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CALCULATION OF THERMOPHYSICAL PROPERTIES OF HORTICULTURAL PRODUCE FROM THEIR COMPOSITION BETWEEN -40°C AND +20°C

Uitgebracht aan de directeur van het Sprenger Instituut
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CONTENTS blz.

follows from:

$$\varepsilon_{air,\ bulk} = 1 - \frac{\rho_{measured,\ bulk}}{\rho_{pr}} \qquad (3)$$

3.0 SPECIFIC HEAT OF PRODUCT AND BULK

3.1 Temperature above the initial freezing point

The specific heat of product and bulk are almost equal because of the neglect of the mass of enclosed air. The specific heat is:

$$c_{pr\ =\ bulk} = \Sigma(c_i \cdot g_i) \qquad (4)$$

3.2 Temperature below the initial freezing point

Now the water and ice fractions vary with temperature. The relation between ice fraction and temperature is given by the law of Raoult (3)(4):

$$g_i' = 1 - \frac{t_f}{t} \qquad (5)$$

The specific heat is:

$$c_{pr\ =\ bulk} = c_{solids}\,(1 - g_w) + c_w \cdot g_w\,(1 - g_i') + c_i \cdot g_i' \cdot g_w - r_o \cdot g_w \cdot \frac{dg_i'}{dt} \qquad (6)$$

Differentiation of equation 5 to t gives:

$$\frac{dg_i'}{dt} = \frac{t_f}{t^2} \tag{7}$$

while the specific heat of the solid components (not ice) is:

$$c_{solids} = \frac{\Sigma(g_i \cdot c_i)}{\Sigma g_i} \tag{8}$$

4.0 THERMAL CONDUCTIVITY OF PRODUCT

We use the equation of Eugen-Maxwell (5):

$$\lambda_{1+2} = \frac{2 \cdot \lambda_1 + \lambda_2 - 2 \cdot \varepsilon_2 (\lambda_1 - \lambda_2)}{2 \cdot \lambda_1 + \lambda_2 + \varepsilon_2 (\lambda_1 - \lambda_2)} \cdot \lambda_1 \tag{9}$$

The index 1 is related to the continuous phase and 2 to the disperse phase. Table 2 points out which components have index 1 or 2 in the different calculations, if $g_w > 0,5$.

Table 2

equation	temperature	λ_{1+2}	λ_1	λ_2	ε_2
9_a	$t \geq t_f$	flesh	water	protein	protein + fat
9_b	$t \geq t_f$	product	flesh	air	air
9_c	$t \leq t_f - \Delta T$	flesh	ice	water	water + carbohydrates
9_d	$t \leq t_f - \Delta T$	product	flesh	air	air
9_e	all t	bulk	product	air	air

The value of ΔT is approximately 0,5 K. The calculation of λ_{bulk} $(t \leq t_f)$ follows 3 steps: 1st 9_c, 2nd 9_d, 3rd 9_e.

The volume fraction of protein, fat and carbohydrates are:

$$\varepsilon_i = \frac{\rho_{pr}}{\rho_i} g_i \tag{10}$$

The volume fraction of water below the initial freezing point is:

$$\varepsilon_w = \frac{\rho_{pr}}{\rho_w} \cdot g_w \cdot (1 - g_i^!) \tag{11}$$

5.0 THERMAL DIFFUSIVITY

The thermal diffusivity is for all temperatures equal to:

$$a = \frac{\lambda}{\rho \cdot c} \tag{12}$$

6.0 ENTHALPY

At $t = 0^{o}C$ the zero point for the enthalpy of foods is chosen. Above the initial freezing point t_f the enthalpy is:

$$h = t \cdot \Sigma(c_i - g_i) \tag{13}$$

Below the freezing point:

$$h = \int_{t_f}^{t} c_{pr} \cdot dt + t_f \cdot \Sigma(c_i \cdot g_i) \tag{14}$$

Substitution of equation 6 and 7 in equation 14 gives:

$$h = c_{solids}(1-g_w)\ (t-t_f) + c_w \cdot g_w \cdot t_f \cdot \ln\frac{t}{t_f} + c_i \cdot g_w \cdot (t-t_f) - c_i \cdot g_w \cdot \ln\frac{t}{t_f}$$
$$- r_o \cdot g_w \cdot (1 - \frac{t_f}{t}) + t_f \cdot \Sigma(c_i \cdot g_i) \tag{15}$$

7.0 EXAMPLE

The example is given for apple. Figure 1 to 5 give the results of the calculations. Report 1919 (6) discusses the difference between calculation and experimental values above the freezing point, and report 2025 (7) shows that the calculated enthalpy is in good agreement with the measured enthalpy below the freezing point.

