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Chuma, Yutaka
Laboratory of Agricultural Process Engineering, Faculty of Agriculture, Kyushu University

Uchida, Susumu
Laboratory of Agricultural Process Engineering, Faculty of Agriculture, Kyushu University

Shemsanga, Kassim H. H.
Laboratory of Agricultural Process Engineering, Faculty of Agriculture, Kyushu University

Matsuoka, Takahisa
Laboratory of Mechanical Engineering, Faculty of Agriculture, Kochi University

https://doi.org/10.5109/23739

出版情報：九州大学大学院農学研究院紀要. 26 (1), pp.57-70, 1981-10. Kyushu University
バージョン：
権利関係：

J. Fac. Agr., Kyushu Univ., 26(1), 57-70 (1981)

Bulk Physical and Thermal Properties of Cereal Grains as Affected by Moisture Content

Yutaka Chuma, Susumu Uchida and Kassim H. H. Shemsanga

Laboratory of Agricultural Process Engineering, Faculty of Agriculture, Kyushu University 46-05, Fukuoka 812

Takahisa Matsuoka

Laboratory of Mechanical Engineering, Faculty of Agriculture, Kochi University, Nangoku, Kochi Pref. 783

(Received July 10, 1981)

Specific gravity (true density), apparent density (bulk density), and thermal properties such as thermal conductivity, thermal diffusivity and specific heat of rough rice, wheat. milled rice, corn and soybean were investigated. Except for corn and soybean, all the properties tested were investigated at different moisture contents. The apparent density with the exception of rough rice, was observed to increase with increase in moisture content. The thermal properties were found to be strongly dependent on moisture content of the materials and the dependence was observed to be linear in specific heat and thermal conductivity unlike in thermal diffusivity. The effect of apparent density on the thermal conductivity was also investigated and found to increase the thermal conductivity as it increases. The correlation between the properties was also investigated. There was a correlation between the properties except in milled rice.

INTRODUCTION

Proper storage of grains without loosing their quality requires the prediction of the grain temperature in the stock-pile. The success of the prediction of this temperature depends on the knowledge of the thermal properties of the grains. Moreover, in the storage of the grains many handling processes take place such as drying, aeration, neumatic conveyance and cooling. These properties in addition to the requirement of the thermal properties of the materials will require the knowledge of the physical properties of the materials. For example in neumatic conveyance, the full understanding of the specific gravity of the material is required. The full understanding of the apparent density on the other hand is required for a successful aeration of the materials.

The physical and thermal properties of the materials are affected by many factors such as time, temperature, humidity, and the degree of compactness of the material. The main factor however, was assumed to be moisture content of the grains and soybean. This study was therefore, mainly devoted on the investigation of the apparent density, specific gravity, thermal conductivity, thermal diffusivity and specific heat of wheat, rough rice, milled rice, corn and soybean in bulk at different moisture contents.

MATERIALS AND METHODS

Wheat, rough rice, milled rice, corn and soybean at different moisture contents were used in this study. Throughout the experiment, materials of the same variety in a given test harvested in 1979 and 1980 were used. Wheat of the variety Nohrin 61 which was cultivated in Oita and Saga Prefectures were supplied by Tohfuku and Torigoe Milling Companies. Soybean of the variety Akisengoku was bought from Farmers Cooperative Union in Fukuoka City; yellow corn of the variety Nagano 1 was obtained from Takii Seed Company. Milled rice of the variety Reiho from Kyushu University Farm was used while rough rice of the variety Reiho was used in the specific gravity and apparent density tests. For the thermal properties tests rough rice of the varieties Koshihikari and Tsuyuhakaze were used.

To be able to investigate the properties of the materials at high moisture contents, the materials were soaked in water for two days except for soybeans which were soaked for 4 hr only because of their high adsorption rate of water. To obtain moisture contents between the initial content and after soaking, the materials were subsequently redried at short intervals of time. It was presumed that the materials would behave in the same way as they would do before their initial drying. After soaking, the materials were freed of the surface water attached to them by spreading them on plastic sheets after which they were conditioned in airtight plastic bags for 24 hr inside the experimental room to acquire uniform moisture content throughout the samples. The reconditioning was also done on the materials after redrying.

