

# MILLED RICE FISSURE FORMATION KINETICS

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**ABSTRACT.** Milled rice samples at various moisture contents (MCs) were exposed to air inside a chamber that was equipped with a video camera and monitoring system that enabled observation of fissure formation over a 24-h exposure duration. The effects of milled rice kernel MC (11%, 12%, 13%, or 14%), cultivar (Bengal, Wells, and CL161), air relative humidity (RH; 10%, 20%, 30%, 45%, 60%, 75%, or 90%), and air temperature (5 °C, 10 °C, 15 °C, 20 °C, or 30 °C) on the rate and amount of kernel fissuring were quantified. Rice cultivar and MC played minor roles in determining the rate and amount of fissuring relative to air temperature and RH. Fissuring rates were greatest at low (10%) and high (90%) RH levels; fissuring occurred almost immediately after kernels were exposed to these RH levels. Greater air temperatures considerably increased the rate and total amount of fissured kernels. Little fissuring was observed in an RH range of 30% to 75%, at any air temperature tested, providing a safe window for milled rice exposure to environmental conditions.

**Keywords.** Equilibrium moisture content, Kernel fissuring, Kinetics, Rice quality.

Fissured milled rice kernels cause great financial losses to post-milling processors in terms of both product waste and processing plant production limitations. Quantifying the rates of fissure formation in rice kernels at all stages of rice milling, transport, and end-use processing is necessary to design equipment and implementation procedures to minimize fissure formation.

Fissures form within rice kernels when internal hygroscopic stress exceeds material strength. Such stress is caused by intra-kernel moisture content (MC) gradients resulting from moisture transfer between the kernel surface and the surrounding environment that in turn causes moisture transfer within the kernel endosperm. The moisture adsorbing or desorbing potential of an air environment is characterized by the grain equilibrium MC (EMC) associated with the temperature and relative humidity (RH) of that air environment. As such, the magnitude of intra-kernel MC gradients results from the difference between the kernel MC and the grain EMC associated with the surrounding air.

Kunze and Hall (1965) observed that rice fissuring can be caused by moisture adsorption. When a kernel adsorbs moisture, the surface expands, causing compressive stresses at the kernel surface and tensile stresses at the drier inner core; fissures initiate at the inner core when the tensile stress exceeds the tensile strength of that portion of the kernel. Banaszek and Siebenmorgen (1990) reported that the extent of milling quality reduction of a rice sample exposed to high RH air was inversely related to initial sample MC. Kunze and Choudhury

(1972) explained that fissures likewise form at the kernel surface under rapid desorption.

Lan and Kunze (1996) compared the effects of environmental and kernel MC differences on rough rice, brown rice, and milled rice fissure formation. They found that milled rice was most susceptible to fissuring resulting from RH changes. Lan and Kunze state that due to the hull and bran, the rates of moisture adsorption, as well as the potential for fissuring, for rough and brown rice in a given environment were reduced relative to milled rice. Siebenmorgen et al. (1998) quantified the amount of fissuring in milled rice kernels exposed to air temperatures of 20 °C, 30 °C, and 40 °C and RH levels ranging from 25% to 85%. The results showed that at low (< approx. 40%) air RH levels, fissuring occurred in direct proportion to the rice MC, while the reverse trend was observed at high (> approx. 75%) air RH levels. At a given air RH, milled rice breakage increased with exposure air temperature. For milled rice at 13% to 14% MC (all moisture contents are expressed on a wet basis), an RH range of 40% to 65% produced little to no fissuring, indicating that the rate of adsorption or desorption was too low to produce sufficient intra-kernel MC gradients that would cause material failure. Lloyd and Siebenmorgen (1999) found that the extent of fissuring was greater in medium-grain than long-grain cultivars, given comparable kernel to air moisture gradients. This was explained by the observation of Jindal and Siebenmorgen (1994) that, in general, fissuring propensity was directly proportional to kernel thickness.

Limited fissure formation kinetic data have been reported, due in large part to the complexity of measuring the percentage of fissured kernels through time. Stermer (1968) reported that changes in air RH of 20 percentage points or more were likely to cause rice kernel stress cracks in less than 15 min of exposure. In addition, Siebenmorgen et al. (1998) showed that nearly all milled rice breakage occurred within 20 min of exposure to air. These studies quantified the amount of fissure formation after rice kernels had been exposed to certain environments comprising a fairly narrow range of temperatures. However, milled rice can be exposed to a wide range of air conditions during transport and conveyance, particular-

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ly during winter periods. As such, this study measured fissure occurrence kinetics of milled rice exposed to a wide range of environments, including low-temperature environments.

## MATERIALS AND METHODS

This study comprised exposing three cultivars of milled rice, conditioned to various MCs, to a range of air temperature and RH conditions. The air settings ranged from dry, low-RH conditions causing moisture desorption from kernels to moist, high-RH conditions causing moisture adsorption by kernels. During exposure, fissures in kernels were illuminated by fiber optic light sources, and images were captured by a video camera and cassette recorder every 4 min over the course of a day. The images were later viewed, and those kernels that were fissured after given exposure durations were enumerated. From this data, fissuring kinetics, in terms of percentages of fissured kernels throughout 24-h exposures, were quantified.

