Moisture Content as a Function of Temperature Rise Under Microwave Radiation

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ABSTRACT

SAMPLES of shelled corn and whole burley tobacco leaves were heated for a fixed time interval in a microwave oven and the resulting temperature rise was correlated to the sample moisture content. The results showed that the moisture content of tobacco leaves, from 14 to 24% wb, is a linear function of temperature rise when 50-g samples are heated for 18 s at maximum power of 625 W in a home microwave oven, although the accuracy is reduced by the uneven heating that occurs with whole leaf samples. For shelled corn, with 200-g samples heated for 50 s at 625 W at maximum power, moisture content from 8 to 16% wb is a function of temperature rise. For higher moisture content corn the technique must be changed so as to induce less temperature rise in the samples.

INTRODUCTION

The moisture content of grain is used during its sale to apply discounts for the amount of water in the grain's gross weight. In tobacco sales, the moisture content is considered only if, in the opinion of the Agricultural Marketing Service grader, the tobacco is so moist that it may spoil; although, the actual moisture content is never determined. This system encourages farmers to sell considerable amounts of water along with their tobacco. It may also be the reason for the reported increase in moisture content of tobacco sold in recent years (Nelson, 1979). For both grain and tobacco, knowledge of the moisture content is requisite when deciding if the product can be safely stored without drying.

Rapid moisture content determinations in the grain industry are nearly always made with electronic moisture meters (Nelson, 1977). When properly calibrated, these meters are generally accurate to within 0.5% moisture content at moisture contents below 20 to 25% wb (Hurburgh et al., 1980; Nelson, 1977; and Noomhorn and Verma, 1981), whereas at higher moisture contents their performance is erratic (Hurburgh et al., 1980). Standard oven methods (ASAE Standard 352, 1981) are much more accurate but are not fast enough to be useful at the elevators. The Karl Fischer method (Hart and Neustadt, 1957) is a strictly stoichiometric technique and, therefore, should be very accurate. This method has been used to determine oven drying times and temperatures (Hart et al., 1959 and USDA, 1971), but is far too complicated for general use.

Recently, many researchers have modified oven drying methods for grain by using microwave ovens to drive off moisture much faster than is possible with an air oven (Click and Baker, 1980; Farmer and Brusewitz, 1980, and Verma et al., 1981). These method have shown promise, although removing all of the moisture while still protecting the magnetron can be a problem. Gorakhpurwalla et al. (1975) tested an experimental microwave applicator and dried grain for moisture content determination. Okabe et al. (1973) effectively determined moisture content of rice and wheat by measuring the microwave attenuation as a function of grain type and moisture content.

Since the amount of microwave energy absorbed by a material largely depends on the moisture present, the temperature rise of samples subjected to microwave radiation for a fixed time interval should increase with increasing sample moisture content. Thus, the temperature rise of a material during a short period of exposure to microwave radiation may correlate well with the moisture content of the material. The objective of this study was to determine the potential for using temperature rise under microwave radiation as a measure of the moisture content of biological materials.

METHODS

Shelled Corn

In preliminary tests, samples of 150, 200, and 250 g were heated for 50 s in a microwave oven.* The results showed no effect of sample size in this range on temperature, therefore only 200 g samples were used thereafter. The samples were placed in a rectangular plastic container approximately 11.4 cm x 12.7 cm x 3.2 cm deep, with 5 cm of polystyrene foam insulation on all sides. Each 200-g sample of corn was about 2.5 cm deep in this container. After removing the sample from the oven, five thermocouples were immediately inserted through holes in the top, of the insulation and the grain temperatures reorded for 30 min. These five temperatures were averaged to find the sample temperature rise at any given time.

After initial testing, the technique selected was to apply the maximum power setting with our oven (625 W) for a time that gave the highest temperature that would not melt the plastic sample container (50 s). Using the maximum power decreased the heating time and, thus, decreased the heat loss from the container during the heating cycle. The greater temperature rise was sought to

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*All tests were conducted in a Sears Kenmore Microwave Oven model 99601 rated by the manufacturer as 625W at 2450 Mhz. Use of tradenames does not imply endorsement of the product by the authors or by the Kentucky Agricultural Experiment Station.

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exaggerate the difference between moisture contents. While in the oven, the sample was rotated continuously to facilitate even heating.

Because of the variations between samples of the same moisture content, three separate samples of 200 g each were randomly selected from the same batch of corn. Thus, three replications were run for each mositure level (approximately 8, 12, 16, 20 and 24% wb). The actual moisture content of each sample was determined by oven drying according to ASAE Standard S352 (1981). When the three replications were averaged, a percent coefficient of variation of the temperature rise for a given time after radiation ceased was calculated from,

$$\text{percent c.v.} = \frac{\text{standard deviation}}{\text{mean}} \times 100 \quad \text{[1]}$$

The coefficient of variation was used as a criterion for determining the minimum time after cessation of radiation to read the sample temperature.

