas supply valve of the emitter. For example, the temperature of the emitter surface was 752 ± 22 °C in the early heating stage. It took 8, 11 and 13 min to heat the product to the set temperatures of 60, 70 and 80°C, respectively, without air circulation. A large amount of moisture has been removed during this drying period. After the product reached the set temperature, the emitter was automatically turned off and the emitter temperature started to decrease. Once the product temperature was below the set temperature, the emitter was turned on again to maintain the product temperature. During the intermittent heating period, because a large amount of moisture has been removed, relatively small amount of energy was needed to maintain the product temperature. The ratio of emitter on and off time decreased with the increase of moisture removed and drying time.

Thermocouples and balance inputs were processed by using a data acquisition system which was developed at University of California, Davis and consisted of a personal computer with Test Point software (Capitol Equipment, Bedford, N. Hamp., U.S.A.).

7.3.3 FAC dryer setup

The forced air convection (FAC) dryer used in the tests was an electrically heated column dryer with diameter of 33 cm. A fan powered by a ¾ HP permanent magnet DC motor (Dayton Electric Mnfg., Niles, Ill., U.S.A.) blew heated air through an electric coil heater and then through the column. Product was placed in a circular mesh tray near the bottom of the column and suspended by wires to the Ohaus balance to record product weight change during drying. The temperature of heated air was also controlled by the same computer control system as the IR dryer using a Type T thermocouple to measure the temperature of the air before it reached the product. The on and off cycles of the electric heating coils were controlled automatically to maintain the set point temperature. The air velocity for all of the tests was maintained at 0.5 m/s.

7.3.4 Drying trials

Nine conditions were tested: CIR heating with and without air recirculation, and FAC each operated at 60, 70 and 80 °C. An onion sample, 250 g for CIR and 150 g for FAC, of intact slices was arranged in a single layer on the drying tray at a loading rate of 2.5 kg/m^2. For CIR the drying tray was placed in the preheated CIR drying chamber and the thermocouples were positioned as described above. Distance between the emitter and drying tray was 15 cm with maximum intensity of 4752 W/m^2. CIR drying tests with air recirculation had both the recirculation fans on during the entire test. Average air velocity was set at 0.5 m/s. Each weight point was averaged with the two prior and two consecutive points to correct for noise. Weight data was also corrected for lift created by air inside the dryers based on the weights with and without air flow. Onion weight and temperature were recorded every 60 seconds with the aforementioned data acquisition and control system.

Targeted final moisture content (MC) of the dried onion was set at 10% (d.b.) in this study. The final weight of dried onion sample was determined based on the initial and final MC and initial sample weight. The experiments were replicated two or more times.

7.3.5 Drying kinetics

Drying rate was calculated in gram of moisture loss per kilogram of initial weight of onion sample per minute (g/kg$_{\text{initial weight}}$ *min). The exponential model was chosen to describe the drying process. Model curves were fitted to the experimental data and the performance of the model was determined by the correlation coefficient (R^2).

The exponential model is as follows:

$$MR = \frac{M - M_e}{M_0 - M_e} = \exp[-kt] \qquad (7\text{-}1)$$

where MR is the moisture ratio; M is the moisture content (% d.b.) at any given time during drying; M_0 is the initial moisture content; M_e is the equilibrium moisture content; k is the drying constant (h^{-1}); and t is time in hours.

Moisture ratio (MR) was determined using the moisture content data collected in the drying experiments. The fixed 4% (d.b.) equilibrium moisture content (EMC) was estimated from findings in literature (Wang 2002). For each drying condition, MR data were plotted on semi-logarithmic axis versus the time (h) and the slope of the fitting line was the constant k. Correlation coefficients, means, and standard deviations were also calculated for all nine drying conditions.

7.3.6 Quality tests

7.3.6.1 Pungency

The effect of drying on pungency was determined with four trays each containing 40 g of sliced onions which were dried simultaneously. Trays were removed at 10, 20, 30, and 40 min for 80 °C experiments; 10, 20, 40, and 60 min for 70 °C experiments; and 30, 60, 120, and 180 min for 60 °C experiments. These times correspond to the approximate times that were required to achieve a 10% MC (d.b.) at each temperature. After removal, sample weight was measured and corresponding MC was calculated. Deionized water was added to the dried products until the total weight of water plus product was 90 ± 1 g. After rehydrating for 5 min, the samples were homogenized for 30 s at 7,000 rpm and 30 s at 10,000 rpm using a hand-held homogenizer (Bahmix Bio-Mixer, Bartlesville, Oklah., U.S.A.). Slurries were held for 30 min at room temperature before filtering through two layers of cheesecloth.

Pungency was measured using a chemical pyruvic acid assay outlined by Anthon and Barrett (2003). Filtrate (25 µl), deionized water (1.0 ml) and 1.0 ml of 0.25 g l^{-1} DNPH in 1 M HCl were placed in 13 mm x 100 mm test tubes, and tubes were heated in a 37 °C water bath for 10 min. Upon removal, 1.0 ml of 1.5 M NaOH was added. Absorbance at 515 nm was measured on a Beckman DU 7500 spectrophotometer. Inherent, non-enzymatically formed pyruvate was measured after heating a fresh 40-g sample in an 800 W microwave oven for 1 min. Standards were prepared by adding 25 µl of sodium pyruvate solution in concentrations of 0, 2, 4 and 8 mM instead of the onion filtrate. Enzymatically-formed pyruvate was calculated from the difference between the amount of total pyruvate and the non-enzymatically formed pyruvate. The average results of duplicate tests were reported as percentage losses in pungency from a fresh onion sample at various moisture contents.