### EXPERIMENTAL DESIGN

Bengal, a medium-grain cultivar, and Wells and CL161, both long-grain cultivars, were harvested at MCs ranging from 18% to 22% from Stuttgart, Jonesboro, and Pocahontas, Arkansas, respectively. Rough rice samples of each cultivar were dried to approximately 14% MC by spreading the samples on screened trays in a chamber maintained at 22°C and 55% RH by a temperature and RH controller (AA5582, Parameter Generation & Control, Inc., Black Mountain, N.C.). Moisture content was then measured by drying triplicate 15-g samples at 130°C for 24 h in a convection oven (model 1370FM, Sheldon Manufacturing, Inc., Cornelius, Ore.) according to Jindal and Siebenmorgen (1987).

Four 150-g, 14% MC samples from each cultivar were dehulled using a laboratory huller (THU-35A, Satake Engineering Co., Ltd., Tokyo, Japan) and then milled for 30 s with a laboratory mill (McGill No. 2, Rapsco, Brookshire, Tex.). Broken kernels were separated from head rice (milled kernels

with length 3/4 or greater of the original kernel length) using a shaker table (Grainman Machinery Mfg. Corp., Miami, Fla.). Head rice sample MCs were measured using the oven procedure described previously. The four head rice samples were then dried to desired MCs of 11%, 12%, 13%, or 14% by spreading the samples on screened trays in the above-mentioned walk-in chamber, but with air conditions maintained at 28°C and 48% RH. By milling all samples within a cultivar at one MC and then drying the samples to the design MC levels, differences in the degree to which each sample was milled were minimized; rice sample MC is a significant factor in determining the degree to which rice is milled (Bennett et al., 1993).

Once each desired MC was attained, samples were sealed in plastic bags and placed in a 68 L insulated container (Rubbermaid Home Products, Wooster, Ohio) and stored at 4°C for approximately 3 weeks until testing. Samples were allowed to equilibrate in the storage bags in a room at ~22°C for 24 h prior to exposure tests.

### TEST SYSTEM

All tests were conducted inside an environmental chamber (Platinous Sterling Series T and RH chamber, ESPEC North America, Hudsonville, Mich.) capable of controlling temperature from -35°C to 150°C ( $\pm 0.5^\circ\text{C}$ ) and RH from 10% to 90% ( $\pm 3\%$ ). Open plastic dishes (Petri dishes, 55 mm in diameter by 14 mm in height) containing milled rice samples were mounted on a 0.51-m diameter Plexiglas (United States Plastic Corp., Lima, Ohio) platform mounted to a stepper motor (model 3700CNC, Sherline Products, Inc., Vista, Cal.) (fig. 1). The stepper motor was controlled by a motion controller (model 8800, Sherline Products, Inc., Vista, Cal.) interfaced to a timing system (MicroSet 2, Mumford Micro Systems, Santa Barbara, Cal.). The plastic dishes were held on the platform using metal pegs and were positioned 2.5 cm from the edge of the platform at an equidistant spacing of 22.5°. The motion controller was programmed to cause the stepper motor to incrementally rotate the platform 22.5° every 15 s. One complete revolution (360°) of the platform was

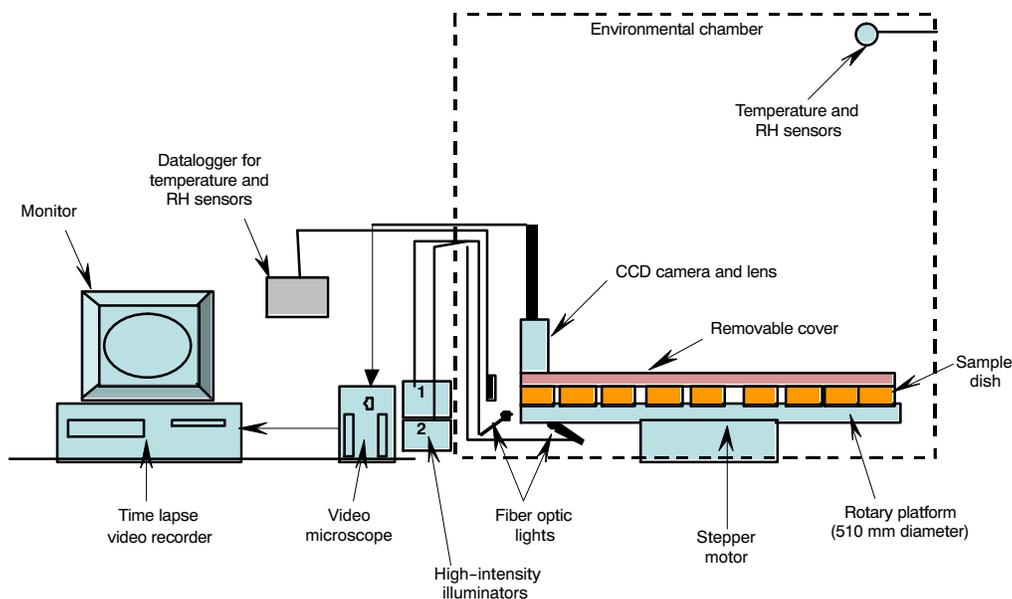


Figure 1. Schematic of the system used to detect and record fissures in milled rice kernels exposed to air at various temperature and relative humidity (RH) levels.

completed every 4 min, which also corresponded to the frequency at which each plastic dish sample was positioned under the camera and images viewed and recorded, as explained below.