The moisture content was determined by air oven dry method at 135°C for 24 hr (Yamashita, 1975), for wheat, rough rice and milled rice. That of soybean and corn was determined at 105°C for 24 hr (ASAE, 1978). In each moisture determination test, 15 grams of the samples, repeated five times were used. All the moisture contents were calculated on wet basis.

Specific gravity

Ten grams of each material at three levels of moisture contents replicated three times were used. The specific gravity was determined by the conventional picnometer method described by Mohsenin (1970). The specific gravity of toluene, γ_t was determined at different temperatures and was found to be related to the temperature, T by the linear relationship $\gamma_t = 0.917 - 2.32 \times 10^{-3}\,T$ with a correlation coefficient of -1.00. For every test the temperature of the toluene was measured and the actual specific gravity of the toluene at this temperature was used in the specific gravity calculation of the samples from the relationship,

$$\gamma_s = \frac{\gamma_t \cdot W_s}{W_s - (W_t - W_1)} \tag{1}$$

where, γ_s = specific gravity of the sample,

γ_t = specific gravity of toluene (toluene wt/water wt),

W_s = weight of sample,

W_t = weight of picnometer plus toluene and sample,

W_1 = weight of picnometer and toluene.

Kerosine was also investigated whether it could be used instead of toluene. It was found to respond to temperature changes as toluene and gave the same specific gravity values for wheat, but gave different values with the other sample materials. For rough rice the specific gravity was 1.10 with toluene and 1.08 with kerosine, for soybean, corn and milled rice with toluene it was 1.07, 1.10 and 1.13 respectively while with kerosine it was 1.09, 1.08 and 1.1. These results were significantly different at 5 % level. The difference might have been due to absorption of the kerosine by the samples, although this needs to be established. If the measurement time could be reduced especially during removing of the air bubbles by vacuum pump and weighing the samples this liquid which is cheaper than toluene might have a good possibility of being used in the determination of specific gravity.

Apparent density

Boerner weight-volume tester (Kiya 128) was used. The apparatus consists of a marked glass cylinder which is oval at the bottom. The samples to be tested were weight balanced with 50 grammes weight provided with the apparatus. The samples were then poured into the cylinder and its volume read directly on the cylinder. The readings were repeated three times.

Thermal conductivity

Non-steady state method for the determination of the thermal conductiv-

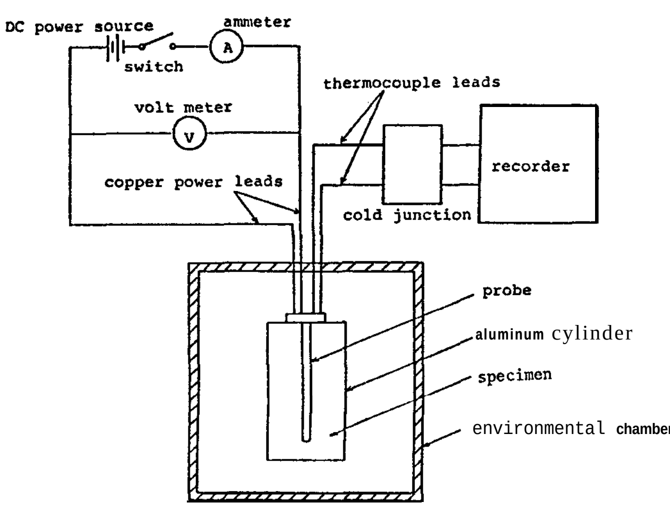

Fig. 1. Block diagram of experimental apparatus for thermal conductivity.