7.3.6.2 Color measurement and microbial load reduction tests

L and b color measurements of L.a.b. color were performed for milled dried onion samples from the drying rate trials using a Minolta CM-508 spectrophotometer. The ‘a’ measurement was not reported because it is not often used to indicate dried onion quality. The average of five readings from each sample was reported.

For determining the microbial load reduction, six 50 g sliced samples were dried with CIR and FAC at 60, 70 and 80 °C to 10% MC. Dried sample (10 g) was stored for 5 days. The sample was added to a 90 ml Butterfield’s buffer dilution blank and allowed to rehydrate for 10 min at 4 °C. Sample was homogenized for 1 min in a stomacher blender (Stomacher 400, Seward, Thetford, U.K.) and serial dilutions were made and plated on Tryptic Soy Agar (TSA) (Difco, Becton Dickinson, Sparks, Md., U.S.A.)) for aerobic plate counts, Dicholroan Rose Bengal Chloramphenicaol agar (DRBC, Difco, Becton Dickinson) for yeast and mold counts, and Coliform Petrifilm (3M, St.Paul, Minn., U.S.A.) for coliform counts. Duplicates of each dilution were made. TSA and Coliform Petrifilms were incubated at 35 °C for 24 ± 2 h. DRBC plates were held at room temperature (24 ± 2 °C) for 5 days. The average results from duplicate test samples were recorded as Colony Forming Unit (CFU)/10 g dried sample. The tests were performed in duplicate.

7.3.7 Statistical analysis

Data from the quality test experiments and drying times were statistically evaluated in Excel using the t-test with the assumption of equal variances. The pungency values for FAC and CIR were compared at each time interval for each temperature. Any value that was statistically significant ($p < 0.05$) is indicated in table 2. The measured color results were compared for all three drying methods and any method that was significantly different was indicated in table 3.

7.4 Results and Discussions

7.4.1 Drying rates and kinetics

7.4.1.1 Drying rates

When the drying rates were calculated and plotted against moisture content (Fig. 7-2), for each of the three drying temperatures the CIR tests showed much higher drying rates throughout the course of drying than the FAC drying before the MC reached 50%. Below this moisture content the decreased drying rates for CIR drying could be due to lower moisture transfer rate in the onion slices for the CIR than the FAC. The air flow might help with the moisture removal at the low moisture range. Increasing the drying temperature in the CIR drying trials increased the drying rate. A minimal increase in drying rate was noted for FAC drying as air temperature was increased.

It is apparent that air recirculation in the CIR drying caused lower drying rates, especially for the 60 °C and 80 °C trials although an slight increase was seen in the 70 °C trial. The recirculation of warm air did not improve the drying rate under CIR drying as expected. Recirculation air decreased the drying rate and increased drying time, which has been reported by Sandu (1986) and Paakkonen and others (1999).

Drying rates changed with the drying temperature as expected. For each of the plots from the CIR drying tests there was an absence of or just a very brief appearance of a constant rate period because onions are hygroscopic and hygroscopic foods tend to quickly enter the falling rate period (Rahman and Perera 1999). Additionally, surface drying may occur more rapidly with CIR drying which results in quicker entrance to the falling rate period due to slow water diffusion to the surface of the onion. It is similar to many other foods that do not exhibit a constant rate drying period due to the colloidal and hydrophilic nature (Mazza and LeMaguer 1980; Baker 1997).

The FAC drying tests showed more of a distinct constant rate period at each of the three temperatures tested although the 80 °C rate period was not as profound as the other two temperatures. This might be due to the lower heat flux which resulted in a longer time to reach the critical moisture content. Almost all of all tests showed linear relationships between the drying rates and moisture contents for the period of moisture content from 50% to 225% (d.b.).

Based on the drying rate results, IR drying is recommended to dry onion until about 50% MC, then followed by FAC drying in the latter stage if a combined IR/convection drying system is used for drying onion. For existing drying facilities, IR drying could be considered by adding a unit at the front of current conventional drying systems to take advantage of the high drying rate of IR for improving the overall rate of drying.

The maximum drying rates and times required to reach 50% MC (d.b.) under various conditions are summarized in table 1. The maximum drying rates of IR were significantly higher ($p<0.05$) than that of FAC drying at corresponding temperatures. But no significant difference ($p>0.05$) was observed between the CIR drying with and without air recirculation at each corresponding temperature.

7.4.1.2 Drying modeling

Based on the modeling results, the exponential model fits well with the experimental data from CIR drying (Table 7-1 and Figure 7-3). The correlation coefficients (R^2) were greater than 0.988. It has been reported that the Page model can be used for modeling the drying characteristics of onions under infrared heating (Wang 2002; Sharma and others 2005). After the examining the fitness of the Page model for the CIR drying, it was found that the drying exponents of the Page models were close to 1 and the improvement in correlation coefficients was limited. Therefore, it is concluded that exponential model can be used to reasonably well predict the drying characteristics of onions under the CIR drying. However, the correlation coefficients of exponential model for the FAC drying were in the range 0.844 - 0.927, which indicates that the exponential model may not be appropriate model for describing the drying characteristics. The predicted and experimental data of the FAC drying in Fig. 3 have shown that they did not fit well at the middle of the FAC drying process (Figure 7-3), which could be due to the long constant rate periods observed. This was most apparent for the 80°C FAC trial.