Fissure formation was monitored and recorded using a camera (Scopeman MS-803, Moritex Corp., San Jose, Cal.) with 10× magnification installed inside the environmental chamber. The camera was interfaced to a computer with a monitor (Dell Corp., Bracknell, U.K.) and a videocassette recorder (Time Lapse 168, Sony Corp., Tokyo, Japan) located outside the chamber. Rice kernels viewed under the camera were illuminated using two fiber optic light sources (Fiber Lite high-intensity illuminator, Dolan-Jenner Industries, Inc., Boxborough, Mass.). The light sources were oriented to bi-directionally illuminate kernels (fig. 1) so as to allow fissures to be detected in the camera images. Aluminum squares (2.54 × 2.54 cm) were placed in the center of each plastic dish in order to enhance kernel viewing with the camera and for ease of fissure enumeration from the videotape.

Kernel images from the camera were projected onto the monitor. These images, along with the associated exposure duration, were simultaneously recorded onto the videocassette recorder. The videotapes were subsequently viewed to quantify the number of kernels that fissured throughout the exposure to a given air condition.

Two temperature and RH sensors (HOBO Pro/Temp data logger, Onset Computer Corp., Bourne, Mass.) were placed in the chamber to record air conditions during the exposure trials. The air conditions were also periodically checked using a dewpoint hygrometer (Hygro-MZ dewpoint monitor, General Eastern Instruments, Woburn, Mass.).

#### EXPERIMENTAL PROCEDURE

Kernels from each of the 12 milled rice lots (three cultivars at four MCs) were randomly selected and examined for fissures using a fissure inspection box (TX-200 Grainscope, Kett Electric Laboratory, Tokyo, Japan) inside the 26 °C and 55% RH walk-in chamber. This procedure was conducted inside this chamber at these air conditions to avoid possible fissuring resulting from exposure to ambient air conditions. The milled rice EMC associated with these air conditions is approximately 12.3%; the MC gradient between this EMC and the milled rice MC was deemed sufficiently low to cause fissures. For a given experimental design air setting, 30 unfissured kernels from each of the 12 lots were selected and placed in plastic dishes and covered with the dish lid. The 12 dishes were randomly distributed around the periphery of the rotary platform.

Once kernels were loaded into the plastic dishes and the dishes secured to the rotary platform, the dish lids were removed and a foam cover was used to cover the samples and prevent sample exposure to prevailing air conditions. The rotary platform was then transferred from the walk-in chamber to the environmental chamber, the chamber door was closed, and air conditions were allowed to stabilize to a desired design level. The foam cover was then raised via a cable placed through an entry port in the top of the chamber to expose the samples. The stepper motor program was then engaged, and each of the samples was introduced to the camera viewing area every 4 min for a 24-h exposure duration. The videotape was subsequently examined to delineate the number of the 30 kernels that were fissured in each plastic dish after exposure durations of 4, 8, 16, 32, and 60 min, and then

after 2, 4, 8, 12, and 24 h. Any kernel having at least one endosperm fissure was counted as a fissured kernel.

The above procedure was conducted for 35 environmental chamber air conditions, comprising five temperatures (5 °C, 10 °C, 15 °C, 20 °C, and 30 °C) and seven RH levels (10%, 20%, 30%, 45%, 60%, 75%, and 90%).

## RESULTS AND DISCUSSION

### CULTIVAR EFFECTS

Figure 2 shows the percentages of fissured kernels in Bengal, Wells, and CL161 milled rice at 12% MC when exposed to air at 10 °C or 30 °C and RH levels of 10%, 75%, or 90%; fissured kernel percentages are presented at 0, 4, 8, 16, 32, and 60 min and then at 720 and 1440 min (24 h) of exposure. Rice cultivars were vulnerable to fissuring at both low (10%) and high (90%) RH levels, while at mid-range RH (75%), milled rice kernels incurred little fissuring.

The medium-grain cultivar (Bengal) generally showed greater fissuring than the long-grain cultivars (CL161 and Wells), particularly after extended exposures. The greater fissure formation in Bengal was most profound when kernels were exposed to the 30 °C, 10% RH air condition. Kernel size has been shown to affect rice fissuring, with thicker kernels being more susceptible to moisture sorption than thinner kernels (Jindal and Siebenmorgen, 1994; Siebenmorgen et al., 1998). In addition, Lan and Kunze (1996) showed a greater percentage of fissured rice in thicker (Lemont) than thinner (Newbonnet) cultivars when exposed to air at 24 °C and 100% RH. Subsequent data will primarily show results involving exposure of the medium-grain cultivar Bengal in order to focus on the effects of kernel MC and air RH and temperature on fissure occurrence kinetics.

### KERNEL MOISTURE CONTENT EFFECTS

The percentages of Bengal milled rice kernels of different initial MCs that fissured during exposure to various air temperature and RH levels are presented in figure 3. The number of fissured kernels increased rapidly at both low (10%) and high (90%) RH levels; however, the rate of fissuring was greater under low-RH, moisture-desorbing conditions compared to high-RH, moisture-adsorbing conditions, regardless of cultivar and exposure temperature. Almost immediate fissuring occurred as soon as the foam cover was removed from the plastic dishes under the 30 °C, low- and high-RH conditions. Figure 3 indicates that the effects of milled rice MC on rice fissuring became more prominent as exposure temperature increased, particularly in the moisture-adsorbing environments. Little fissuring was observed when milled rice was exposed to an RH of 75%, providing evidence of conditions that would not cause fissuring, particularly for exposure durations less than 30 min.

