Related Commercial Resources

CHAPTER 9

THERMAL PROPERTIES OF FOODS

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THERMAL properties of foods and beverages must be known to perform the various heat transfer calculations involved in designing storage and refrigeration equipment and estimating process times for refrigerating, freezing, heating, or drying of foods and beverages. Because the thermal properties of foods and beverages strongly depend on chemical composition and temperature, and because many types of food are available, it is nearly impossible to experimentally determine and tabulate the thermal properties of foods and beverages for all possible conditions and compositions. However, composition data for foods and beverages are readily available from sources such as Holland et al. (1991) and USDA (1975). These data consist of the mass fractions of the major components found in foods. Thermal properties of foods can be predicted by using these composition data in conjunction with temperature-dependent mathematical models of thermal properties of the individual food constituents.

Thermophysical properties often required for heat transfer calculations include density, specific heat, enthalpy, thermal conductivity, and thermal diffusivity. In addition, if the food is a living organism, such as a fresh fruit or vegetable, it generates heat through respiration and loses moisture through transpiration. Both of these processes should be included in heat transfer calculations. This chapter summarizes prediction methods for estimating these thermophysical properties and includes examples on the use of these prediction methods. Tables of measured thermophysical property data for various foods and beverages are also provided.

THERMAL PROPERTIES OF FOOD CONSTITUENTS

Constituents commonly found in foods include water, protein, fat, carbohydrate, fiber, and ash. Choi and Okos (1986) developed mathematical models for predicting the thermal properties of these components as functions of temperature in the range of –40 to 150°C (Table 1); they also developed models for predicting the thermal properties of water and ice (Table 2). Table 3 lists the composition of various foods, including the mass percentage of moisture, protein, fat, carbohydrate, fiber, and ash (USDA 1996).

THERMAL PROPERTIES OF FOODS

In general, thermophysical properties of a food or beverage are well behaved when its temperature is above its initial freezing point. However, below the initial freezing point, the thermophysical properties vary greatly because of the complex processes involved during freezing.

Table 1 Thermal Property Models for Food Components ($-40 \le t \le 150$°C)

Thermal Property	Food Component	Thermal Property Model
Thermal conductivity, W/(m·K)	Protein	$k = 1.7881 \times 10^{-1} + 1.1958 \times 10^{-3}t - 2.7178 \times 10^{-6}t^2$
	Fat	$k = 1.8071 \times 10^{-1} - 2.7604 \times 10^{-4}t - 1.7749 \times 10^{-7}t^2$
	Carbohydrate	$k = 2.0141 \times 10^{-1} + 1.3874 \times 10^{-3}t - 4.3312 \times 10^{-6}t^2$
	Fiber	$k = 1.8331 \times 10^{-1} + 1.2497 \times 10^{-3}t - 3.1683 \times 10^{-6}t^2$
	Ash	$k = 3.2962 \times 10^{-1} + 1.4011 \times 10^{-3}t - 2.9069 \times 10^{-6}t^2$
Thermal diffusivity, m^2/s	Protein	$\alpha = 6.8714 \times 10^{-8} + 4.7578 \times 10^{-10}t - 1.4646 \times 10^{-12}t^2$
	Fat	$\alpha = 9.8777 \times 10^{-8} - 1.2569 \times 10^{-11}t - 3.8286 \times 10^{-14}t^2$
	Carbohydrate	$\alpha = 8.0842 \times 10^{-8} + 5.3052 \times 10^{-10}t - 2.3218 \times 10^{-12}t^2$
	Fiber	$\alpha = 7.3976 \times 10^{-8} + 5.1902 \times 10^{-10}t - 2.2202 \times 10^{-12}t^2$
	Ash	$\alpha = 1.2461 \times 10^{-7} + 3.7321 \times 10^{-10}t - 1.2244 \times 10^{-12}t^2$
Density, kg/m^3	Protein	$\rho = 1.3299 \times 10^{3} - 5.1840 \times 10^{-1}t$
	Fat	$\rho = 9.2559 \times 10^{2} - 4.1757 \times 10^{-1}t$
	Carbohydrate	$\rho = 1.5991 \times 10^{3} - 3.1046 \times 10^{-1}t$
	Fiber	$\rho = 1.3115 \times 10^{3} - 3.6589 \times 10^{-1}t$
	Ash	$\rho = 2.4238 \times 10^{3} - 2.8063 \times 10^{-1}t$
Specific heat, kJ/(kg·K)	Protein	$c_p = 2.0082 + 1.2089 \times 10^{-3}t - 1.3129 \times 10^{-6}t^2$
	Fat	$c_p = 1.9842 + 1.4733 \times 10^{-3}t - 4.8008 \times 10^{-6}t^2$
	Carbohydrate	$c_p = 1.5488 + 1.9625 \times 10^{-3}t - 5.9399 \times 10^{-6}t^2$
	Fiber	$c_p = 1.8459 + 1.8306 \times 10^{-3}t - 4.6509 \times 10^{-6}t^2$
	Ash	$c_p = 1.0926 + 1.8896 \times 10^{-3}t - 3.6817 \times 10^{-6}t^2$

Source: Choi and Okos (1986)

The preparation of this chapter is assigned to TC 10.9, Refrigeration Application for Foods and Beverages.