8.0 LITERATURE

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6) Beek, G. van en W. Verbeek, *Berekening van thermofysische eigenschappen van tuinbouwprodukten uit hun samenstelling, Sprenger Instituut, rapport no. 1919 (1975)*

7) Verbeek, W., *Calorimetrische bepaling van het vriespunt, de enthalpie en de warmteproduktie van leliebollen cv. Enchantment na opslag bij temperaturen beneden het vriespunt, Sprenger Instituut, rapport no. 2025 (1978).*

9.0 SYMBOLS AND DIMENSIONS

a	m^2/s	thermal diffusivity
c	$J/(kg \cdot K)$	specific heat
g	kg/kg	mass fraction
h	J/kg	enthalpy
r_o	J/kg	latent heat of fusion
t	^oC	temperature
t_f	^oC	initial freezing point
ΔT	K	temperature difference
ε	m^3/m^3	volume fraction
λ	$W/(m \cdot K)$	thermal conductivity
ρ	kg/m^3	density

Composition of the apple

component		fraction	density kg/m^3	specific heat kJ/(kg·K)
protein	(in g)	0.000	1380	1.900
fat	(in g)	0.000	930	1.900
carbohydrate	(in g)	0.100	1550	1.220
Ca	(in mg)	0.000	2400	0.840
Na	(in mg)	0.000	2400	0.840
K	(in mg)	0.001	2400	0.840
rest	(in g)	0.028	1550	1.220
water	(in g)	0.870	1000	4.182

Initial freezing point: -1°C
Density and porosity

	product	bulk
density (in kg/m^3)	800	500
porosity (in %)	23.7	37.5

Thermophysical properties of the apple

temp. 'C	h kJ/kg	c kJ/kg.K	l(p) W/m.K	a(p) m2/s	l(b) W/m.K	a(b) m2/s	g (%)
20.0	76	3.80	0.42	1.38E-07	0.24	1.24E-07	0.5
15.0	57	3.80	0.42	1.36E-07	0.23	1.23E-07	0.5
10.0	38	3.80	0.41	1.34E-07	0.23	1.21E-07	0.5
5.0	19	3.80	0.40	1.32E-07	0.23	1.19E-07	0.5
0.0	0	3.80	0.40	1.31E-07	0.22	1.17E-07	0.5
-1.0	-4	3.80	0.40	1.30E-07	0.22	1.17E-07	0.5
-1.5	-103	132.75	0.40	3.73E-09	0.22	3.35E-09	33.8
-1.6	-115	116.99	0.89	9.50E-09	0.48	8.24E-09	38.0
-1.7	-126	103.92	0.92	1.10E-08	0.50	9.57E-09	41.6
-1.8	-136	92.96	0.95	1.27E-08	0.51	1.10E-08	44.9
-1.9	-144	83.69	0.97	1.44E-08	0.52	1.25E-08	47.8
-2.0	-152	75.77	0.99	1.63E-08	0.54	1.41E-08	50.5
-2.1	-160	68.95	1.01	1.83E-08	0.55	1.58E-08	52.8
-2.2	-166	63.04	1.03	2.04E-08	0.56	1.76E-08	55.0
-2.3	-172	57.88	1.05	2.26E-08	0.57	1.95E-08	57.0
-2.4	-178	53.35	1.06	2.48E-08	0.57	2.15E-08	58.8
-2.5	-183	49.35	1.08	2.72E-08	0.58	2.35E-08	60.5
-2.6	-187	45.81	1.09	2.97E-08	0.59	2.56E-08	62.0
-2.7	-192	42.64	1.10	3.23E-08	0.60	2.79E-08	63.4
-2.8	-196	39.81	1.12	3.50E-08	0.60	3.02E-08	64.7
-2.9	-200	37.27	1.13	3.78E-08	0.61	3.26E-08	66.0
-3.0	-203	34.98	1.14	4.06E-08	0.61	3.50E-08	67.1
-3.1	-207	32.90	1.15	4.36E-08	0.62	3.75E-08	68.2
-3.2	-210	31.02	1.16	4.66E-08	0.62	4.01E-08	69.2
-3.3	-213	29.30	1.17	4.97E-08	0.63	4.28E-08	70.1
-3.4	-216	27.73	1.18	5.29E-08	0.63	4.56E-08	71.0
-3.5	-218	26.30	1.18	5.62E-08	0.64	4.84E-08	71.9
-3.6	-221	24.98	1.19	5.95E-08	0.64	5.13E-08	72.7
-3.7	-223	23.76	1.20	6.30E-08	0.64	5.42E-08	73.4
-3.8	-225	22.64	1.21	6.65E-08	0.65	5.72E-08	74.1
-3.9	-228	21.61	1.21	7.01E-08	0.65	6.03E-08	74.8
-4.0	-230	20.65	1.22	7.37E-08	0.66	6.34E-08	75.5
-5.0	-246	14.00	1.27	1.13E-07	0.68	9.75E-08	80.5
-10.0	-286	5.04	1.40	3.46E-07	0.75	2.97E-07	90.5
-15.0	-305	3.32	1.46	5.50E-07	0.78	4.71E-07	93.8
-20.0	-320	2.69	1.51	7.01E-07	0.81	6.01E-07	95.5
-25.0	-333	2.38	1.55	8.17E-07	0.83	6.99E-07	96.5
-30.0	-345	2.19	1.59	9.09E-07	0.85	7.78E-07	97.1
-35.0	-356	2.06	1.63	9.89E-07	0.87	8.45E-07	97.6
-40.0	-367	1.96	1.66	1.06E-06	0.89	9.05E-07	98.0