Figure 3 indicates that the amount of fissuring after given exposures, while primarily dictated by temperature and RH levels, was influenced by kernel MC. During exposures to an air temperature of 30 °C and 10% RH, the percentage of fissured kernels was directly related to kernel MC; a greater percentage of kernels at 14% MC fissured compared to those at 11% MC. Conversely, at air conditions of 90% RH and 10 °C or 30 °C, the percentage of fissured kernels was inversely related to kernel MC; a greater percentage of kernels at 11% MC fissured compared to 14% MC. These trends can be ex-

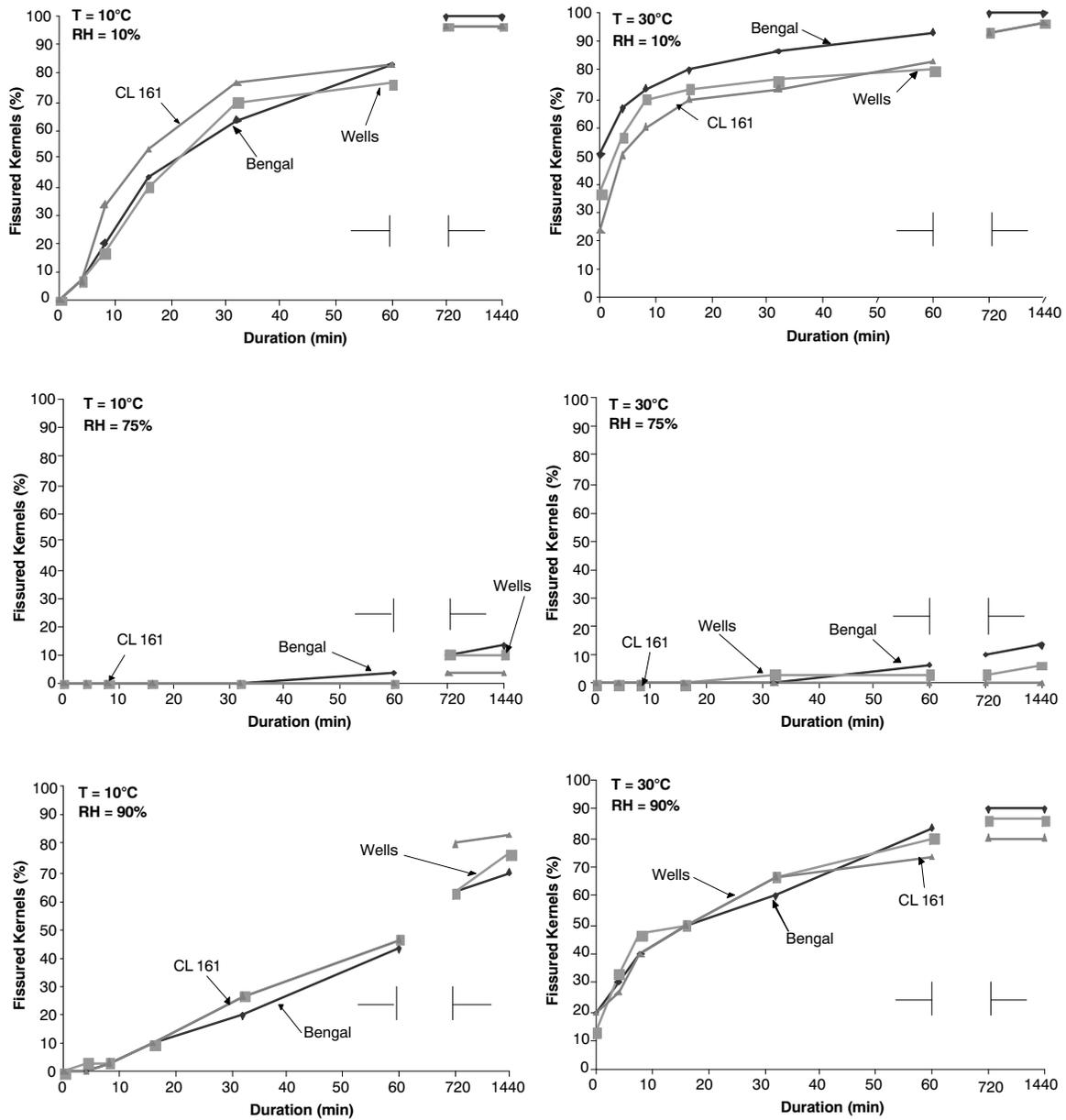


Figure 2. Effects of cultivar on the percentage of fissured kernels when milled rice at 12% moisture content was exposed to air at 10°C or 30°C and 10%, 75%, or 90% relative humidity (RH) over a one-day duration.

plained by the development of intra-kernel hygroscopic stresses resulting from rapid moisture transfer rates to or from the kernel; these moisture transfer rates are dictated by the difference in MC between the kernel and the rice EMC associated with the exposure air. For example, high-MC (14%) rice kernels experienced greater moisture gradients than that of low-MC (11%) kernels when exposed to low RH levels (10%), resulting in a greater percentage of fissured kernels. These results agree with Lloyd and Siebenmorgen (1999) and Siebenmorgen et al. (1998); Lloyd and Siebenmorgen (1999) showed that low-MC (10.4%) samples experienced more breakage at high-RH conditions than did high-MC (14.8%) samples; the reverse was observed at low-RH conditions.

