Thermal Properties of Sugarbeet Roots

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ABSTRACT

Sugarbeet (*Beta vulgaris* L.) roots are subjected to heating and cooling during storage and processing and their response to heat transfer is dependent on thermal properties of the roots. Specific heat and thermal conductivity values are used in the design and modeling of ventilated storage of sugarbeet roots. Specific heat of sugarbeet roots was measured using the method of indirect mixtures. A probe was constructed using a small diameter brass tube, type T thermocouple wire, and a constantan wire acting as heater to measure thermal conductivity of sugarbeet roots. The measured specific heat of sugarbeet roots (3.5464 kJ/kgK) was similar to the predicted specific heat values from Siebel's correlation and Reidel's calculation. The measured specific heat of sugarbeet roots was similar to values for apple pomes and potato tubers. The thermal conductivity for frozen sugarbeet roots was twice that of unfrozen roots. Observed thermal conductivity values for sugarbeet roots were similar to values reported for apple pomes and potato tubers.

Additional key words: *Beta vulgaris* L., specific heat, thermal conductivity, thermal conductivity probe.

Sugarbeet roots undergo repeated heating and cooling during storage and processing. The response of roots during heating and cooling cycles is dependent on their thermal properties. Cooling load calculations for crops such as sugarbeet require information on specific heat. The rate of heating or cooling of sugarbeet roots during storage depends on thermal diffusivity. Thermal diffusivity (á) quantifies a material's ability to conduct heat relative to its ability to store heat. It is the ratio of thermal conductivity (k) to the product of density (ñ) and specific heat (c_p). The information presented here will be useful in the design and modeling of ventilated storage of sugarbeet roots as well in the quantitative analysis of important thermal processes during sugarbeet processing. The study was conducted to determine the specific heat and thermal conductivity of sugarbeet roots. The effect of temperature on thermal conductivity of sugarbeet roots was also determined.

The method of mixtures is the most widely used for measuring specific heat of food and agricultural materials due to its simplicity and accuracy. Hwang and Hayakawa (1979) developed the method of indirect mixtures, which eliminates direct contact between the sample and the calorimetric fluid, thus eliminating the heat of solution of dissolvable chemical entities of food. Using the method of indirect mixtures, Peralta Rodriguez et al. (1995) determined the specific heat of cornish pastry which consisted of a filling in a pastry crust. They used a wide-mouth thermos bottle consisting of a metallic jacket, O-rings, Dewar flask, and a plastic lid with a metallic jacket. The sample was placed in a nylon-polypropylene retortable pouch so that it did not mix with the calorimetric fluid (water). The measured specific heat of the calorimeter included the effect of the retortable pouch. Rice et. al. (1988) measured the specific heat of potato tubers (*Solanum tuberosum* L.) (variety 'Record') using the method of mixtures with distilled water as the calorimetric fluid. Specific heat was measured at temperatures from 40 to 90C and at moisture contents of 70 to 80% wet basis (wb).

Two categories of thermal conductivity measurement are used: a) steady-state; and b) transient state methods. The steady-state method is appropriate for measuring the thermal conductivity of materials that are homogeneous and are poor heat conductors. The transient-state method is more appropriate for biological materials because they are non-homogeneous, high moisture content, and moisture migration during heating is possible. The thermal conductivity probe uses a modification of the line heat source method of thermal conductivity measurement and was the method used in this study. A constant heat source is embedded in the material whose thermal conductivity is to be measured. The constant heat source is energized and the temperature rise at a given distance from the source is measured after a short heating time (Mohsenin 1980).

Ramaswamy and Tung (1981) measured the thermal conductivity of apple (*Malus pumila* Mill.) pomes (variety 'Golden Delicious' and 'Granny Smith') using a 3.80 cm long and 0.08 cm diameter thermal conductivity probe. Apple pomes were peeled and sliced into eight longitudinal pieces. The probe was inserted into a slice in the longitudinal direction. The sample slice was placed inside a long closely fitting retort pouch and clamped securely at both the ends. The slices contained in the retort pouch were then cooled to different temperatures (-25 to 25C) in a constant temperature bath.

Wang and Brennan (1992) reported the thermal conductivity measurement of potato tubers (cv. 'Desiree') using a thermal conductivity probe. The potato tubers had an initial moisture content of 82.1% wb and were dried to several moisture contents. The probe was made from a 38 mm long, 21 gauge hypodermic needle with an outside diameter of 0.80 mm. The line heat source was a 0.076 mm diameter constantan wire. Temperature was measured using a 0.076 mm diameter type T thermocouple. The heater and thermocouple wires were inserted in the needle and sealed with epoxy glue. The potato sample was placed in a bottle and the probe was inserted into its center until the probe's length was covered by the sample. The sample bottle was equilibrated to the desired temperature (40, 50, 60 and 70C) in a water bath. When the probe reached constant temperature, the DC power supply was turned on to energize the heater. A typical run lasted about 30 seconds.