Table 2 Thermal Property Models for Water and Ice ($-40 \le t \le 150$°C)

	Thermal Property	Thermal Property Model
Water	Thermal conductivity, W/(m·K)	$k_w = 5.7109 \times 10^{-1} + 1.7625 \times 10^{-3} t - 6.7036 \times 10^{-6} t^2$
	Thermal diffusivity, m²/s	$\alpha = 1.3168 \times 10^{-7} + 6.2477 \times 10^{-10} t - 2.4022 \times 10^{-12} t^2$
	Density, kg/m³	$\rho_w = 9.9718 \times 10^2 + 3.1439 \times 10^{-3} t - 3.7574 \times 10^{-3} t^2$
	Specific heat, kJ/(kg·K) (For temperature range of –40 to 0°C)	$c_w = 4.1289 - 5.3062 \times 10^{-3} t + 9.9516 \times 10^{-4} t^2$
	Specific heat, kJ/(kg·K) (For temperature range of 0 to 150°C)	$c_w = 4.1289 - 9.0864 \times 10^{-5} t + 5.4731 \times 10^{-6} t^2$
Ice	Thermal conductivity, W/(m·K)	$k_{ice} = 2.2196 - 6.2489 \times 10^{-3} t + 1.0154 \times 10^{-4} t^2$
	Thermal diffusivity, m²/s	$\alpha = 1.1756 \times 10^{-6} - 6.0833 \times 10^{-9} t + 9.5037 \times 10^{-11} t^2$
	Density, kg/m³	$\rho_{ice} = 9.1689 \times 10^2 - 1.3071 \times 10^{-1} t$
	Specific heat, kJ/(kg·K)	$c_{ice} = 2.0623 + 6.0769 \times 10^{-3} t$

Source: Choi and Okos (1986)

The initial freezing point of a food is somewhat lower than the freezing point of pure water because of dissolved substances in the moisture in the food. At the initial freezing point, some of the water in the food crystallizes, and the remaining solution becomes more concentrated. Thus, the freezing point of the unfrozen portion of the food is further reduced. The temperature continues to decrease as separation of ice crystals increases the concentration of solutes in solution and depresses the freezing point further. Thus, the ice and water fractions in the frozen food depend on temperature. Because the thermophysical properties of ice and water are quite different, thermophysical properties of frozen foods vary dramatically with temperature. In addition, the thermophysical properties of the food above and below the freezing point are drastically different.

WATER CONTENT

Because water is the predominant constituent in most foods, water content significantly influences the thermophysical properties of foods. Average values of moisture content (percent by mass) are given in Table 3. For fruits and vegetables, water content varies with the cultivar as well as with the stage of development or maturity when harvested, growing conditions, and amount of moisture lost after harvest. In general, values given in Table 3 apply to mature products shortly after harvest. For fresh meat, the water content values in Table 3 are at the time of slaughter or after the usual aging period. For cured or processed products, the water content depends on the particular process or product.

INITIAL FREEZING POINT

Foods and beverages do not freeze completely at a single temperature, but rather over a range of temperatures. In fact, foods high in sugar content or packed in high syrup concentrations may never be completely frozen, even at typical frozen food storage temperatures. Thus, there is not a distinct freezing point for foods and beverages, but an initial freezing point at which crystallization begins.

The initial freezing point of a food or beverage is important not only for determining the food's proper storage conditions, but also for calculating thermophysical properties. During storage of fresh fruits and vegetables, for example, the commodity temperature must be kept above its initial freezing point to avoid freezing damage. In addition, because there are drastic changes in the thermophysical properties of foods as they freeze, a food's initial freezing point must be known to model its thermophysical properties accurately. Experimentally determined values of the initial freezing point of foods and beverages are given in Table 3.

ICE FRACTION

To predict the thermophysical properties of frozen foods, which depend strongly on the fraction of ice in the food, the mass fraction of water that has crystallized must be determined. Below the initial freezing point, the mass fraction of water that has crystallized in a food is a function of temperature.