#### RELATIVE HUMIDITY EFFECTS

Figure 4 shows the effect of RH on the rate of kernel fissuring in Bengal milled rice at 12% MC during exposure to air

temperatures of 5°C, 10°C, 20°C, and 30°C. At any temperature, increasing the RH from 10% to 20% to 30% showed progressively reduced fissuring levels. As RH increased from the 10% level, the EMC associated with the air correspondingly increased to EMCs closer to the grain MC, thereby decreasing the MC gradient between the air and the rice kernels. This resulted in progressively less fissuring and associated rates of fissuring. Relative humidities of 45% and 60% produced little to no fissuring, representing situations in which the MC gradient between the air and rice was too small to induce intra-kernel stresses sufficient to cause fissures. However, as RH increased to the 75% level and beyond to 90%, fissuring rates and amounts progressively increased due to increasing moisture adsorption rates.

The rate of fissuring was greater when exposing milled rice kernels to 10% and 90% RH than at other RH levels tested regardless of exposure temperature. After exposure of

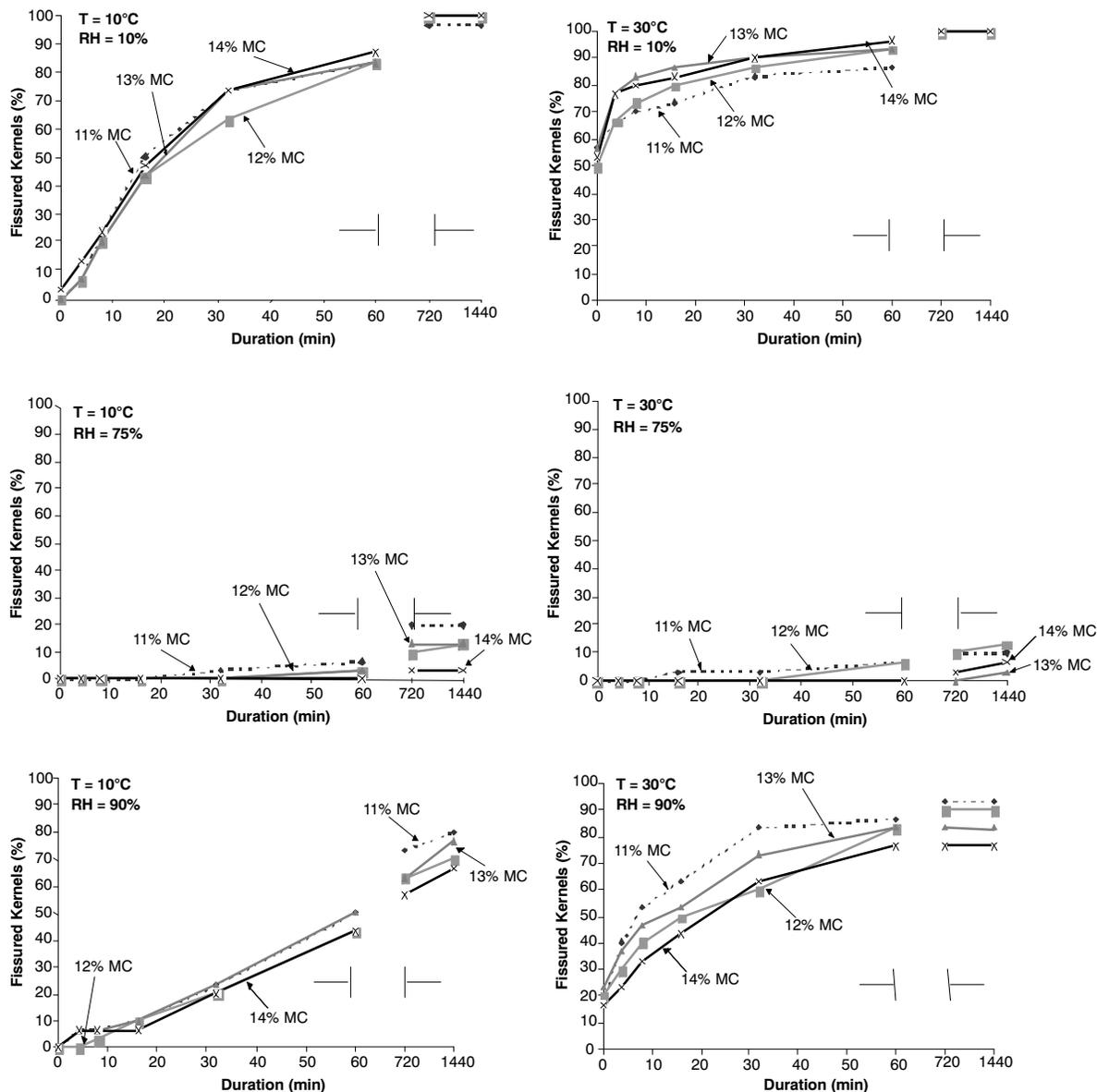


Figure 3. Effects of rice moisture content (MC) on the percentage of fissured kernels when Bengal medium-grain milled rice was exposed to air at 10°C or 30°C and 10%, 75%, or 90% relative humidity (RH) over a one-day duration.

rice kernels to 10°C and 10% RH for 4, 16, and 60 min, the percentage of fissured kernels increased from 7% to 43% to 83%, respectively. In the case of 10°C and 90% RH, the corresponding percentages of fissured kernels increased from 0% to 10% to 43%. Exposure of milled rice kernels to increasing temperatures, at given RH levels, increased the rates of fissured kernel formation.