MATERIALS AND METHODS

Sample selection

Fifty sugarbeet roots were randomly chosen from clean roots sampled from the storage piles in Taber, AB in the fall of 1998. The sampled roots were washed with water containing about 2% bleach and air dried to remove residual moisture. The roots were stored at 4C for later use (approximately one month). Fifteen roots for thermal conductivity determination were randomly selected from the stored roots. Ten of the 15 roots chosen were also used for specific heat measurements.

Assembly of calorimeter

A calorimeter was assembled to measure specific heat of sugarbeet roots using the method of indirect mixtures (Figure 1) similar to the calorimeter reported by Peralta Rodriguez et al. (1995) for measuring the specific heat of cornish pastry. The calorimeter was made of a 3 L Dewar flask with dimensions of 185.4 mm inside diameter, 200.7 mm outside diameter and 190.5 mm high. The lid consisted of a machined 9.0 mm thick acrylic plate. An O-ring was fitted to the lid to make the calorimeter watertight. A thin layer of vacuum grease was applied to the O-ring to ensure the seal. Two holes were drilled in the

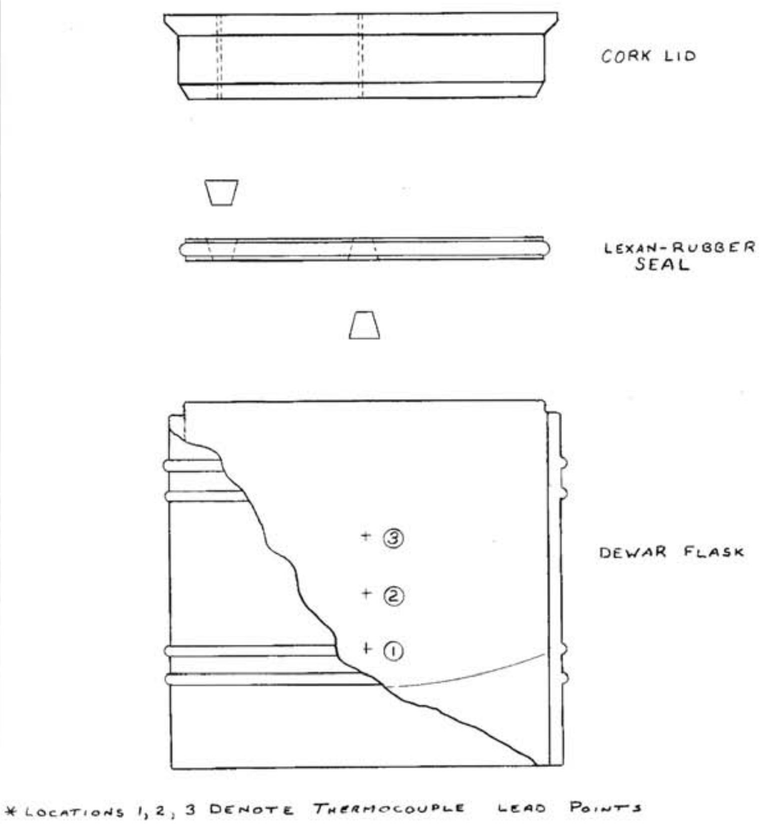

Figure 1. Schematic diagram of the calorimeter used for measuring specific heat of sugarbeet roots.

acrylic plate and plugged with rubber stoppers. Three type T thermocouple wires were inserted through each rubber stopper. One group of thermocouple wires measured the flask temperature, while the other group measured the temperature of the sample. A tapered cork lid, 36.7 mm thick machined to fit the opening of the Dewar flask, was placed on top of the acrylic plate. The cork lid minimized heat transfer across the mouth of the Dewar flask.

The sample holder was a 219 mm x 412 mm 76.2 ìm-thick nylon-polyethylene bag used for vacuum packaging. Three holes were punctured in the bag to allow type T thermocouples to be inserted. Each thermocouple was inserted through an Ecklund C-5.1 thermocouple receptacle (TechniCAL Inc., New Orleans, LA) designed for use with plastic pouches. The sample holder was placed in the calorimeter during measurements. Since the roots were heavier than water, no additional weights were placed in the sample holder. Thermocouples were connected to the datalogger using type T mini-connectors (Omega Engineering, Inc., Stamford, CT) to ensure easy attachment and removal.

Hermecity of the calorimeter was checked during each test by weighing the calorimeter (including the lid and plastic pouch) before and after each test. A trial was discarded when more than 1 g of water was gained or lost.