Actual moisture contents were plotted as a function of temperature rise for the various time intervals after the radiation stopped. Fifth order polynominal equations were fit to these data using the least-squares method. The accuracy of these moisture content prediction curves was evaluated by the standard error of regression, defined as

$$\text{S.E.} = \sqrt{\frac{\sum_{i=1}^{n} (Y_a - Y_p)^2}{n-1}} \quad \text{[2]}$$

where,

S.E. = standard error of regression,
Y_a = actual moisture content,
Y_P = predicted moisture content, and
n = number of observations.

Burley Tobacco Leaves

The trials with whole burley leaves were conducted in the same container as the corn, except that nine thermocouples were used to obtain the average temperaure in this nonhomogeneous sample. Whole leaves were used with the exception that the last leaf was torn and part of it discarded as necessary, to obtain samples of 50 ± 1 g. The leaves were folded for placement in the sample holder. The tobacco was irradiated at maximum power of 625 W for 18 s and temperatures were recorded for 18 min after removal from the oven. Preliminary tests were conducted with the highest moisture content tobacco (24% wb) in the study; the length of time that the sample was irradiated was varied in these tests to determine the maximum time and, thus, the maximum sample temperature that would avoid an apparent discontinuity in the data.

As in the corn trials, the samples were rotated continuously while being heated to improve the uniformity of heating. After the samples were removed from the oven and the thermocouples inserted through the top, the container was inverted to reduce the convective heat loss from the thermocouple holes.

A series of tests was conducted with leaves from the middle stalk position at five moisture levels from 14 to 24% wb. Each test consisted of three replications, with the replications averaged together. The actual moisture content of each sample was determined by air oven drying at 70 °C for 72 h.

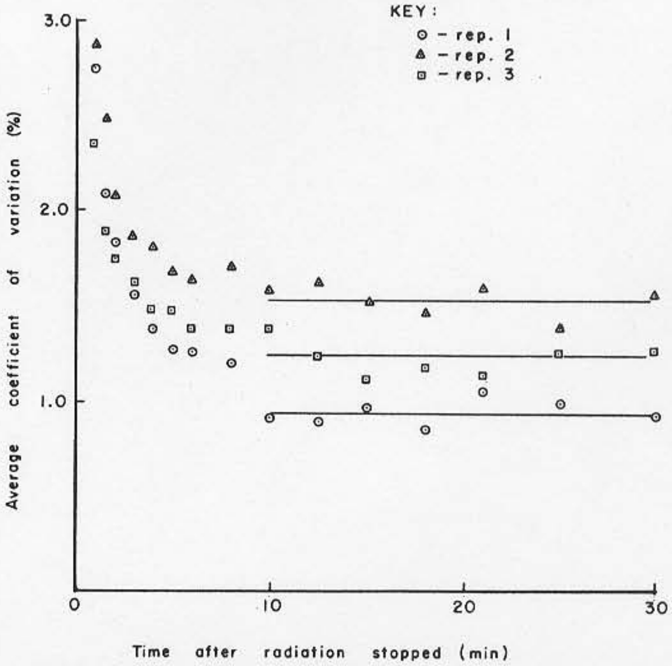

Fig. 1—Coefficient of variation for corn, averaged over moisture level, as a function of time after cessation of radiation.

Moisture content was determined as a function of temperature rise at each time interval by linear regression. The standard errors of regression were calculated according to equation [2].

RESULTS AND DISCUSSION

Shelled Corn

The coefficient of variation, averaged over moisture level, was plotted as a function of time after cessation of radiation in Fig. 1. The percent coefficient of variation decreased sharply during the first five minutes after removal from the oven, as the hot and cool spots within the sample equilibriated and a truer average temperature was obtained. After ten minutes the continued equilibration of the samples caused the standard deviation to decrease at about the same rate as the mean temperature, resulting in no further decrease in the percent c.v. after minutes and very little after five minutes.

A fifth order polynomial equation was used to describe the moisture content as a function of temperature rise at each time interval. A fifth order polynomial equation was the lowest order that would follow the data well. The results at six minutes are shown in Fig. 2. The resulting standard error of regression is shown as a function of time in Fig. 3. At 6 min the standard error of regression was 1.06% content, which was 6.78% of the average moisture content in the test. A major reason for the standard error improving with time after radiation stopped was the discontinuity in the data between 16 and 19% moisture content in Fig. 2; the vertical jump between these points became less significant as the curve itself became more nearly vertical. Also, the differences between tests were decreasing just as the differences within tests did in Fig. 1.