In general, foods consist of water, dissolved solids, and undissolved solids. During freezing, as some of the liquid water crystallizes, the solids dissolved in the remaining liquid water become increasingly more concentrated, thus lowering the freezing temperature. This unfrozen solution can be assumed to obey the freezing point depression equation given by Raoult's law (Pham 1987). Thus, based on Raoult's law, Chen (1985) proposed the following model for predicting the mass fraction of ice x_{ice}:

$$x_{ice} = \frac{x_s R T_o^2 (t_f - t)}{M_s L_o t_f t} \tag{1}$$

where

x_s = mass fraction of solids in food
M_s = relative molecular mass of soluble solids, kg/kmol
R = universal gas constant = 8.314 kJ/(kg mol·K)
T_o = freezing point of water = 273.2 K
L_o = latent heat of fusion of water at 273.2 K = 333.6 kJ/kg
t_f = initial freezing point of food, °C
t = food temperature, °C

The relative molecular mass of the soluble solids in the food may be estimated as follows:

$$M_s = \frac{x_s R T_o^2}{-(x_{wo} - x_b) L_o t_f} \tag{2}$$

where x_{wo} is the mass fraction of water in the unfrozen food and x_b is the mass fraction of bound water in the food (Schwartzberg 1976). Bound water is the portion of water in a food that is bound to solids in the food, and thus is unavailable for freezing.

The mass fraction of bound water may be estimated as follows:

$$x_b = 0.4 x_p \tag{3}$$

where x_p is the mass fraction of protein in the food.

Substituting Equation (2) into Equation (1) yields a simple way to predict the ice fraction (Miles 1974):

$$x_{ice} = (x_{wo} - x_b)\left(1 - \frac{t_f}{t}\right) \tag{4}$$

Because Equation (4) underestimates the ice fraction at temperatures near the initial freezing point and overestimates the ice fraction at lower temperatures, Tchigeov (1979) proposed an empirical relationship to estimate the mass fraction of ice:

$$x_{ice} = \frac{1.105 x_{wo}}{1 + \dfrac{0.7138}{\ln(t_f - t + 1)}} \tag{5}$$

Fikiin (1996) notes that Equation (5) applies to a wide variety of foods and provides satisfactory accuracy.

Table 3 Unfrozen Composition Data, Initial Freezing Point, and Specific Heats of Foods*