7.4.2 Quality of dried onions

7.4.2.1 Pungency

Both CIR and FAC drying methods had similar trends in pungency changes of onion samples, especially at 60 °C or 70 °C (Table 7-2). Pungency of FAC dried samples at the latter drying stage showed a greater decrease at the lower temperatures (60 °C and 70 °C) when compared to the 80 °C test. This result could be due to longer drying times causing more degradation of the product. The 80 °C test with both drying methods showed that the pungency did not change significantly until the moisture reached approximately 75%. Below 75% MC the pungency of FAC dried samples did not change significantly. This is consistent with the findings of Lee and others (1995), in which high drying temperature had high pungency in the dried onion. It can also be explained that accelerated drying in the initial stages would retain volatiles (Mazza and Maguer 1979; Brewster and Rabinowitch 1990). This is because the volatiles become "locked" into the product when it reaches the critical moisture content.

In general, the pungency of CIR dried samples decreased with the moisture reduction. Although the measured pungencies varied with drying conditions and moisture during drying, the pungencies in the samples with the longest drying time and equivalent moisture content were similar, except for the 80°C trial. The 80°C trial showed a greater loss in pungency in the samples dried in the CIR, especially at the latter drying stage. This decrease may be caused by the large heat flux delivered to the product and may have resulted in alliinase inactivation and/or precursor degradation (Brewster and Rabinowitch 1990). Significant color changes were also noted during this time (Table 7-3).

The large variability of measured pungency results could be caused by non-uniform drying among the samples, difficulties in achieving a homogenous sample, and human error during the assay. Based on the obtained results, if 80°C drying temperature of CIR drying is used, it is recommended to use it in the early drying stage before the moisture content of the samples reach 75%. Then low temperature drying can be used in the latter drying stage to prevent severe browning and pungency degradation.

7.4.2.2 Color

The color measurement results of onion samples with 10% MC are summarized in table 3. The L values showed a decrease with increasing temperatures for the CIR drying and the opposite effect for the FAC drying. The FAC results were opposite findings from those of Lee and others (1995) where L values decreased with higher air temperatures for convection drying of onion. The low L values for the 60 °C FAC sample may be a result of extended drying time resulting from low drying temperatures. For the CIR drying, a high drying temperature could increase browning and result in a dark color.

The 60 °C FAC dried sample was significantly ($p<0.05$) less white than either of the CIR samples. Samples from the other drying temperatures are not significantly different from each other. The L color parameter alone may not describe well the color changes occurring during the drying process. The b parameter of the samples was also compared for evaluating the color data in its entirety.

A higher b value indicates a higher degree of browning and other color developments caused by enzymatic and non-enzymatic browning reactions. Thus there was more color development in the CIR dried samples at higher temperatures due to the aforementioned reasons. Likewise, FAC drying has less browning at higher temperatures due to a shorter drying time. The higher b values of samples dried at 60 °C and 70 °C with CIR plus air recirculation could be due to increased drying times compared to using CIR drying without air recirculation.

To produce dried onion with a desirable light or white color CIR drying is recommended to dry the product at a mild temperature, such as 70 °C, to take advantage of higher drying rates than observed at 60 °C drying and avoid the increased amount of browning seen in 80 °C drying.

7.4.2.3 Microbial load reduction

The results of aerobic plate counts (APC) for all of the dried samples were similar (Table 7-4). For both drying methods, the APC decreased by an average of about 1.7 log from the fresh sample. There was no significant difference between the two drying methods nor was there a difference in counts at different drying temperatures. The composition of the surviving population was not determined. The predominant microorganisms in dehydrated spices are aerobic sporeformers (Gray and Pinkas 2001) and it is possible that this was true for the dried onion samples. The APC of the dried product was not significantly different ($p<0.05$) for any of the drying temperatures or either drying method.

It was difficult to achieve a homogeneous sample of sliced onions to be used for the microbiological testing. The variation between the trials was a result of different amounts and type of microflora represented on each of the samples used. Large standard deviations were a result of averaging the results of the variable trials.

Coliform levels in fresh samples were 5.39 log CFU/10 g dried sample. The coliform count for fresh sample was not significantly different from the APC suggesting that this group of bacteria dominated the fresh aerobic microflora. As drying temperature increased, coliform counts decreased in the final product. Coliform counts were reduced during the drying process by over 2 logs at 60 °C for both drying methods and by 3 logs at 80 °C. There was no significant difference between the FAC and CIR dried samples at corresponding drying temperatures.

Yeast and mold counts, unlike coliforms, were not accounted for on the APC (Gray and Pinkas 2001). Yeasts and molds do not grow fast enough to appear on APC agar. It is important not to correlate APC to yeast and mold counts. Yeast and mold counts were significantly different for the two drying methods. Greater reductions were observed in samples dried in the CIR dryer which may have been a result of greater heat fluxes from the CIR emitter. The reduction of yeast and mold in the dried samples with either drying method was no greater than 1.4 log.

7.5 Conclusions

These experiment results indicate that CIR heating is an effective method for onion drying. Greater drying rates and shorter drying times were seen in CIR drying compared to FAC drying but only at MC greater than 50%. For achieving high quality product and drying rate, a recommended combination of CIR and convection dryings is to use CIR to achieve 75% MC and then use convection for later stages of drying. This type of processing would be beneficial for commercial dehydrators who would not have to replace existing equipment to incorporate a CIR unit. The recommended product temperature for CIR drying is 70 °C and 80 °C. The higher temperature (80 °C) should be used at the beginning of drying to achieve maximum drying rates while product degradation is minimal. The lower temperature (70 °C) should be used for the remainder of drying because it achieves high drying rates but does not have the same adverse effects on quality factors, especially pungency and color, as does continual 80 °C heating. Further research is needed to determine the point at which the temperature should be reduced from 80 °C to 70 °C. Additional studies are also necessary to determine drying characteristics and quality changes that occur to onions below 10% MC.