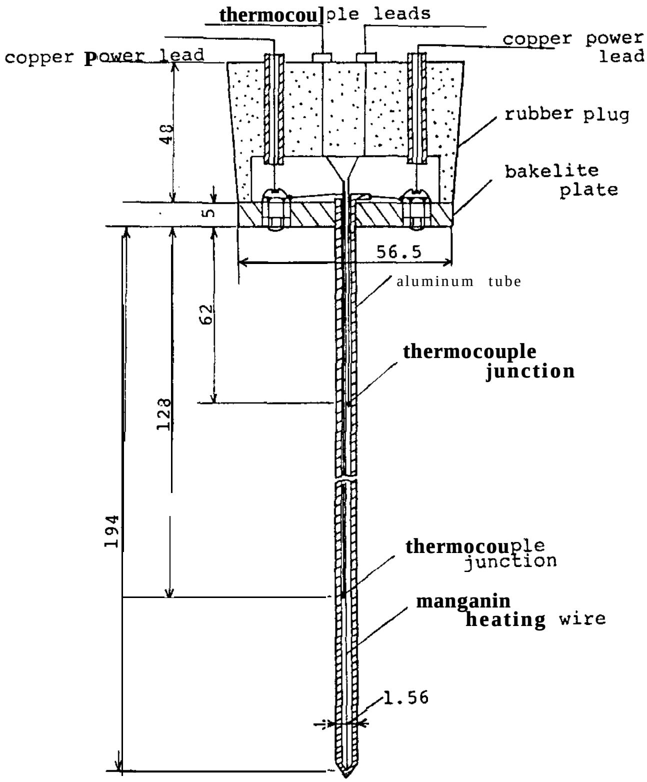

Fig. 2. **Detailed diagram of probe.**

ity of the materials was used. The method was selected due to the short time required to take the measurements, hence reducing the moisture differences and movements during data taking. The experimental apparatus is shown in Figs. 1 and 2. For rough rice, wheat and milled rice an aluminum cylinder of 350mm height and 150mm internal diameter was used while a 350 mm height and 150 mm diameter cylinder was used in corn and soybean. Aluminum probe of 194 mm in length and 1.56 mm outer diameter enclosing a copper-constantan thermocouple and a manganese heater was inserted into the center of the cylinder. The heater was supplied with 3 volts DC power supply to rise the temperature in the probe up to 30°C. The heat flux was calculated from the electric current and the voltage flowing into the heater. The current and voltage was accurately measured by a DC Voltage current standard (KIKUSUI 101). The variation of the temperature at the probe with time is shown in Fig. 3. The slope of the straight part of the curve was measured and used in the calculation of the thermal conductivity of the material from the following relationship (Seno et al., 1977).

$$\lambda=(q_0/4\pi)\log(t_2/t_2)/\Delta\theta$$

where, λ= thermal conductivity (kcal/m.hr ℃),

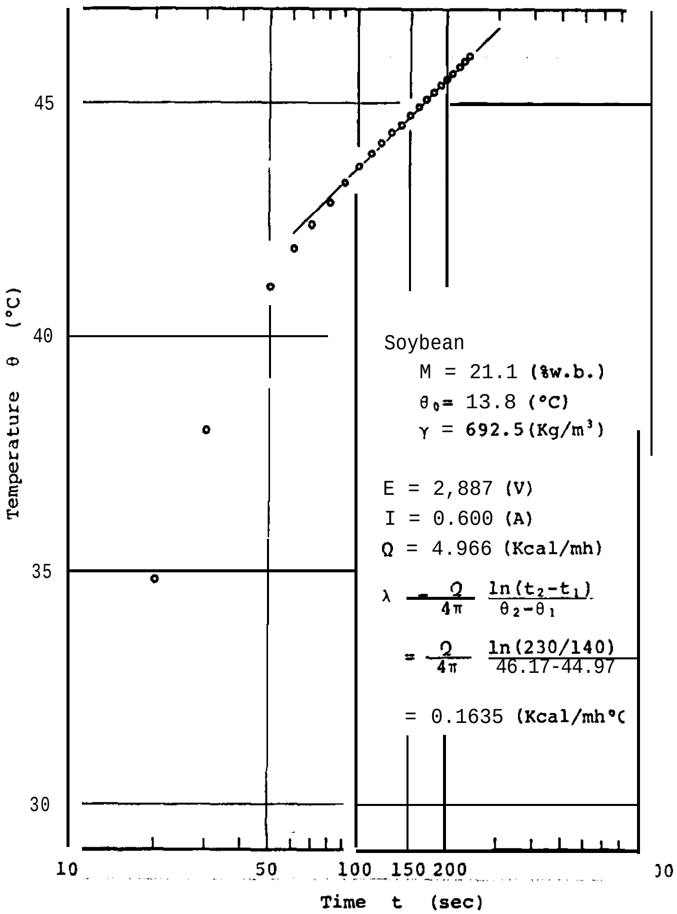

Fig. 3. Logarithmic time and temperature relationship for a typical thermal conductivity test.

q_0 = heat flux (kcal/m.hr),
θ = temperature of the probe (°C),
t_2, t_1 = time (hr).