The discontinuity at 16% moisture content apparently resulted from drying of part of the sample. In the higher moisture content tests, appreciable amounts of moisture had condensed on the inner surfaces of the sample

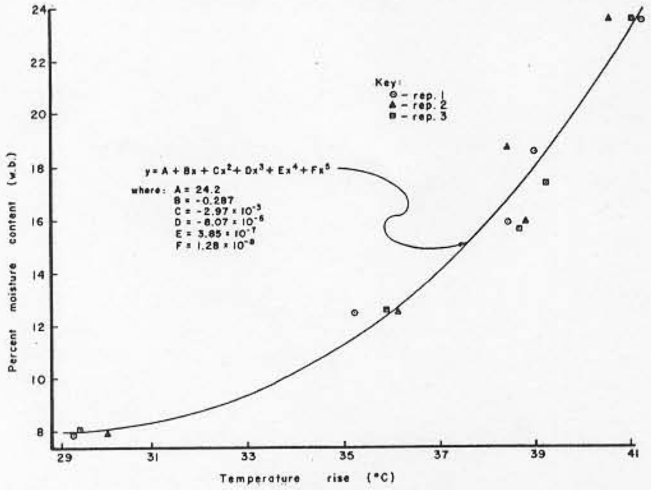

Fig. 2—A fifth-order polynomial used describe moisture content of corn as a function of temperature rise.

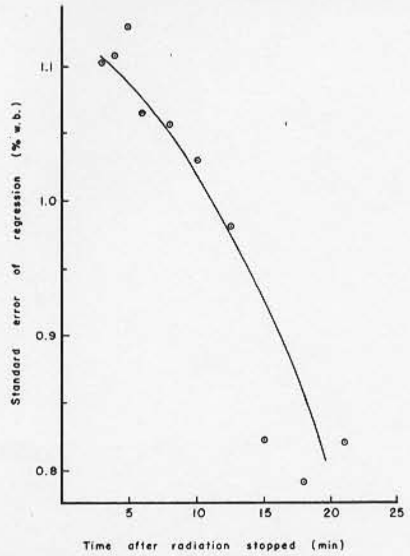

Fig. 3—Standard error of regression for corn as a function of time after cessation of radiation.

container at the conclusion of the test. The microwaves are first attenuated in the outer portion of the sample and more heating takes place on these edges. For moisture contents above 16%, the edge temperatures were apparently high enough to evaporate some of the moisture. For moisture contents from 16 to 19%, the amount of drying increases, allowing little increase in heating of the sample. The amount of drying then levels off (or at least increases at a much slower rate) as the moisture content increase above 19%, and the heating again increases with increasing moisture content.

A critical factor in using microwave heating for determining moisture content is the temperature rise per percentage increase in moisture content, i.e. the inverse of the slope of the moisture content prediction curve in Fig. 2. The inverse slope for the worst case, 24% moisture content, is plotted as a function of time in Fig. 4. Unlike the parameters in Figs. 1 and 3, the temperture rise per percent moisture content worsens at increasing time intervals due to the faster cooling of the higher moisture content (and higher temperature) samples. Therefore, the proper time interval for measuring the temperature rise will be after the coefficient of variation and standard error of regression reach acceptable levels, but before the temperature rise per percent moisture content gets too small.

Desirable levels would be one half degree of temperature rise per percent moisture content and a

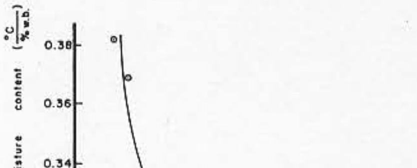

Fig. 4—Temperature rise per % moisture content for corn as a function of time after cessation of radiation.

standard error of 0.5% moisture content with any coefficient of variation associated with the desirable standard error being acceptable. The present technique does not meet both criteria, but its best results are at 6 min after radiation stopped. A technique that does not have the discontinuity between 16 and 19% moisture content, but is otherwise similar, should come closer to meeting both criteria. Fig. 2 indicates that the absence of the discontinuity should also enable a fifth order polynomial equation to be used to predict the moisture content.

Using a shorter period of time to irradiate the sample should reduce the problem of drying, since that will reduce the maximum temperature in the samples. Also, because very little energy will be taken to evaporate moisture in the higher moisture content samples, the slope of the curves should improve and produce more degrees of temperature rise per percent moisture content.