Heat capacity of the calorimeter

Two calorimeters, designated as "A" and "B", were used to determine heat capacity. Two liters of deionized water were heated to about 50C. The heated water was poured into calorimeter B and placed in an oven maintained at 37±1.5C for at least 30 min. The calorimeter was covered to prevent evaporation. Temperature of water was monitored and the temperature decrease was noted. When the temperature steadily decreased, calorimeter B was taken out from the oven and placed in the laboratory. After the warm water in calorimeter B reached a constant rate of heat exchange as assessed by the temperature readings of the thermocouples at appropriate time intervals (constant slope, C/min), calorimeter B was opened and water was poured into calorimeter A. Calorimeter A was then closed.

Just before water was transferred to calorimeter A, the datalogger (Campbell Scientific CR 21X (Campbell Scientific Inc., Logan, UT)) started recording the temperatures. Temperature measurement of the empty pouch and of calorimeter A were continued after the water was poured into calorimeter A. Calorimeter A was then placed in an insulated cardboard box. The box was manually shaken every 15 min to ensure uniformity of temperature throughout the calorimeter. An experimental run lasted at least 3 hours. At the end of a run, calorimeter A was opened and the pouch was emptied of water. Any water on surfaces of the pouch and the calorimeter was carefully removed by wiping with a pre-weighed dry paper towel. The remaining water was poured into a beaker and weighed. The rest of calorimeter A was wiped with the pre-weighed paper towel. The amount of water used in a run was calculated using the following:

$$M_W = M_B + M_P \tag{1}$$

where:

M_W = total mass of water, kg
M_B = mass of water collected in the beaker, kg
M_P = mass of water absorbed by the pre-weighed paper towel, kg

From the time-temperature curve of calorimeter A, and the initial temperatures of calorimeter A and water, the heat capacity of the calorimeter A was calculated from:

$$H_c = \frac{c_{pw} M_w \left(T_e - T_{0w} - \frac{dT}{dt} t_e \right)}{T_{0c} - T_e + \frac{dT}{dt} t_e} \qquad (2)$$

where H_c = heat capacity, kJ/K
c_p = specific heat, kJ/K
M = mass, kg
T_e = temperature of water when it reached equilibrium with the calorimeter, K
T_0 = initial temperature, K
T_f = final temperature, K
dT/dt = rate of temperature change (from graph of time and temperature), K/min
t_e = time when water reached equilibrium with the calorimeter, min
subscripts w, c and s stand for water, calorimeter and sample, respectively.

The heat capacity test of the calorimeter was repeated five times using a different pouch each time.

Specific heat of sugarbeet roots

Determination of the specific heat of roots was done in the same manner as the determination of heat capacity of the calorimeter except that roots were placed in the sample holder. Roots which were previously stored at 4C, were sliced into 60-mm cubes to fit in the sample holder. Three openings large enough to accommodate a type T thermocouple wire were made in the sample holder. A thermocouple receptacle was then placed into each hole, with a small amount of vacuum grease applied to the rubber gaskets. The thermocouple wire was inserted through the thermocouple receptacle. The three thermocouple wires were embedded in different places on the sample. The sample holder containing the root sample was vacuum-sealed.

Thermocouple wires were attached to the calorimeter and the datalogger. Temperatures were recorded just before water from calorimeter B was poured to calorimeter A. After water had been poured, the calorimeter lids were put in place and the calorimeter was placed in an insulated box. The box was shaken every ten minutes. A run typically lasted for 3 hours. Ten roots were selected for specific heat measurement. Runs with more than 1 g of water lost or gained were discarded. Run number five was discarded; therefore eleven runs were performed (ten good runs out of eleven).

The specific heat of roots was calculated from heat balance equation:

$$c_{ps} M_s T_{0s} + H_c T_{0c} + c_{pw} M_w T_{0w} = c_{ps} M_s T_{fs} + c_{pw} M_w T_{fw} + H_c T_{fc} - R \quad (3)$$

where R = total heat gain or loss given as:

$$R = \left(c_{pw} M_w + c_{pc} M_c + c_{ps} M_s\right)\frac{dT}{dt} t_1 \quad (4)$$

$$R = \Delta Q = \frac{dQ}{dt} t_1 = \frac{dT}{dt}\sum_{i=1}^{3} c_{pi} M_i t_1 \quad (5)$$

where t = time, min

Therefore,

$$c_{ps} = \frac{H_c\left(T_{fc} - T_{0c} - \frac{dT}{dt} t_1\right) + c_{pw} M_w\left(T_{fw} - T_{0w} + \frac{dT}{dt} t_1\right)}{M_s\left(T_{0s} - T_{fs} + \frac{dT}{dt} t_1\right)} \quad (6)$$

assuming that:

$$T_{fw} = T_{fc} = T_f \quad (7)$$

$$T_{fw} = T_{fc} \quad (8)$$

$$T_R = \frac{dT}{dt} t_1 \quad (9)$$

Therefore:

$$c_{ps} = \frac{H_c\left(T_{fc} - T_{0c} - T_R\right) + c_{pw} M_w\left(T_{fw} - T_{0w} + T_R\right)}{M_s\left(T_{0s} - T_{fs} + T_R\right)} \quad (10)$$