Example for thermal conductivity calculation is shown in Fig. 3.

Thermal diffusivity

The experimental apparatus is shown in Figs. 4 and 5. The sample cylinder was as that used in the thermal conductivity test except that copper was used in place of aluminum. The cylinder was made air tight and the heater in the probe was not used. Another thermocouple was attached to the outer surface of the cylinder to monitor temperature changes at the surface of the cylinder. The samples were placed into the cylinder, sealed and left to stand until the temperature became constant after which it was sub-

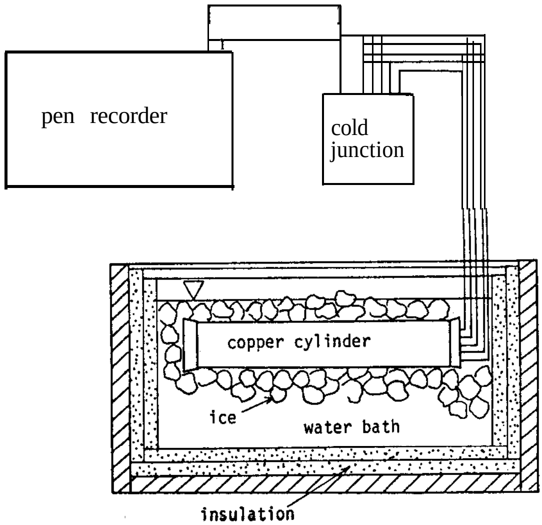

Fig. 4. Schematic diagram of thermal diffusivity apparatus.

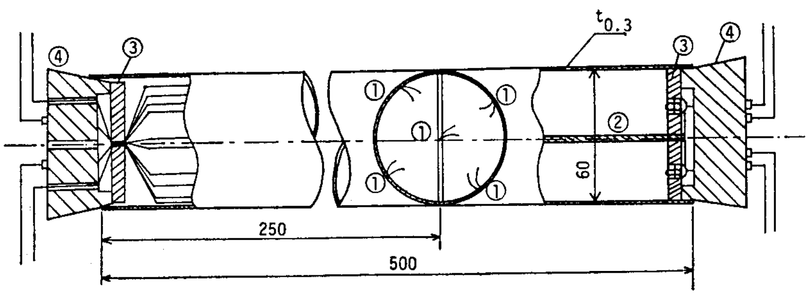

Fig. 5. Details of copper cylinder.

merged into an ice cold water bath at 0 °C. The temperature at the center and surface of the cylinder was recorded on a temperature pen recorder balanced on a cold junction, The surface and center temperatures were recorded at the same interval. The temperature time relationship is shown in Fig. 6. As in thermal conductivity the thermal diffusivity was calculated from the straight part of the curve of the surface and center temperatures. The thermal diffusivity was then calculated from the relationship (Chuma and Murata, 1969),

$$\frac{\theta_{r=a}}{\theta_{r=0}} = J_0(a\alpha_1) \qquad (t=t_1)$$

$$\kappa = (1/\alpha_1^2)(1/(t_1-t_1))\,\mathrm{Ln}(\theta_{t=t_1}/\theta_{t=t_2}) \qquad (r=a)$$