Explanation of symbols and indices:

h = enthalpy
c = specific heat
l = thermal conductivity
a = thermal diffusivity
(p) = of product
(b) = of bulk
g = ice fraction

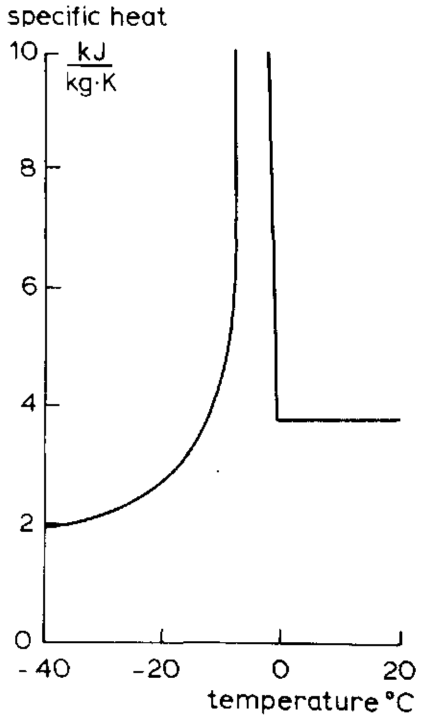


Fig. 1

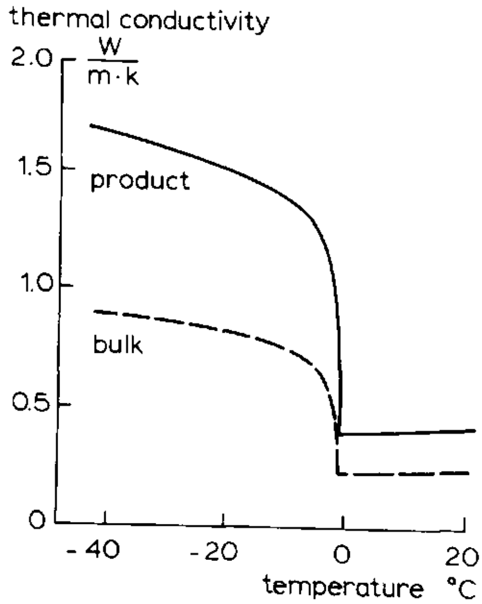
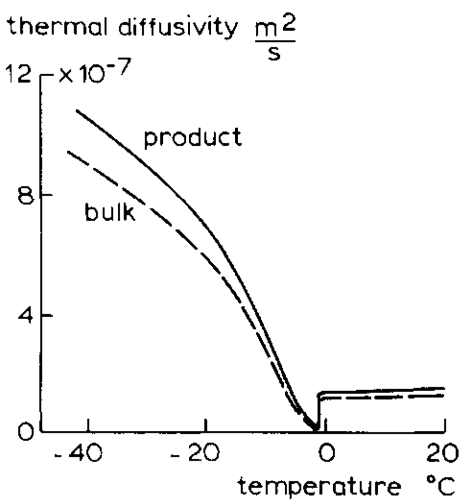


Fig. 2



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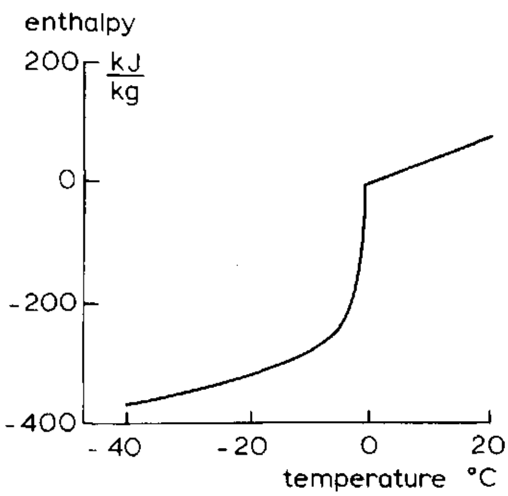

Fig. 4

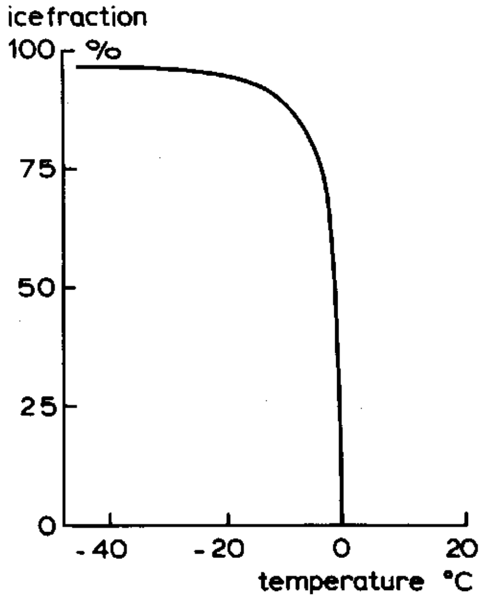

Fig. 5