T_{0w}, T_{fw} and T_{2w} are the temperatures measured at t_0, t_1 and t_2, thus T_R is found from:

$$T_R = \frac{T_{2w} - T_{fw}}{t_2 - t_1} t_1 \quad (11)$$

According to Peralta Rodriguez et al (1995), the choice of t_1 and t_2 is critical in estimating T_R. Different values of t_1 and t_2 were selected from the temperature history curve. This was done by taking values of t_1 when the temperature of the water in the calorimeter and of the sample were within ±0.1C of each other for the first time and then increasing in steps of five or ten minutes. This procedure allowed variations of T_R and that of c_{ps} to be taken into account due to the choice of t_1 and t_2 within a run.

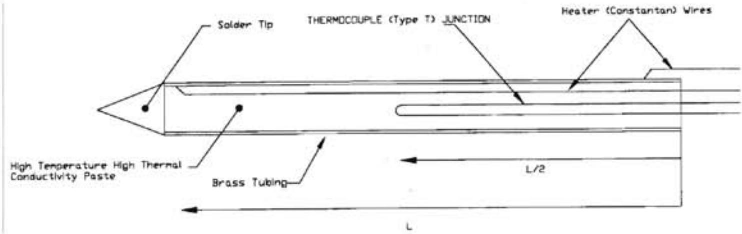

Figure 2. Diagram of thermal conductivity probe.

Thermal conductivity probe construction

A thermal conductivity probe similar to what was described by Wang and Brennan (1992) was assembled. The probe (Figure 2) was constructed by cutting a piece of 1.91 mm diameter brass tubing to a length of 76.20 mm. The tubing was then filled with a high-temperature high-thermal conductivity paste (Omegatherm 201 (Omega Engineering, Inc., Stamford, CT)), using a hypodermic syringe. A thermocouple made from type T thermocouple wire was attached using a 1.59 mm heat shrink, to the midpoint of a 127.0 mm long piece of constantan wire that had been stripped at both ends. The constantan wire and the attached thermocouple wire were fed through the brass tubing until the constantan wire emerged from the paste at the opposite end. The end of the tubing from which the wire had emerged was then crimped and soldered closed. One lead of the 16 gauge signal wire was then attached to the uncrimped end of the constantan wire and the other lead was soldered to the end of the brass tube. A piece of 4.76 mm diameter heat shrink was applied to the uncrimped end of the brass tube to cover all exposed wires and hold the assembly in place. A total of six probes were constructed for the experiment.

The line heat source was assumed to have constant strength in an infinite homogeneous body at a uniform initial temperature. Under these conditions, the temperature at any point in the body is a function of time and thermal conductivity. The Fourier equation is applicable in this case when only the radial temperature gradient exists. The solution for this equation at the source of a heat input of q' per unit length of the heater is:

$$k = \frac{q'}{4\pi(T_2 - T_1)} \ln \frac{t_2}{t_1} \qquad (12)$$

where $q' = I^2R$ = heat input per meter of the line source, W/m
I = current, A
R = resistance of the probe per meter length, ohms/m
k = thermal conductivity of the medium infinite in size surrounding the heat source, W/m K
T = temperature, K
t = time, s
subscripts 1 and 2 refer to any two points on a straight line resulting from the plot of temperature and time

Thermal conductivity measurement of sugarbeet roots

Sugarbeet roots for thermal conductivity measurement were randomly chosen from the cleaned roots stored at 4C. The temperatures at which thermal conductivity experiments were conducted were: a) 4±0.5C which involved the use of a cooler; b) 10±0.5C using an environmental chamber; c) 23±0.5C using the laboratory room; d) -1±0.25C using a conditioning chamber; and e) -14±0.5C using a freezer. Three roots were stored at each temperature.

A hole was bored into the sample using a thin hollow tubing deep enough for the probe to be inserted. The root was placed in a nylon-polyethylene bag and the probe was inserted through the bag. The hole was dabbed with silicone to ensure sealing. The bag with the sample was vacuum packaged to prevent water loss and minimize respiration. The packaged roots were stored overnight (from 10 to 16 h) at temperatures indicated previously to allow them to equilibrate with chamber temperatures.