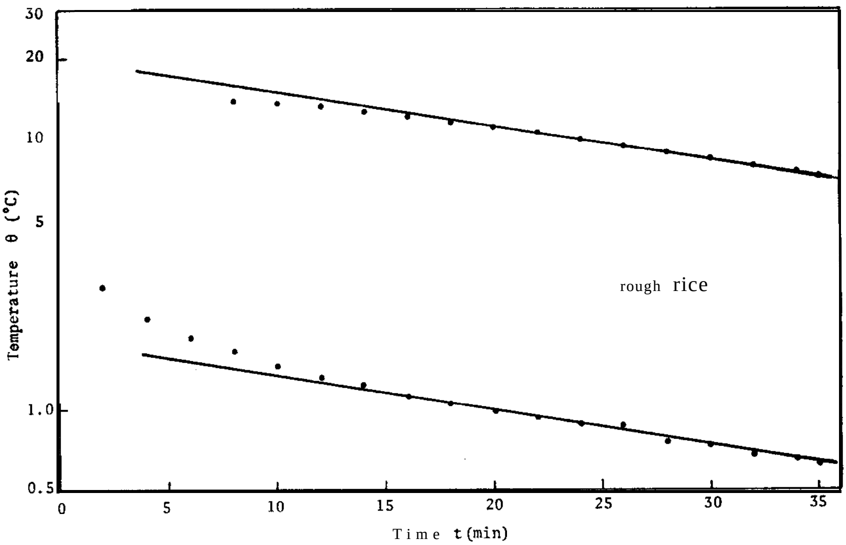

Fig. 6. Logarithmic temperature and time relationship for a typical thermal diffusivity test.

where, κ = thermal diffusivity (m^2/hr),
J_0=Bessel function of the zero order,
a=radius of the cylinder (m),
α_1 = constant.

In this experiment, only wheat, rough rice and milled rice were investigated. In every thermal diffusivity as well as in thermal conductivity the apparent density of the materials were accurately measured.

Specific heat

The thermal conductivity and thermal diffusivity obtained above with their respective apparent densities were used to calculate the specific heat of the samples from the relationship (Kazarian and Hall, 1965),

$$c=\lambda/\kappa.\rho_0$$

where, c=specific heat (kcal/kg °C),
ρ_0=apparent density (kg/m^3).

RESULTS AND DISCUSSION

Without exception, all the properties of the investigated materials were found to be highly dependent on the moisture content of the material.

Specific gravity

The specific gravity of soybean and corn was observed to decrease linearly with correlation coefficients of 0.952 and 0.947 respectively as the moisture

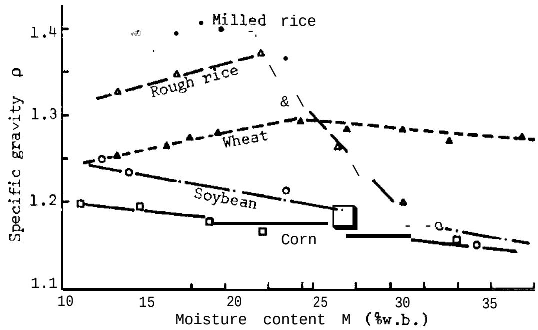

Fig. 1. Variation of specific gravity of grains with moisture content.

content increases as shown in Fig. 7. This is in confirmity to the results reported by Brusewitze (1975) except that the values in this work was higher than those reported by the other researcher.

In contrast to these results, wheat and rough rice showed an increase, reaching a peak at 21.6 % for rough rice and 23.9 % for wheat and then decrease in rough rice, and remain constant in wheat. Morita and Singh (1979) has reported a continuous decrease in the specific gravity of rough rice with increase in moisture content while Brusewitze (1975) has reported a continuous decrease of the specific gravity of wheat. Milled rice also showed the same trend but it was not so clear as in the others may be due to the small range of moisture content within which it was investigated. For rough rice and corn, a continuous increase with increase in moisture content has been reported by Seno *et al.* (1976). The peak in the specific gravity which was observed in wheat and rough and milled rice is yet to be explained. The failure of other workers to observe this peak value might have been due to the small range of moisture content under which the density was studied.

Apparent density

The experimental results are shown in Fig. 8. The apparent density was observed to decrease linearly with increase in moisture content in milled rice, corn and soybean with correlation coefficients of 0.715, 0.948 and 0.952 respectively. The linear relationship was reported by Brusewitze (1975) on soybean, however, he reported the density for corn to reach a minimum value of 30% moisture content (w. b.) after which the density increased. On the contrary, the apparent density of rough rice increased linearly with increase in moisture content with a correlation coefficient of 0.887. That of wheat was found to decrease linearly up to 26 % moisture and then increase slightly up to 36.8 % moisture content. The correlation coefficient in the lower moisture region was 0.997 while in the high moisture region was 0.715. The decrease followed by increase in the density of wheat has been confirmed by Brusewitze (1975), while the linear increase with increase in moisture content in rough rice has been confirmed by Morita and Singh (1975).