Burley Tobacco Leaves

The results of the preliminary tests on leaves at 24% moisture content, in which the time of radiation was varied, are shown in Fig. 5. The smaller slope of the line through the data at 20 s and longer, as compared to the line through the data at less than 20 s, was due to increasing amounts of energy being used to evaporate moisture as the time increased above 20 s. Based on the effect from evaporating moisture for heating times lnger than 20 s, 18 s was selected as the time for all tobacco tests with 50-g samples so that no test samples would reach temperatures high enough to cause significant energy loss from evaporating moisture.

The variation in the temperature rise of three replications at 20 s appeared to be a result of the different initial temperatures of the three samples. Those that started at a lower temperature and thus, were at a lower temperature throughout the trial, had a greater temperature rise since apparently less energy was used up in evaporating moisture at this lower temperature. The average percent coefficient of variation was calculated as a function of time and is shown in Fig. 6. The percent coefficient of variation decreased with time, as it did for shelled corn, and approaches a constant

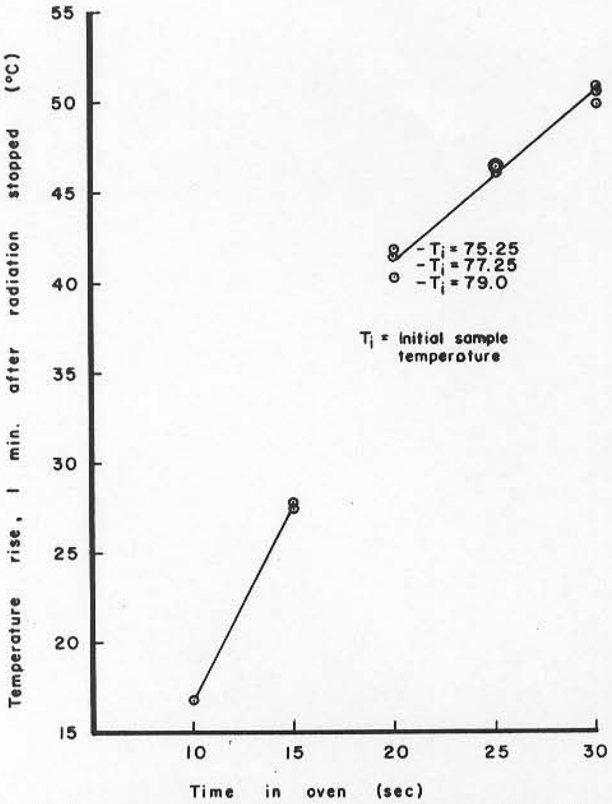

Fig. 5—Temperature rise of tobacco samples as a function of time in microwave oven.

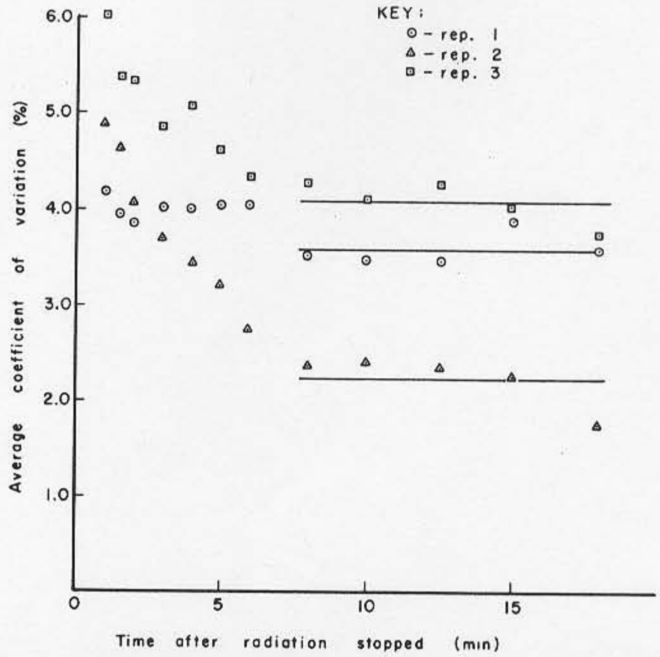

Fig. 6—Coefficient of variation for tobacco, averaged over moisture content, as a function of time after cessation of radiation.

value at eight minutes. The average percent coefficient of variation values were, though, much higher for tobacco than for corn; this was caused by the nonhomogeneous nature of the tobacco. With six to eight leaves folded into the container and both the midrib and lamina portions of the leaf present, there were large density variations within the samples resulting in uneven heating as compared to shelled corn.