For thermal conductivity measurement, the lead wires of the heater were connected to the BK Precision Model No. 1688 regulated DC voltage supply (B&K Precision Corp., Placentia, CA) set at 3V. The regulated DC voltage supply was adjustable between 3 and 14 V with current ranging between 0 and 25 A. At 3V DC, the maximum DC current was 4.5 A. Temperature data was recorded at 0.3 s intervals using the Campbell Scientific CR21X datalogger (Campbell Scientific, Inc., Logan, UT). A typical test lasted for 200 s. After each test, probe resistance was measured. The temperature of the chamber was also recorded at 30 s intervals during the test duration. After each test, the moisture content and true density of the roots were determined.

Moisture content of the sugarbeet roots used for thermal properties measurement was determined by the oven method. A portion of each root was ground in a blender and 15 g was weighed as sample.

For each root, three replicated measurements were made. The samples were dried in an oven at 75C for 48 hours and the moisture was reported as percent wet basis.

True density of the sliced samples was determined using the Micromeritics multivolume pycnometer model 1305 (Micromeritics Instrument Corp., Norcross, GA, USA) which uses helium gas.

The maximum slope method of calculating the thermal conductivity (k) values was used (Wang and Hayakawa, 1993). It involves finding the maximum local slope (temperature rise over ln (time)). Local slope was determined by linear regression of 80 pairs of values of the logarithmic value of time (ln (time)) and probe temperature (dependent variable). The k value was calculated using Equation 12 with the maximum local slope. The corresponding average temperature of the maximum line segment was determined.

RESULTS AND DISCUSSIONS

Sugarbeet roots selected for thermal properties measurement weighed less than 1200 g. To prevent spoilage of roots and to hasten the test runs, six thermal conductivity probes were constructed.

Heat capacity of calorimeter

Five heat capacity test runs were conducted. Of the three thermocouples used for measuring the temperature of the calorimetric fluid (deionized water), only two temperature values were used because the readings from the thermocouple located near the top of the water level were unstable. Heat capacity of the calorimeter was calculated using Equation 2. Figure 3 shows a typical time-temperature relationship in

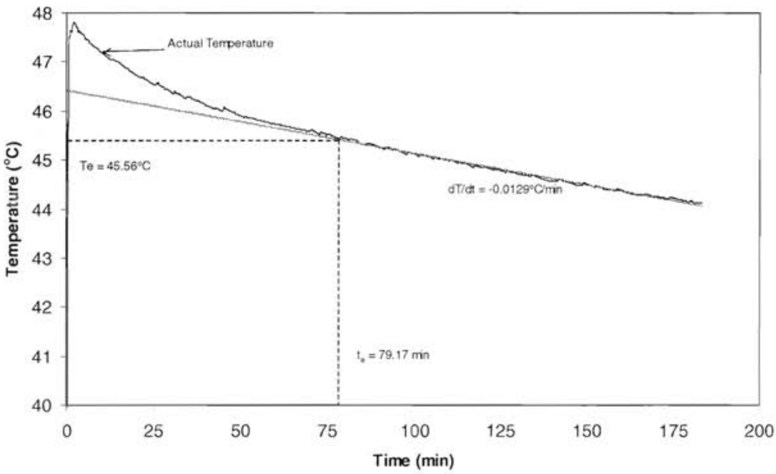

Figure 3. Typical time-temperature relationship of water for heat capacity determination of the calorimeter.

the determination of heat capacity of the calorimeter. The mean heat capacity of the calorimeter from five trials was 0.4468 kJ/K with a standard deviation (SD) of 0.0160 kJ/K. The coefficient of variation (CV) was 3.57% (Table 1). The CV reported by Peralta Rodriguez et al. (1995) for this measurement (from six runs) which forms the basis of this methodology, was 4.23%.

Specific heat of sugarbeet roots

Eleven roots were used for specific heat measurements, but the data from one root was discarded due to excessive mass gained by the calorimeter at the end of the experiment. Figure 4 shows a typical