7.6 References

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7.7 Appendix: Test Equipment and Results

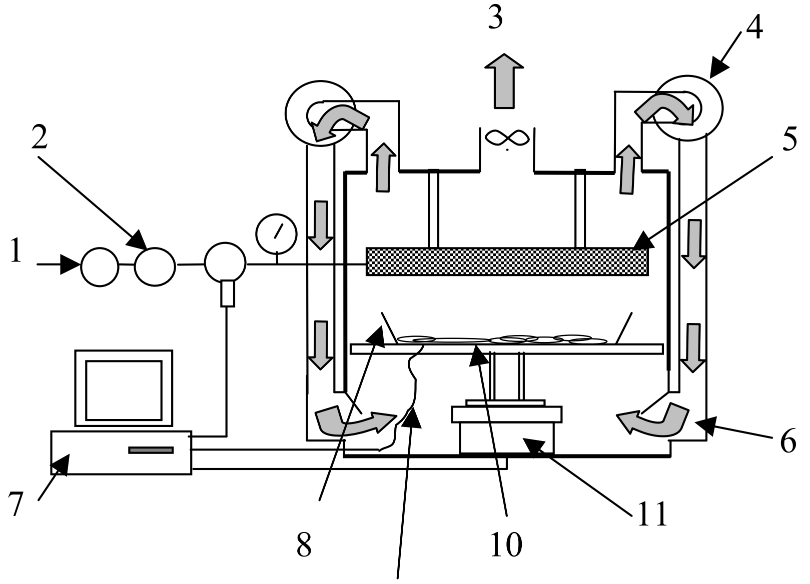
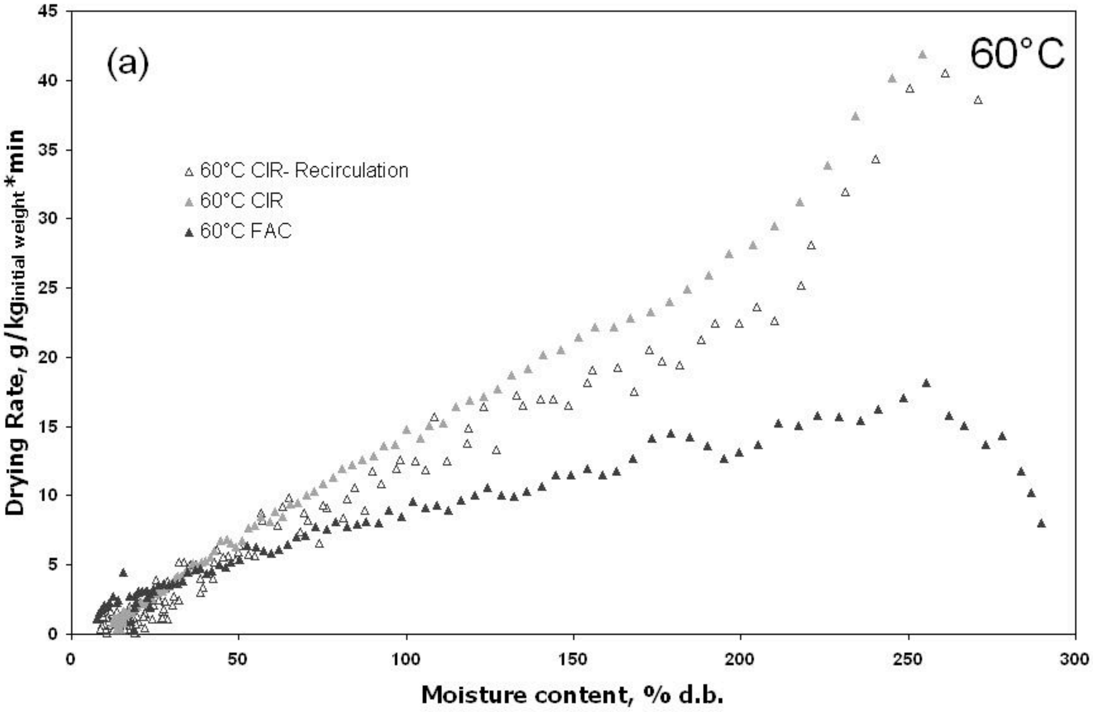


Figure 7-1. CIR Dryer: 1- Natural Gas; 2-Gas Flow Control; 3-Air Exhaust; 4-Blower; 5-CIR Emitter; 6-Recirculation Warm Air; 7-Computer Controller; 8-Wave Guide; 9-Thermocouple, 10-Onion Sample; 11-Balance.