Figure 4 indicates some implications of the rate of fissure formation when exposing milled rice to severe moisture adsorbing and desorbing air conditions that could exist during transport and conveyance. For example, exposing milled rice kernels to 10% RH and 30°C showed 50% fissuring within the duration from when the foam cover was removed from the plastic dishes until the kernels were viewed by the camera; in the case of 90% RH and 30°C, 20% of the kernels fissured immediately. After 16 min exposure to 30°C and 10% and 90% RH air, 80% and 50% of kernels fissured, respectively. These trends corroborate the previously mentioned findings

that greater percentages of kernels fissured when exposed to 10% RH compared to 90% RH.

#### TEMPERATURE EFFECTS

Figure 5 indicates the effects of air temperature on milled rice kernel fissure percentage during exposure to air at RH levels of 10%, 75%, and 90%. At the intermediate RH of 75%, there were no temperature effects as there were only low levels of fissuring, especially within 30 min of exposure duration; this observation also held at RH levels of 45% and 60% (data not shown). At lesser and greater RH levels, increasingly greater rates of fissure formation occurred as air temperature increased; increasing air temperatures promoted greater moisture transfer to or from kernel surfaces, inducing greater intra-kernel MC gradients and fissured kernels. For example, at 10% RH, medium-grain kernel exposure to 10°C, 20°C, and 30°C air for 4 min resulted in 7%, 27%, and 67% fissured kernels, respectively. Exposure at 10% RH and

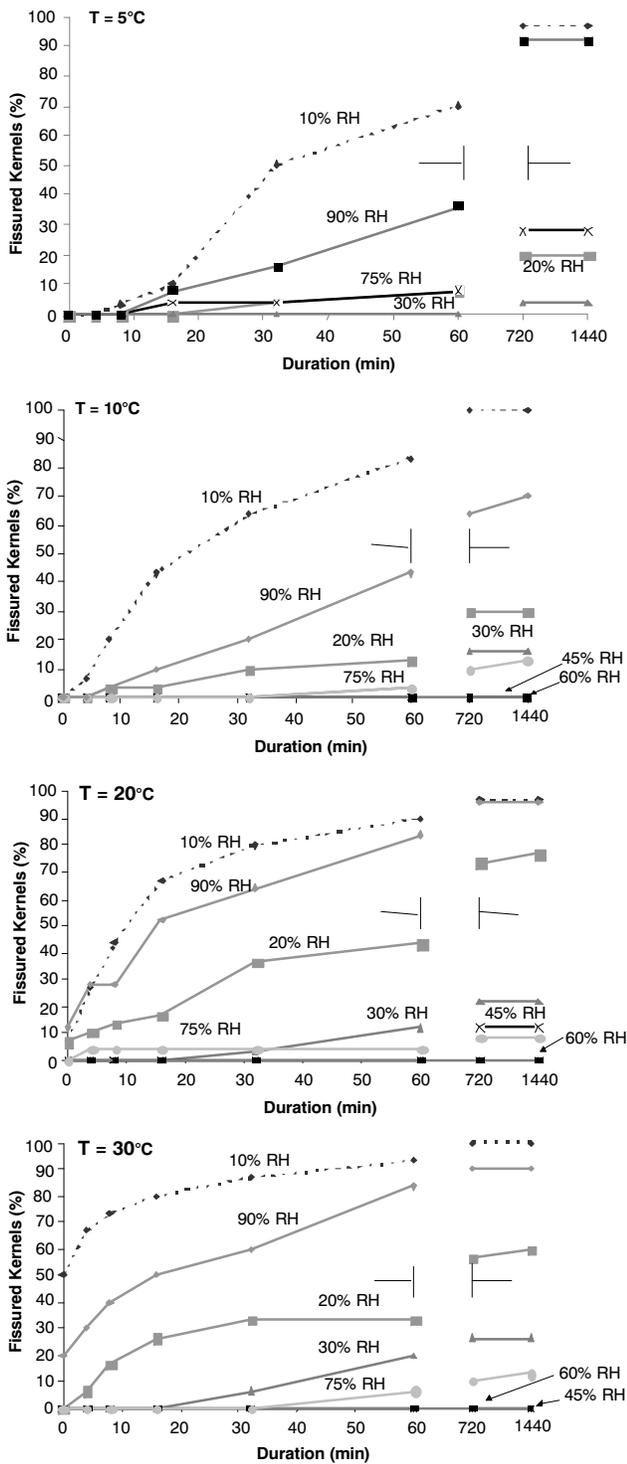


Figure 4. Effects of relative humidity (RH) on the percentage of fissured kernels when Bengal medium-grain milled rice at 12% MC was exposed to air at 5°C, 10°C, 20°C, or 30°C over a one-day duration.

the same temperatures for 16 min resulted in 43%, 67%, and 80% fissured kernels, respectively. Fissuring increased to 97% to 100% after exposure to 10% RH for 24 h, regardless of air temperature. At high RH (90%), the propensity for rice to fissure increased with temperature, but at a lesser rate than at low RH (10%). For example, after 4 min of exposure to 30°C and 90% RH air, milled rice showed 30% fissured kernels, compared to 67% fissured kernels at 10% RH and 30°C.