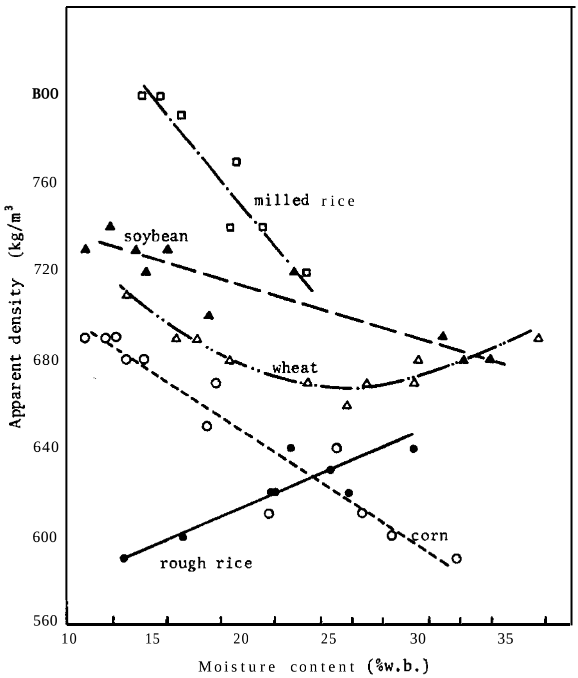

Fig. 8. Effect of moisture content on apparent density of cereal grains and soybean.

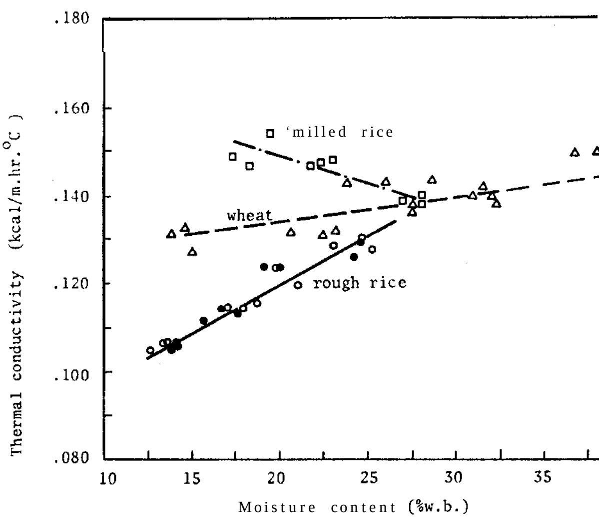

Fig. 9. Change of thermal conductivity of grains with moisture content.

Thermal conductivity

The results are shown in Fig. 9. The thermal conductivity for wheat and rough rice of both Koshihikari and Tsuyuhakaze varieties were found to increase linearly with increase in moisture content with regression coefficients between 0.902 and 0.993. However rough rice was observed to be affected by the moisture content more than wheat. The linear interdependence of the materials with moisture content has been confirmed by some researchers (Kazarian and Hall, 1965 ; Chandra and Muir, 1971; Morita and Singh, 1979). Milled rice was observed to contrast the other grains in that the thermal conductivity decreased with an increase in moisture content. These contrasting results were thought to be due to the variation of apparent density with moisture content in the tested materials. For rough rice, the increase in apparent density lead to the increase in thermal conductivity while the decrease in apparent density in milled rice decreased the thermal conductivity. In wheat the increase in thermal conductivity was in contrast to the decrease in apparent density. However, on plotting the thermal conductivity against the apparent density of the three materials at the same moisture content, all the materials could be represented by one line as shown in Fig. 10. There-

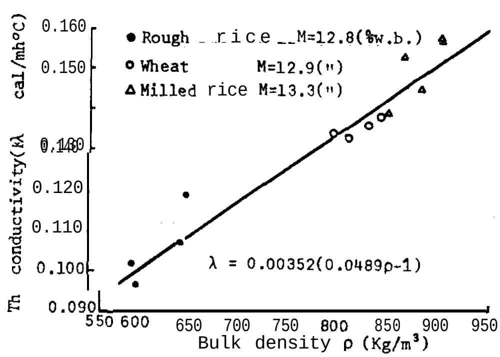

Fig. 10. Correlation of bulk density and thermal conductivity of grains.

fore the deviation in wheat needs- further investigation. The thermal conductivity of corn and soybean was investigated at only one moisture content at 11.1 and 10.1%. At these moisture contents the conductivity was 0.1414 in soybean and 0.1443 in corn. The apparent density of the samples during this test was 760.2 and 769.2 kg/m^3 in the soybean and corn respectively. The conductivities as in the other materials are in kcal/m.hr °C. As in the thermal conductivity, the thermal diffusivity and specific heat of corn and soybean was investigated at these two moisture contents only.