(a)
60°C
△ 60°C CIR- Recirculation
▲ 60°C CIR
▲ 60°C FAC
Drying Rate, g/kginitial weight*min
Moisture content, % d.b.
0
5
10
15
20
25
30
35
40
45
0
50
100
150
200
250
300

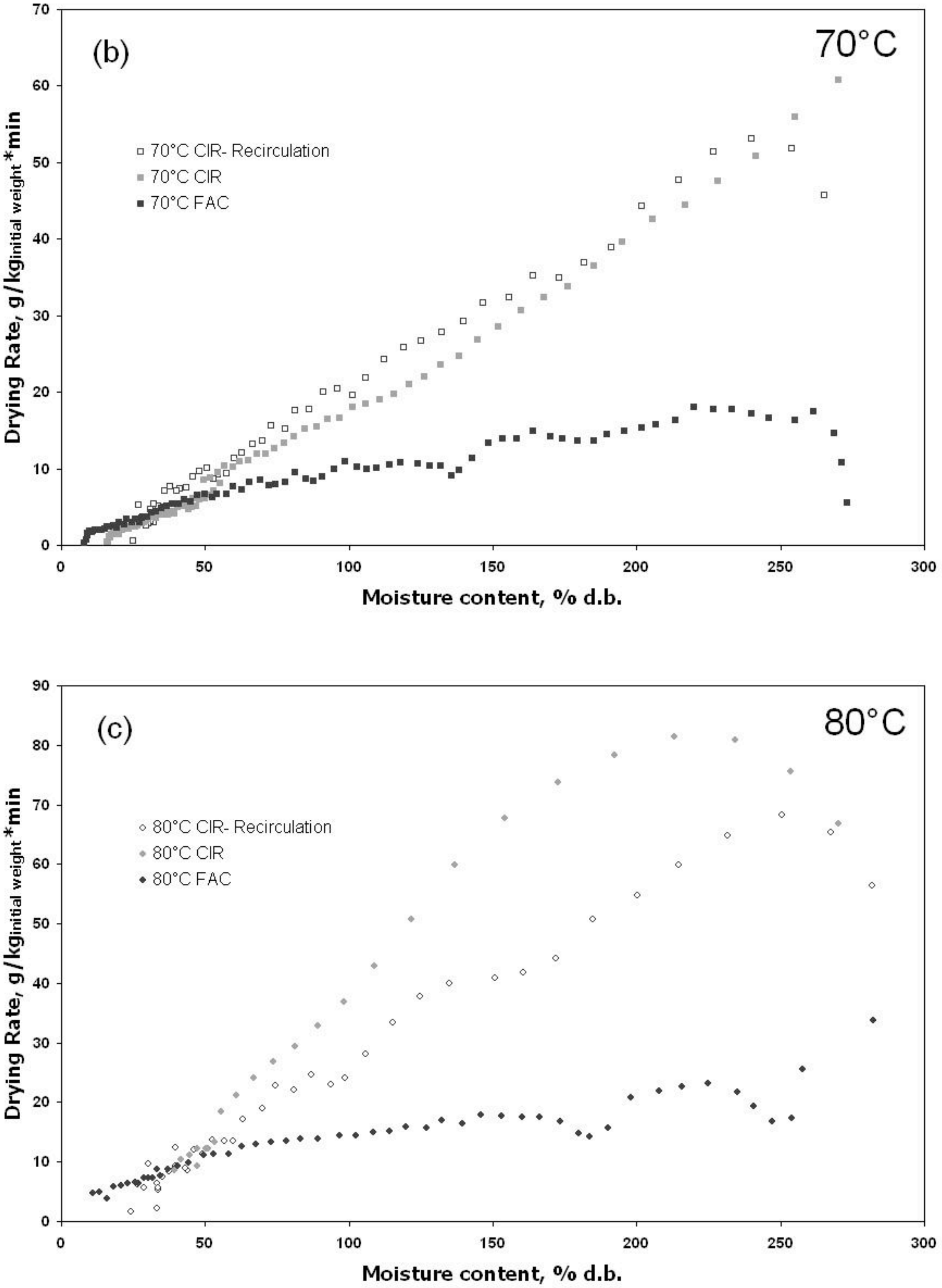
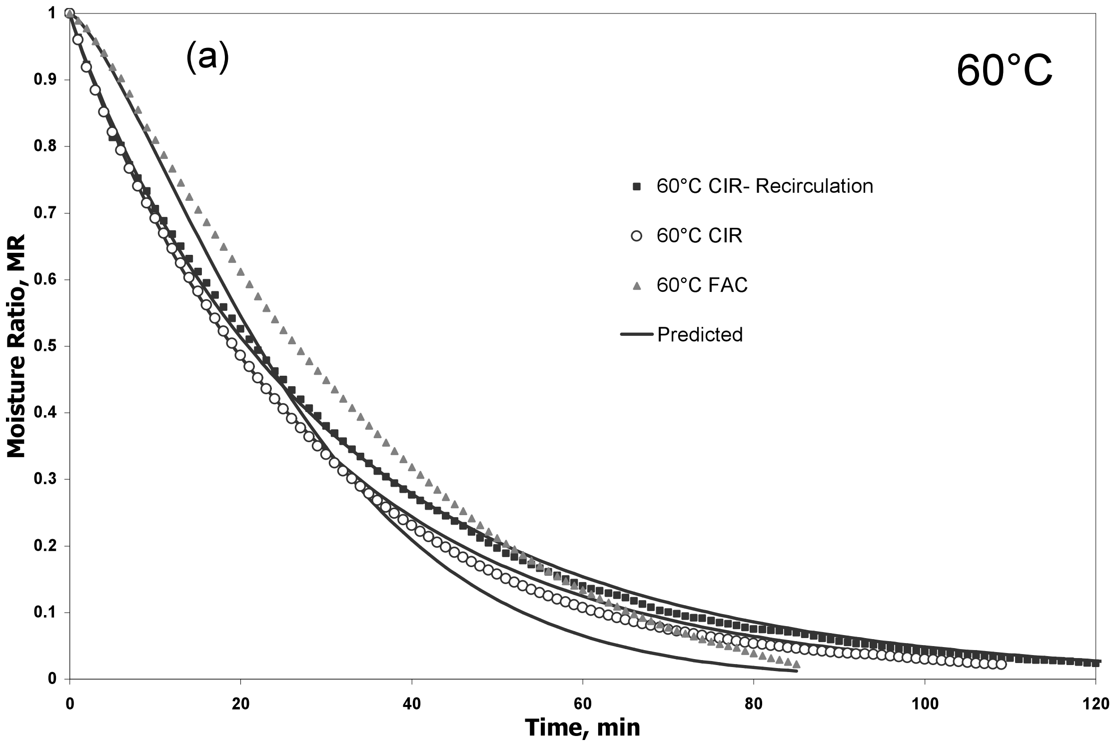
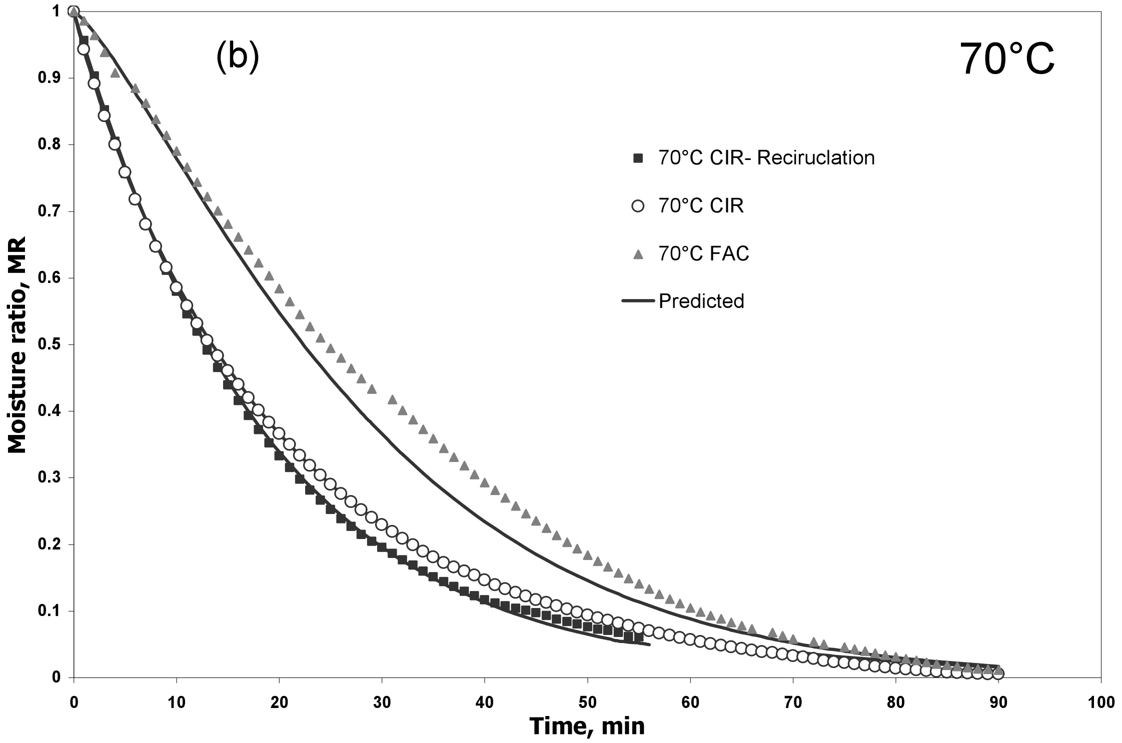