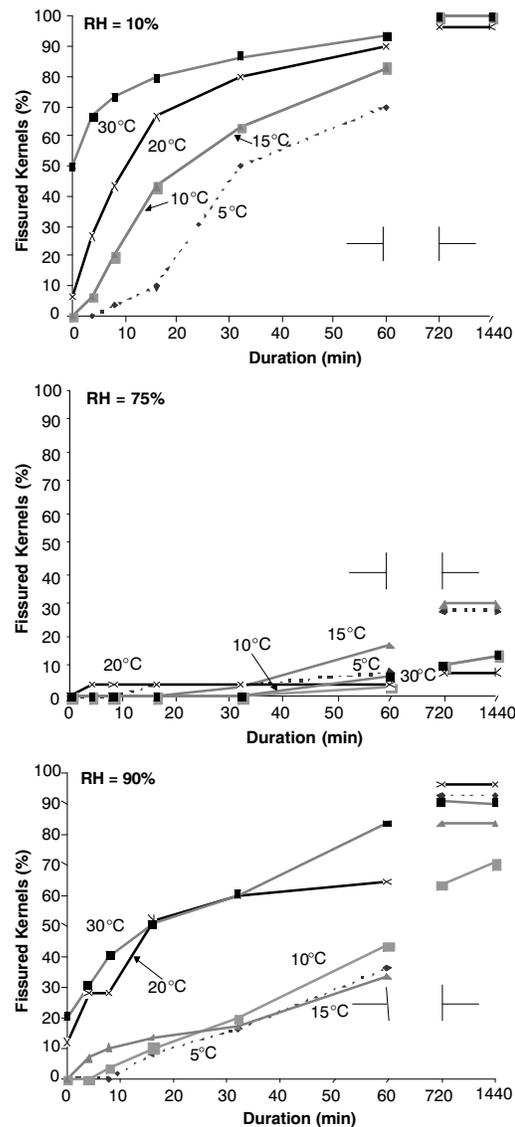


Figure 5. Effects of air temperature on the percentage of fissured kernels when Bengal medium-grain milled rice at 12% moisture content was exposed to air at 10%, 75%, or 90% relative humidity (RH) over a one-day duration.

These results agree with Henderson (1954) in that increases in rice breakage are usually associated with increases in exposure air temperature.

#### AIR CONDITIONS CAUSING MINIMAL FISSURING AT VARIOUS EXPOSURE DURATIONS

Figure 6 serves as a partial summary of this study, showing the level of fissuring measured at 4, 8, 16, and 1440 min (24 h) of exposure to air at 10°C, 20°C, and 30°C over a range of RH levels. The curves indicate the “window” of air conditions in which minimal fissuring occurred. This window can be viewed as the RH range, at a given temperature and exposure duration, in which fissuring was minimal. In general, this range spanned 30% to 75% RH for exposure durations within 16 min; longer exposures reduced the safe RH window, representing the kinetic responses shown in figures 4 and 5. The RH range compressed somewhat as air temperatures increased, resulting from the increased rate of moisture transfer to (high RH levels) or from (low RH levels)