Thermal diffusivity

Thermal diffusivity of wheat, milled rice and rough rice was found to decrease with increase in moisture content curvilinearly as shown in Fig. 11.

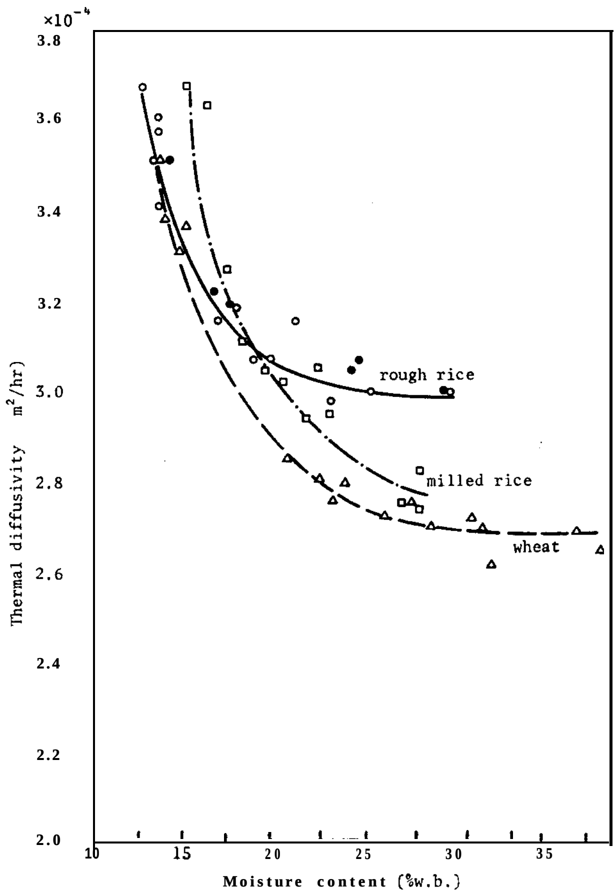

Fig. 11. Variation of thermal diffusivity with change in moisture content for wheat, milled rice and rough rice.

This is in contrast to that reported by Kazarian and Hall (1965) on wheat and Morita and Singh (1979) on rough rice. The researchers reported a linear relationship. The failure in observing this curvilinear relationship might have been due to the small range of the moisture contents at which they carried their tests. The thermal diffusivity for corn and soybean was 3.277 x 10^{-4} and 3.331 x 10^{-4} m/hr respectively.

Specific heat

The experimental results are shown in Fig. 12. From the results it was found out that as the moisture content increased the specific heat for milled rice and rough rice of both varieties increased linearly with correlation coefficients between 0.86 and 0.945. Although the specific heat of wheat could be approximated by a linear relationship with moisture content, the authors think

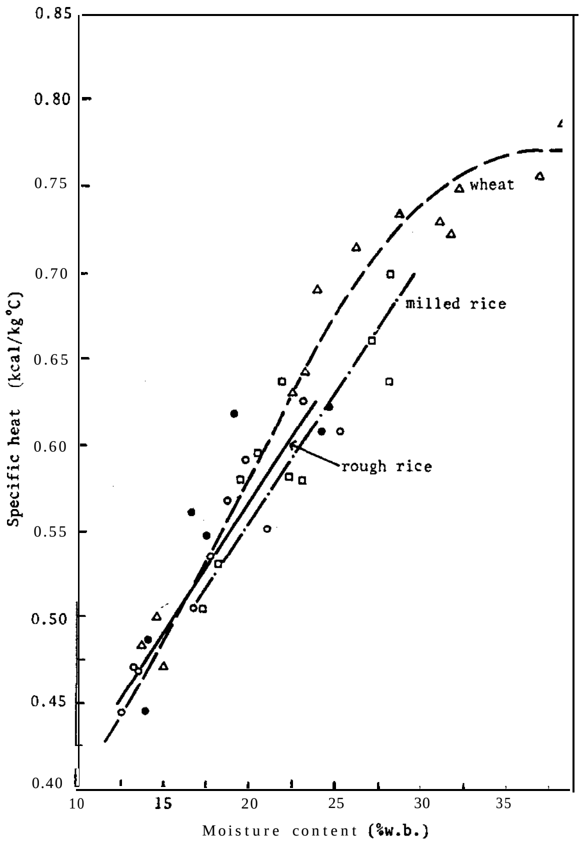

Fig. 12. Relationship between specific heat of wheat, rough rice and milled rice and moisture content of the grains.