Figure 7-2. Drying rates of different drying methods and conditions at various drying temperatures, (a) 60 °C, (b) 70 °C, and (c) 80 °C.


(a)
60°C
60°C CIR- Recirculation
60°C CIR
60°C FAC
Predicted
Moisture Ratio, MR
Time, min
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120


(b)
70°C
70°C CIR- Reciruclation
70°C CIR
70°C FAC
Predicted
Moisture ratio, MR
Time, min
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

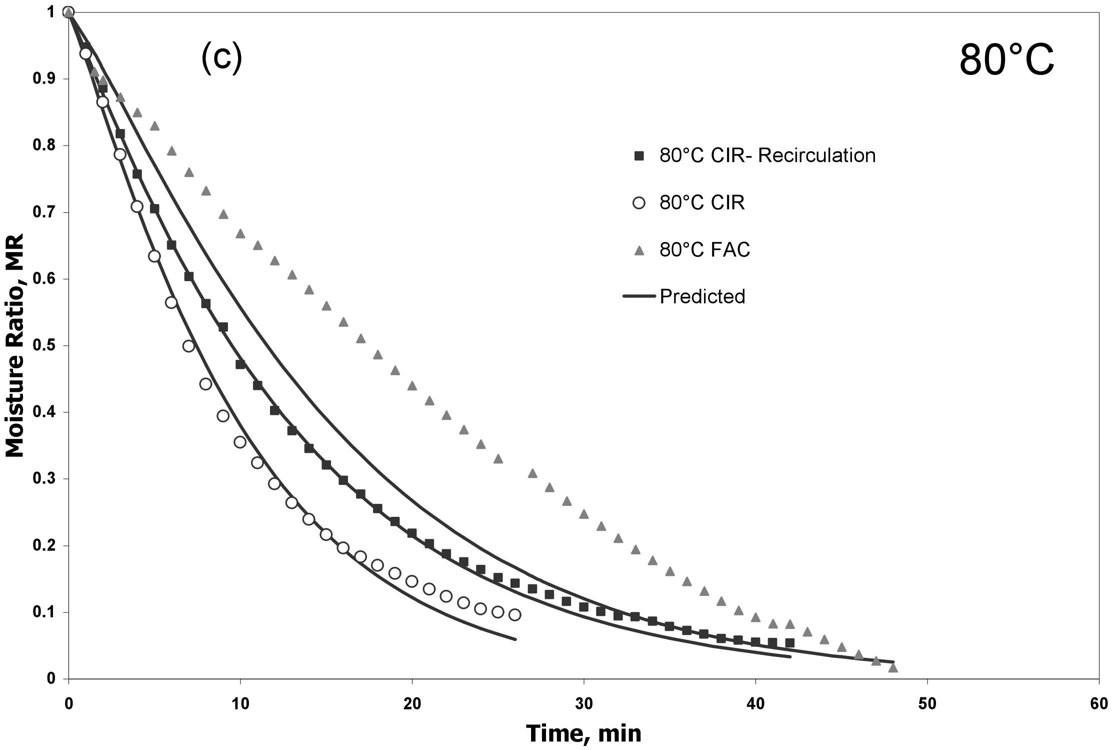


Figure 7-3. Predicted and measured moisture ratio at different drying time and temperatures (a) 60 °C, (b) 70 °C, and (c) 80 °C.

Table 7-1. Result summary of onion drying characteristics.

Drying Condition	Drying time to reach 50% MC (d.b.)	Max drying rate	Drying constant *k*	Correlation Coefficient
	min	g/kg$_{\text{initial weight}}$ *min	h^{-1}	R^2
60°C CIR-Recirculation	54.5±7.8	46.9±8.4*	1.88±0.42	0.988
70°C CIR-Recirculation	32.0±1.0*	59.9±4.2*	3.23±0.39	0.995
80°C CIR-Recirculation	24.0±4.6*	81.5±6.6*	4.47±0.67	0.997
60°C CIR	47.3±7.5	47.5±10.5*	2.04±.0.24	0.992
70°C CIR	36.5±7.8*	67.7±9.2*	2.87±0.83	0.991
80°C CIR	18.0±2.8*	83.4±4.6*	5.95±1.25	0.991
60°C FAC	56.0±8.5	20.7±3.1	2.23±0.26	0.927
70°C FAC	51.0±1.4	23.9±3.9	2.45±0.16	0.937
80°C FAC	33.0±5.7	43.2±22.1	3.82±0.94	0.844

* = Significantly different ($p < 0.05$) when compared to FAC value at same temperature

Table 7-2. Pungency changes during drying at different drying temperatures (percent pyruvate of fresh sample). Moisture content is percent dry basis (d.b.)

		Minutes of Heating			
		30	60	120	180
60°C	**CIR**	89.1 ± 15.7	79.1 ± 3.2	62.4 ± 7.9	59.3 ± 1.0
	Moisture Content (%)	142.4	69.2	22.5	14.4
	FAC	80.7 ± 8.5	70.2 ± 3.7	63.9 ± 7.0	65.1 ± 0.4*
	Moisture Content (%)	106.2	39.3	20.1	15.6

Unheated sample at 180 minutes: 99.2 ± 7.2

		10	20	40	60
70°C	**CIR**	86.1 ± 5.4	80.7 ± 19.4	73.6 ± 1.9	83.6 ± 4.9
	Moisture Content (%)	135.7	69.5	19.6	15.7
	FAC	115.2 ± 11.2*	70.0 ± 17.0	74.9 ± 0.2	74.2 ± 18.2
	Moisture Content (%)	148.6	69.3	21	9.7

Unheated sample at 60 minutes: 104.0 ± 2.3

		10	20	30	40
80°C	**CIR**	93.7 ± 32.5	69.9 ± 25.0	73.0 ± 6.2	61.3 ± 4.6
	Moisture Content (%)	81	30.5	21.1	11.2
	FAC	89.9 ± 20.4	96.2 ± 18.8	97.3 ± 14.8*	94.0 ± 3.8*
	Moisture Content (%)	151.3	73.4	41.6	24.6