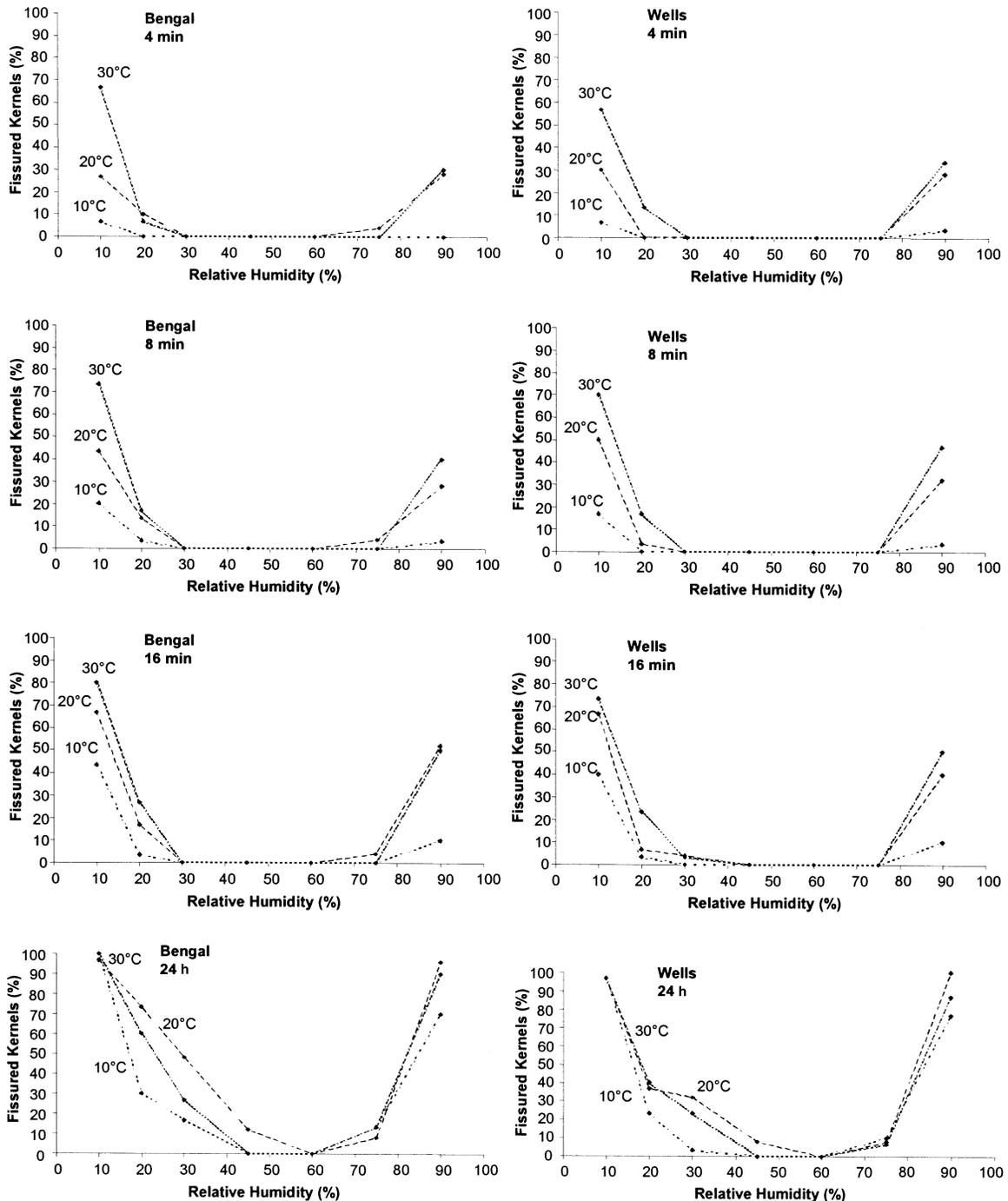


Figure 6. Effects of air temperature and relative humidity on the percentage of fissured kernels when Bengal medium-grain and Wells long-grain milled rice at 12% moisture content was exposed to environmental conditions over 4-, 8-, and 16-min and 24-h durations.

kernel surfaces. Figure 6 indicates that milled rice did not fissure, even through 24 h of exposure at 60% RH, regardless of air temperature.

## SUMMARY

The effects on milled rice kernel fissuring during exposure to a range of RH and temperature conditions were quantified. Results showed that air RH and temperature played significant roles in determining the rate and amount of milled rice fissuring. Fissuring of milled rice kernels occurred practical-

ly instantaneously at very low (10%) and very high (90%) RH levels, particularly at the 20°C and 30°C temperature levels. At these RH extremes, air temperature increases from 5°C to 30°C dramatically increased the rate and total amount of fissured kernel formation. For brief exposure durations of less than approximately 15 min, RH levels in the range of 30% to 75%, at any of the 5°C to 30°C temperatures tested, produced very little milled rice fissuring, providing a safe window for milled rice exposure. Kernel MC and cultivar were found to play a lesser role in determining fissured kernel percentage, with trends agreeing with those of previous research.

These findings have significant implications for process applications or systems in which milled rice is exposed to given air conditions for various durations. Maintaining air temperature and RH levels in the safe range during milled rice exposure to air, or maintaining minimal exposure durations to air conditions just outside the safe range, should limit fissure formation and subsequent breakage.

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#### REFERENCES

- Banaszek, M. M., and T. J. Siebenmorgen. 1990. Head rice yield reduction rates caused by moisture adsorption. *Trans. ASAE* 33(4): 1263-1269.
- Bennett, K. E., T. J. Siebenmorgen, and A. Mauromoustakos. 1993. Effects of McGill No. 2 Miller settings on surface fat concentration of head rice. *Cereal Chem.* 70(6): 734-739.
- Henderson, S. M. 1954. Causes and characteristics of rice checking. *Rice J.* 57(5): 16, 18.
- Jindal, V. K., and T. J. Siebenmorgen. 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. *Trans. ASAE* 30(4): 1185-1192.
- Jindal, V. K., and T. J. Siebenmorgen. 1994. Effects of rice kernel thickness on head rice yield reduction due to moisture adsorption. *Trans. ASAE* 37(2): 487-490.
- Kunze, O. R., and M. S. Choudhury. 1972. Moisture adsorption related to the tensile strength of rice. *Cereal Chem.* 49(6): 684-696.
- Kunze, O. R., and C. W. Hall. 1965. Relative humidity changes that cause brown rice to crack. *Trans. ASAE* 10(4): 448-450.
- Lan, Y., and O. R. Kunze. 1996. Relative humidity effects on the development of fissures in rice. *Cereal Chem.* 73(2): 222-224.
- Lloyd, B. J., and T. J. Siebenmorgen. 1999. Environmental conditions causing milled rice kernel breakage in medium-grain varieties. *Cereal Chem.* 76(3): 426-427.
- Siebenmorgen, T. J., Z. T. Nehus, and T. R. Archer. 1998. Milled rice breakage due to environmental conditions. *Cereal Chem.* 75(1): 149-152.
- Stermer, R. A. 1968. Environmental conditions and stress cracks in milled rice. *Cereal Chem.* 45(4): 365-373.