Table 1. Regression equations for thermal diffusivity. κ and specific heat with moisture content, M.

Material	Thermal diffusivity	Specific heat
Rough rice (Koshihikari)	$\kappa=5.52-0.201M+3.96\times10^{-3}M^2$ s. d. =O. 0664 $r^2=0.86$	$c=0.018+0.0369M$ s. d. =0. 024 $r^2=0.945$
Rough rice (Tsuyuhakaze)	$\kappa=6.4-0.279M+5.64\times10^{-3}M^2$ s. d. =0. 108	$c=0.302+0.0137M$ s. d. =O. 016 $r^2=0.860$
Wheat	$\kappa=4.99-0.142M+2.27\times10^{-3}M^2$ s. d. =0. 054	$c=0.328+0.0133M$ s. d. =0. 034 $r^2=0.891$
Milled rice	$\kappa=7.21-0.329M+6.12\times10^{-3}M^2$ s. d. =0. 124	$c=0.180+0.018M$ s. d. = 0.027 $r^2=0.903$
Over all		$c=0.0915+0.0311M-3.38\times10^{-4}M^2$ s. d. =0. 0396

Table 2. Linear regression coefficients of the properties of the grains.

Comparison	Rough rice		Wheat	Milled rice
	Koshihikari	Tsuyuhakaze		
1 & 2	0.967	0.981	0.883	0.866
1 & 3	0.967	0.953	0.867	0.013
1 & 4	0.901	0.796	0.880	0.896
1 & 5	0.945	0.860	0.891	0.902
2 & 3	0.945	0.929	0.71Y	0.301
2 & 4	0.886	0.759	0.989	0.678
2 & 5	0.915	0.821	0.927	0.765
3 & 4	0.911	0.850	0.717	0.400
3 & 5	0.972	0.943	0.776	0.353
4 & 5	0.935	0.968	0.921	0.979

1-moisture content, 2=apparent density, 3=thermal conductivity, 4=thermal diffusivity, 5=specific heat.

that it would be more exact to consider the linearity only below 26% moisture content and that above to increase more gradually than the former. Kazarian and Hall (1965), however, reported a linear relationship.

Closer observation of the results indicate that the specific heat of all the three grain materials can be approximated by one second degree polynomial function. The interdependence of the thermal diffusivity and specific heat on moisture content of the grain materials were approximated by second degree polynomial equations as shown in Table 1. The interrelationship between all the properties investigated are shown in Table 2. From the correlation coefficient values, for wheat and rough rice interrelationship between the observed properties including moisture content could be estimated through a linear relationship although the accuracy would be lower in the low correlation coefficients such as between thermal conductivity and thermal diffusivity in wheat. Milled rice showed no linear relationship between thermal conductivity and thermal diffusivity; moisture content and thermal conductivity; apparent density and thermal conductivity ; apparent density and thermal diffusivity and between thermal conductivity and specific heat. The specific heat for corn and soybean was 0.567 and 0.558 kcal/kg°C respectively.

CONCLUSION

Specific gravity, apparent density and thermal properties of wheat, rough rice and milled rice were strongly affected by moisture content. The most affected, however, was milled rice except for thermal conductivity where rough rice of the variety Koshihikari was the most affected. Of them all wheat was the least affected. The interrelationship between the properties of the tested materials could be used with a high accuracy in the estimation of specific heat of the grains tested. The specific heat of the tested materials could be approximated by one second degree polynomial function.

ACKNOWLEDGEMENTS

The authors are in dept to Tofuku and Torigoe Milling Companies for supplying the experimental materials which contributed to the success of the research work. Gratitude is extended by the authors to the Ministry of Agriculture, Forestry and Fisheries for providing the funds for the study without which the study could not have been made. The research was also supported by the Ministry of Education through Grant-in-Aid for Co-operative Research A (No, 548053).

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