Unheated sample at 40 minutes: 89.4 ± 2.8

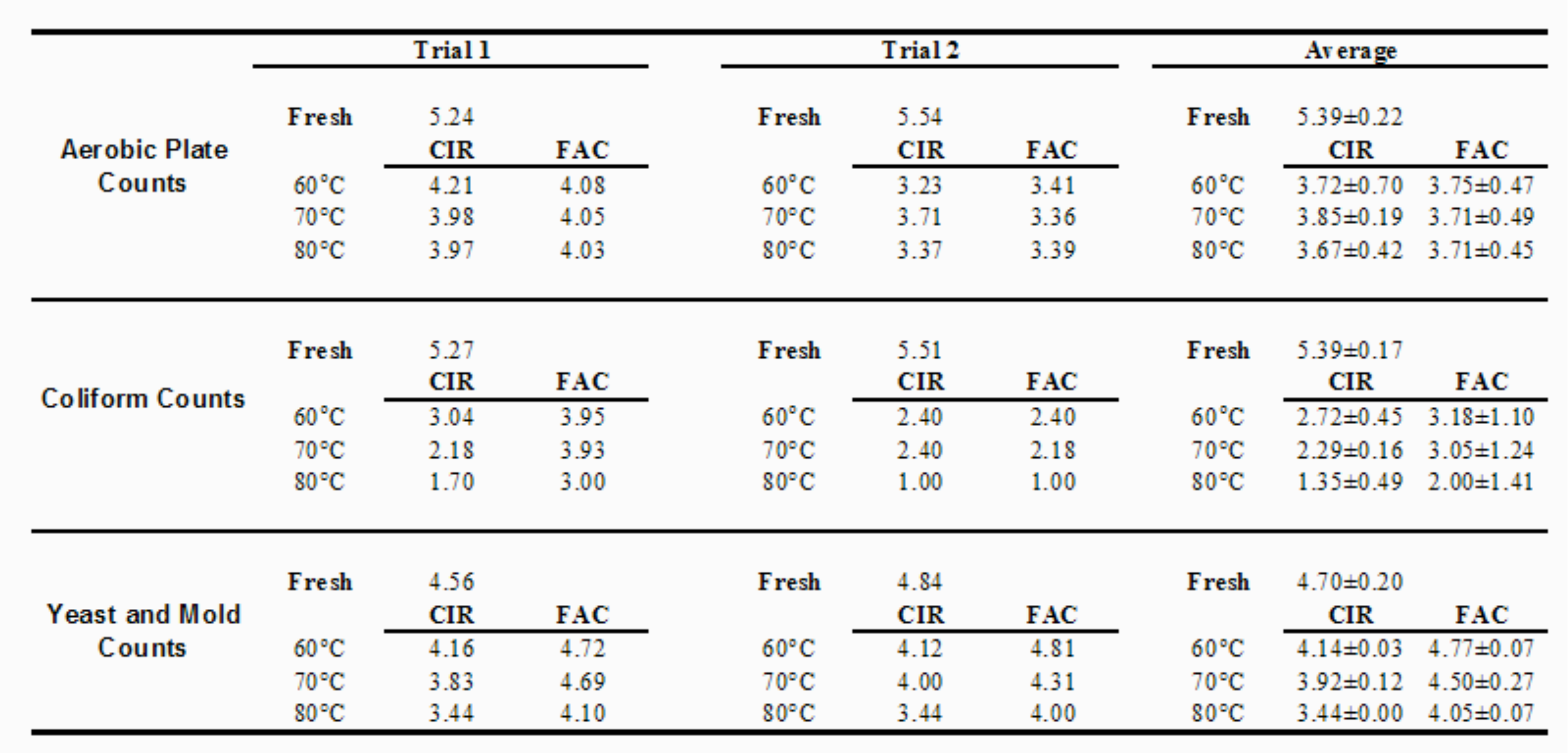
* = Significantly greater value ($p < 0.05$) for same time interval and temperature

Table 7-3. L and b values of onion dried with different methods and temperatures.

Drying Condition	L values	b values
60°C CIR-Recirculation	92.5±2.7	8.6±0.5
70°C CIR-Recirculation	93.4±3.2	6.2±0.5
80°C CIR-Recirculation	88.1±2.4	13.1±1.0
60°C CIR	93.9±2.8	5.2±2.1
70°C CIR	92.9±2.3	7.7±0.6
80°C CIR	89.4±2.1	11.1±1.5
60°C FAC	83.9±3.5 *	12.2±0.7 *
70°C FAC	91.0±4.0	9.9±0.6 *
80°C FAC	93.1±2.7	7.8±0.4

* = Significantly different value ($p < 0.05$) from other drying methods at same temperature

Table 7-4. Microbial data for aerobic plate counts, coliform counts, and yeast and mold counts of CIR and FAC dried samples (Reported as log CFU/ 10 g dried sample)



	Trial 1			Trial 2			Average		
	Fresh	5.24		**Fresh**	5.54		**Fresh**	5.39±0.22	
Aerobic Plate Counts		**CIR**	**FAC**		**CIR**	**FAC**		**CIR**	**FAC**
	60°C	4.21	4.08	60°C	3.23	3.41	60°C	3.72±0.70	3.75±0.47
	70°C	3.98	4.05	70°C	3.71	3.36	70°C	3.85±0.19	3.71±0.49
	80°C	3.97	4.03	80°C	3.37	3.39	80°C	3.67±0.42	3.71±0.45
	Fresh	5.27		**Fresh**	5.51		**Fresh**	5.39±0.17	
Coliform Counts		**CIR**	**FAC**		**CIR**	**FAC**		**CIR**	**FAC**
	60°C	3.04	3.95	60°C	2.40	2.40	60°C	2.72±0.45	3.18±1.10
	70°C	2.18	3.93	70°C	2.40	2.18	70°C	2.29±0.16	3.05±1.24
	80°C	1.70	3.00	80°C	1.00	1.00	80°C	1.35±0.49	2.00±1.41
	Fresh	4.56		**Fresh**	4.84		**Fresh**	4.70±0.20	
Yeast and Mold Counts		**CIR**	**FAC**		**CIR**	**FAC**		**CIR**	**FAC**
	60°C	4.16	4.72	60°C	4.12	4.81	60°C	4.14±0.03	4.77±0.07
	70°C	3.83	4.69	70°C	4.00	4.31	70°C	3.92±0.12	4.50±0.27
	80°C	3.44	4.10	80°C	3.44	4.00	80°C	3.44±0.00	4.05±0.07