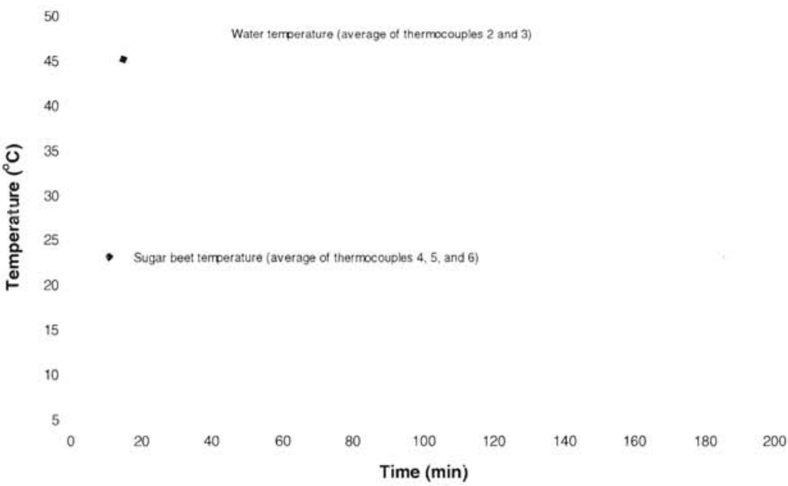

Figure 4. Typical temperature history curve for the determination of specific heat of sugarbeet root.

temperature history curve during the determination of specific heat of sugarbeet roots. The specific heat of the roots was calculated using Equation 10. As mentioned previously, the choice of t_1 and t_2 is critical in estimating T_R. The selection of t_1 and t_2 was done in steps of 5 min.

The specific heat values of the ten sugarbeet roots used in the experiment are shown in Table 2. The original masses of the roots are also listed showing the varying sizes of roots used in the experiment. Moisture content and true density of the roots are also listed, but indicate no statistically significant effect on the specific heat of roots. The mean specific heat of roots is 3.5464 kJ/kgK (n = 10) with a SD of 0.1558 kJ/

Table 1. Heat capacity (H_c) measurement of the calorimeter.

	Trial							
	1	**2**	**3**	**4**	**5**	**Mean**	**SD**	**CV**
M_w (kg)	2.0861	1.999	2.0567	1.9977	2.0776			
T_e (°C)	45.31	45.75	45.17	45.46	45.86			
T_{0c} (°C)	22.78	23.54	22.76	22.13	23.63			
T_{0w} (°C)	47.26	48.01	47.44	47.81	47.82			
dT/dt (°C/min)	-0.0127	-0.0115	-0.0118	-0.0129	-0.0121			
t_e (min)	63.17	84.67	86.5	79.17	67.67			
H_c (kJ/K)	0.4278	0.4627	0.4554	0.4565	0.4314	0.4468	0.016	3.57%

M_w = mass of water
T_e = temperature of water when it reaches equilibrium with the calorimeter
T_{0c} = initial temperature of the calorimeter
T_{0w} = initial temperature of water
dT/dt = rate of temperature change (from graph of time and temperature)
t_e = time when water reaches equilibrium with the calorimeter

Table 2. Specific heat of sugarbeet roots.

Trial	Original mass	Moisture content	True density	Specific heat
	g	% w.b.	kg/m^3	kJ/kgK
1	1315.44	72.89	1198.33	3.5791
2	634.40	78.73	1152.58	3.6293
3	810.43	72.15	1145.15	3.5964
4	1083.66	72.29	1184.68	3.2764
5	943.51	73.22	1170.55	3.4816
6	705.20	74.22	1163.13	3.6635
7	930.26	76.23	1159.55	3.6786
8	1437.46	73.24	1155.88	3.7151
9	1148.77	73.00	1199.17	3.5637
10	922.69	75.48	1169.94	3.2802
Mean	993.18	74.15	1169.90	3.5464
SD	256.06	2.09	18.70	0.1558
CV	25.78%	2.81%	1.60%	4.39%

kgK and a CV of 4.39%. Peralta Rodriguez et al. (1995) obtained a CV of 7.98% for cornish pastry, using the same method.

Predictive equations like the Siebel's correlation for specific heat of foods above the initial freezing point can be used to check the experimental values. A form of this equation was given by Comini et al. (1974) as:

$$c_{ps} = 2.931X_w + 1.256 \qquad (13)$$

where:

c_{ps} = specific heat, kJ/kgK
X_w = mass fraction of water in food, decimal.

The average moisture content of the roots expressed as mass fraction was 0.7415 (Table 2). Thus, the predicted specific heat from Equation 13 was 3.4293 kJ/kgK. The predicted value was close to the experimental value of 3.5464 kJ/kgK. The predicted specific heat calculated underestimated the experimental specific heat by 3.30%.

Ivory (1981) estimated the enthalpy of sugarbeet roots as a function of temperature and compared it to the values reported by Reidel (1951). The specific heat of sugarbeet roots calculated from experimental values of enthalpy as a function of temperature above freezing was much higher than that of water which is 4.2 kJ/kgK (Ivory, 1981). However, the average estimated specific heat above freezing based on the method of Reidel (1951) was 3.6333 kJ/kgK. This value overestimated the experimental value by 2.45%. Thus, the experimental specific heat values were similar to the predictive methods.