Despite this variation the standard error of regression for the moisture content prediction line in Fig. 7 is 1.04% moisture content, which is 5.26% of the average moisture content in the tests. Third order polynomials were also fit to the data, but their standard errors were not significantly better than the linear fits. The R^2 value for the line in Fig. 7 is 0.886, i.e. 88.6% of the variation in the moisture content is explained by the regression. The standard errors of regression for the prediction lines are plotted for the various time intervals in Fig. 8. The standard errors were generally lower than for shelled corn since the problem of evaporating moisture was eliminated in the tobacco tests and, therefore, there was no discontinuity in the tobacco data. Unfortunately, the increased variation from the nonhomogeneity of the tobacco samples masked that improvement and left only a small total improvement over shelled corn.

The temperature rise per percent moisture content at each time interval is shown in Fig. 9. At 5 min (the time selected for moisture content prediction) it was 1.1 °C/percentage point wb, which is twice as good as the desired value of 0.5 °C/percentage point wb. This is considered to be an excellent slope for the prediction line, but the standard error of regression needs to be improved to obtain the desired accuracy of ± 0.5% moisture content. Having the tobacco in a more homogeneous form (shredded, for example) would probably improve the standard error. Shredding of the tobacco was not considered for these tests in order to determine the feasibility of using whole leaves—a much more convenient sample form—to effect an expedient method of mositure content determination. The tobacco

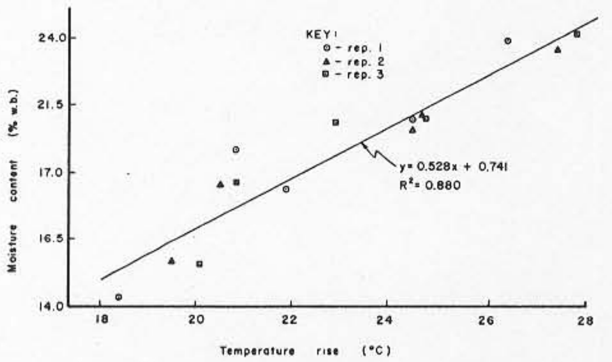

Fig. 7—Linear regression of tobacco leaf moisture content as a function of temperature rise under microwave radiation.

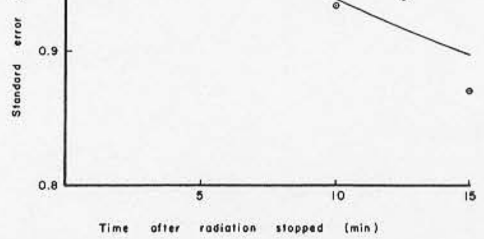

Fig. 8—Standard error of regression for burley tobacco as a function of time after cessation of radiation.

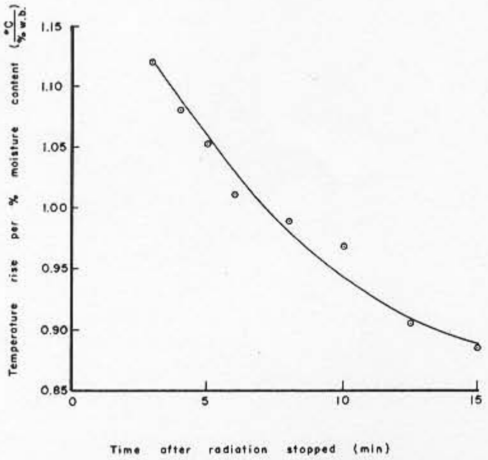

Fig. 9—Temperature rise per % moisture content for burley tobacco as a function of time after cessation of radiation.

leaves will be shredded in future tests, to determine whether or not the variation caused by the nonhomogeneity was significant. Tests on heating of pure water showed that uneven heating in the microwave oven was responsible for a significant amount of variation in the reproductibility of the data as indicated by the coefficient of variation. Thus, a microwave applicator that heats more evenly than the home microwave oven used in this study may improve the accuracy for all materials.

CONCLUSIONS

The following conclusions were drawn from the results of this research:

1. The initial temperture, power setting, and time of irradiation for determining moisture content from microwave heating must not cause significant drying in higher moisture content samples.
2. The technique used for corn (maximum power of 625 W for 50 s) did not distinguish between moisture contents in the range of 16% to 19% wb and gave less accuracy than previously developed techniques.
3. Heating 50-g samples of whole burley tobacco leaves for 18 s gave a linear relationship between moisture content and temperature rise in the range of 14% to 24% wb.
4. Nonhomogeneous samples such as whole tobacco leaves will be heated unevenly in a microwave oven, resulting in decresed accuracy of the moisture content determination.
5. The temperature rise of biological materials under microwave radiation is a function of the material's moisture content, the type of microwave applicator used, the technique used, and the material tested.

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