Specific heat values of fruits and vegetables similar in water content to sugarbeet roots have been reported. For example, 'Golden Delicious' apple had a specific heat of 3.69 kJ/kgK over a temperature range of 20 to 50C and moisture content of 87.3%, whereas 'Granny Smith' had a specific heat of 3.58 kJ/kgK over the same temperature range and a moisture content of 85.8% (Ramaswamy and Tung. 1981). Rice et al. (1988) reported that the specific heat of 'Record' potato tuber ranged between 2.735 to 4.015 kJ/kgK at temperatures of 40 to 90C and moisture content of 76.3%. The values reported for apple pomes and potato tubers are similar to the experimental value found in this study.

Thermal conductivity of sugarbeet roots

Data for the thermal conductivity of sugarbeet roots was collected at 0.3 s intervals over a 200 s period. A test run duration of 200 s was suggested by Wang and Hayakawa (1993), who developed the maximum slope method of determining thermal conductivity of food materials. Heating was usually rapid during the first 50 s of the test as shown on Figure 5. The rate of temperature rise became fairly constant

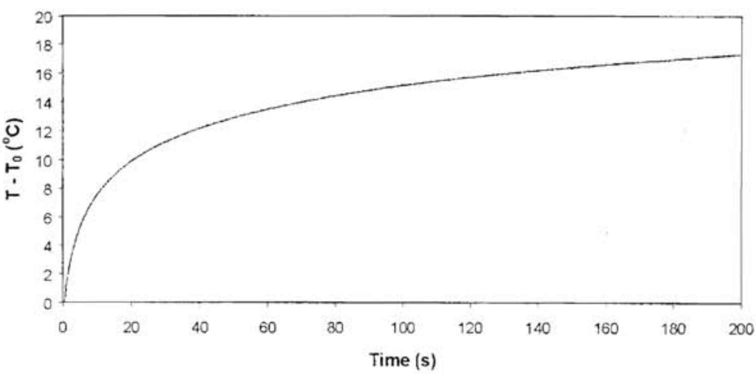

Figure 5. Typical temperature history of sugarbeet root during measurement of thermal conductivity.

and decreased slightly after the first 50 s. During the test, the temperature rose between 4 and 6C for the roots stored at -14C. The temperature rise ($T - T_0$) for roots stored at temperatures above freezing (-1 to 23C) ranged between 9 and 26C.

Using the maximum slope method to determine the thermal conductivity of sugarbeet roots, local slope values were determined by regressing 80 sets of values around a point. Figure 6 shows a test run

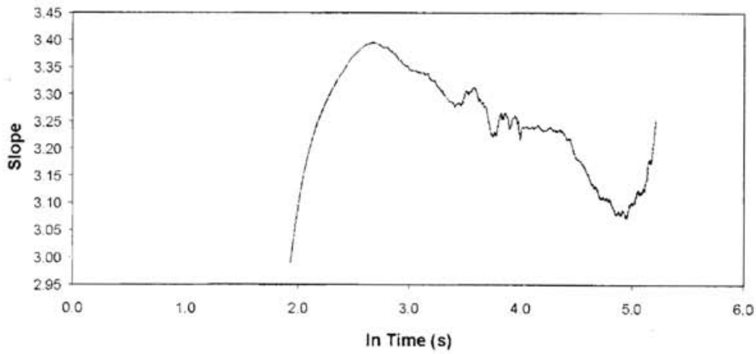

Figure 6. Local slope value for the determination of thermal conductivity of sugarbeet root at an initial temperature of 3.9C.

with the root at an initial temperature of 3.92C. As with the other runs, maximum slope was usually observed 10 to 20 s into the run.

Table 3 shows the thermal conductivity of sugarbeet roots at different temperatures of the conditioning chamber. For the frozen roots (average temperature of -8.41 to -10.79C), the mean thermal conductivity was 1.1572 W/mK. For the unfrozen roots (average temperatures of -1 to 24C), the thermal conductivity ranged from 0.5246 to 0.6052 W/mK. The thermal conductivity of frozen roots was about twice that of unfrozen roots. This trend is similar to water where the thermal conductivity of ice is four times as much as that of liquid.

The CV of the k values ranged from 7.92% to 24.87%. The different probes used in the experiment may have caused this variation. In the temperature range of -1 to 24C, the effect of temperature on thermal conductivity was minor and not statistically significant. The thermal conductivity values of the unfrozen roots represent mean temperature values ranging from 8.11 to 32.57C (Table 3).

Thermal conductivity of some fruits and vegetables has been measured. Ramaswamy and Tung (1981) reported that the k value of 'Golden Delicious' apple in the unfrozen state from 0 to 25C was 0.427

Table 3. Thermal conductivity of sugarbeet roots.

Temperature of chamber	Mean Temperature at k value	Run	Moisture	True Density	k	k_{mean}	SD	CV
°C	°C		% w.b.	kg/m^3	$Wm^{-1}K^{-1}$	$Wm^{-1}K^{-1}$	$Wm^{-1}K^{-1}$	%
-13.83	-10.76	1	*	*	1.1404			
-13.83	-8.41	2	*	*	1.292			
-13.38	-10.32	3	76.61	1266.16	1.1796			
-13.38	-10.26	4	76.61	1266.16	1.1356			
-13.38	-10.79	5	72.44	1284.46	1.0382	1.1572	0.0916	7.92%
-1.35	16.90	1	72.29	1184.68	0.4849			
-1.35	8.13	2	72.15	1145.15	0.5004			
-0.76	8.11	3	72.15	1145.15	0.5843			
-0.76	15.27	4	72.29	1184.68	0.546			
-0.76	8.19	5	72.15	1145.15	0.5743	0.538	0.044	8.19%

* Roots were spoiled after freezing, therefore moisture and density were not measured.

Table 3 (continued). Thermal conductivity of sugarbeet roots.

Temperature of chamber	Mean Temperature At k value	Run	Moisture	True Density	k	k_{mean}	SD	CV
°C	°C		% w.b.	kg/m^3	Wm^{-1}K^{-1}	Wm^{-1}K^{-1}	Wm^{-1}K^{-1}	%
3.92	15.46	1	76.23	1159.55	0.5999			
3.92	13.18	2	72.89	1198.33	0.5573			
3.92	13.71	3	80.43	1148.72	0.6081			
4.10	9.93	4	72.89	1198.33	0.4765			
4.10	19.61	5	76.23	1159.55	0.4951	0.5474	0.0598	10.93%
9.44	17.25	1	80.17	1174.85	0.4129			
9.44	16.24	2	73.55	1170.14	0.4601			
9.44	17.13	3	78.73	1152.58	0.418			
9.44	18.08	4	80.17	1174.85	0.6729			
9.28	17.84	5	73.55	1170.14	0.659	0.5246	0.1304	24.87%
23.43	29.58	1	73.22	1170.55	0.6197			
24.08	32.56	2	73	1199.17	0.6696			
24.68	32.57	3	73	1199.17	0.6563			
23.63	28.7	4	73	1199.17	0.552			
24.51	29.57	5	73	1199.17	0.5284	0.6052	0.0627	10.35%

* Roots were spoiled after freezing, therefore moisture and density were not measured.

W/mK at a moisture content of 87.3%, whereas the k value of frozen apple was 1.45, a three-fold increase in k value. For 'Granny Smith' apple, the k value of unfrozen apple was 0.398 W/mK at a moisture content of 85.8%, compared to 1.22 W/mK for frozen apple, also a three-fold increase in k value.

The k values for potato tuber were similar in magnitude to apple. Califano and Calvelo (1991) reported k values of 'Kennebec' potato tuber ranging from 0.545 to 0.957 W/mK at a temperature range of 50 to 100C and moisture content of 80%. Gratzek and Toledo (1993) reported k values ranging from 0.556 to 0.642 W/mK over a temperature range of 26 to 130C and moisture content of 80%. Buhri and Singh (1993) reported a k value of 0.552 W/mK at 40 to 50C and moisture of 74.9%. Wang and Brennan (1992) reported lower k values (0.03 to 0.47 W/mK) for 'Desiree' potato tuber at temperatures between 50 and 100C and 0 to 82% moisture. The k values of these materials were similar in magnitude to the k values found in this study.

Due to the limited range of temperatures used in the experiment, the relationship between temperature and thermal conductivity was not significant. The mean k value (0.6052 W/m K) was slightly increased at the highest temperature (mean value of 30.6C). Many researchers have reported a direct linear relationship between temperature and thermal conductivity, such as those reported for apple (Ramaswamy and Tung, 1981), sucrose gel (Renaud et al., 1992) and tomato paste (Drusas and Saravacos, 1985).

The experimental values of specific heat and thermal conductivity of sugarbeet roots were measured. These values are used in the design of ventilation system during the storage of sugarbeet roots and in predicting the temperature of the sugarbeet roots during heating and cooling cycles during storage and processing. The following conclusions can be drawn from the study:

1. The measured specific heat of sugarbeet roots (3.5464 kJ/kgK) agreed with the values of predicted specific heat from Siebel's correlation and Reidel's calculation. The measured values were also similar to that of apple pomes and potato tubers.
2. Thermal conductivity, calculated by the maximum slope method for frozen sugarbeet roots, was twice that of unfrozen roots. The k values found for sugarbeet roots were similar to values reported for unfrozen apple pomes and potato tubers.

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