Food Item	Moisture Content, % x_{wo}	Protein, % x_p	Fat, % x_f	Carbohydrate Total, % x_c	Carbohydrate Fiber, % x_{fb}	Ash, % x_a	Initial Freezing Point, °C	Specific Heat Above Freezing, kJ/(kg·K)	Specific Heat Below Freezing kJ/(kg·K)	Latent Heat of Fusion, kJ/kg
Vegetables										
Artichokes, globe	84.94	3.27	0.15	10.51	5.40	1.13	–1.2	3.90	2.02	284
Jerusalem	78.01	2.00	0.01	17.44	1.60	2.54	–2.5	3.63	2.25	261
Asparagus	92.40	2.28	0.20	4.54	2.10	0.57	–0.6	4.03	1.79	309
Beans, snap	90.27	1.82	0.12	7.14	3.40	0.66	–0.7	3.99	1.85	302
lima	70.24	6.84	0.86	20.16	4.90	1.89	–0.6	3.52	2.07	235
Beets	87.58	1.61	0.17	9.56	2.80	1.08	–1.1	3.91	1.94	293
Broccoli	90.69	2.98	0.35	5.24	3.00	0.92	–0.6	4.01	1.82	303
Brussels sprouts	86.00	3.38	0.30	8.96	3.80	1.37	–0.8	3.90	1.91	287
Cabbage	92.15	1.44	0.27	5.43	2.30	0.71	–0.9	4.02	1.85	308
Carrots	87.79	1.03	0.19	10.14	3.00	0.87	–1.4	3.92	2.00	293
Cauliflower	91.91	1.98	0.21	5.20	2.50	0.71	–0.8	4.02	1.84	307
Celeriac	88.00	1.50	0.30	9.20	1.80	1.00	–0.9	3.90	1.89	294
Celery	94.64	0.75	0.14	3.65	1.70	0.82	–0.5	4.07	1.74	316
Collards	90.55	1.57	0.22	7.11	3.60	0.55	–0.8	4.01	1.86	302
Corn, sweet, yellow	75.96	3.22	1.18	19.02	2.70	0.62	–0.6	3.62	1.98	254
Cucumbers	96.01	0.69	0.13	2.76	0.80	0.41	–0.5	4.09	1.71	321
Eggplant	92.03	1.02	0.18	6.07	2.50	0.71	–0.8	4.02	1.83	307
Endive	93.79	1.25	0.20	3.35	3.10	1.41	–0.1	4.07	1.69	313
Garlic	58.58	6.36	0.50	33.07	2.10	1.50	–0.8	3.17	2.19	196
Ginger, root	81.67	1.74	0.73	15.09	2.00	0.77	—	3.75	1.94	273
Horseradish	78.66	9.40	1.40	8.28	2.00	2.26	–1.8	3.70	2.12	263
Kale	84.46	3.30	0.70	10.01	2.00	1.53	–0.5	3.82	1.86	282
Kohlrabi	91.00	1.70	0.10	6.20	3.60	1.00	–1.0	4.02	1.90	304
Leeks	83.00	1.50	0.30	14.15	1.80	1.05	–0.7	3.77	1.91	277
Lettuce, iceberg	95.89	1.01	0.19	2.09	1.40	0.48	–0.2	4.09	1.65	320
Mushrooms	91.81	2.09	0.42	4.65	1.20	0.89	–0.9	3.99	1.84	307
Okra	89.58	2.00	0.10	7.63	3.20	0.70	–1.8	3.97	2.05	299
Onions	89.68	1.16	0.16	8.63	1.80	0.37	–0.9	3.95	1.87	300
dehydrated flakes	3.93	8.95	0.46	83.28	9.20	3.38	—	—	—	13
Parsley	87.71	2.97	0.79	6.33	3.30	2.20	–1.1	3.93	1.94	293
Parsnips	79.53	1.20	0.30	17.99	4.90	0.98	–0.9	3.74	2.02	266
Peas, green	78.86	5.42	0.40	14.46	5.10	0.87	–0.6	3.75	1.98	263
Peppers, freeze-dried	2.00	17.90	3.00	68.70	21.30	8.40	—	—	—	7
sweet, green	92.19	0.89	0.19	6.43	1.80	0.30	–0.7	4.01	1.80	308
Potatoes, main crop	78.96	2.07	0.10	17.98	1.60	0.89	–0.6	3.67	1.93	264
sweet	72.84	1.65	0.30	24.28	3.00	0.95	–1.3	3.48	2.09	243
Pumpkins	91.60	1.00	0.10	6.50	0.50	0.80	–0.8	3.97	1.81	306
Radishes	94.84	0.60	0.54	3.59	1.60	0.54	–0.7	4.08	1.77	317
Rhubarb	93.61	0.90	0.20	4.54	1.80	0.76	–0.9	4.05	1.83	313
Rutabaga	89.66	1.20	0.20	8.13	2.50	0.81	–1.1	3.96	1.92	299
Salsify (vegetable oyster)	77.00	3.30	0.20	18.60	3.30	0.90	–1.1	3.65	2.05	257
Spinach	91.58	2.86	0.35	3.50	2.70	1.72	–0.3	4.02	1.75	306
Squash, summer	94.20	0.94	0.24	4.04	1.90	0.58	–0.5	4.07	1.74	315
winter	87.78	0.80	0.10	10.42	1.50	0.90	–0.8	3.89	1.87	293
Tomatoes, mature green	93.00	1.20	0.20	5.10	1.10	0.50	–0.6	4.02	1.77	311
ripe	93.76	0.85	0.33	4.64	1.10	0.42	–0.5	4.08	1.79	313
Turnip	91.87	0.90	0.10	6.23	1.80	0.70	–1.1	4.00	1.88	307
greens	91.07	1.50	0.30	5.73	3.20	1.40	–0.2	4.01	1.74	304
Watercress	95.11	2.30	0.10	1.29	1.50	1.20	–0.3	4.08	1.69	318
Yams	69.60	1.53	0.17	27.89	4.10	0.82	—	3.47	2.06	232
Fruits										
Apples, fresh	83.93	0.19	0.36	15.25	2.70	0.26	–1.1	3.81	1.98	280
dried	31.76	0.93	0.32	65.89	8.70	1.10	—	2.57	2.84	106
Apricots	86.35	1.40	0.39	11.12	2.40	0.75	–1.1	3.87	1.95	288
Avocados	74.27	1.98	15.32	7.39	5.00	1.04	–0.3	3.67	1.98	248
Bananas	74.26	1.03	0.48	23.43	2.40	0.80	–0.8	3.56	2.03	248
Blackberries	85.64	0.72	0.39	12.76	5.30	0.48	–0.8	3.91	1.94	286
Blueberries	84.61	0.67	0.38	14.13	2.70	0.21	–1.6	3.83	2.06	283
Cantaloupes	89.78	0.88	0.28	8.36	0.80	0.71	–1.2	3.93	1.91	300
Cherries, sour	86.13	1.00	0.30	12.18	1.60	0.40	–1.7	3.85	2.05	288
sweet	80.76	1.20	0.96	16.55	2.30	0.53	–1.8	3.73	2.12	270
Cranberries	86.54	0.39	0.20	12.68	4.20	0.19	–0.9	3.91	1.93	289

Table 3 Unfrozen Composition Data, Initial Freezing Point, and Specific Heats of Foods* (*Continued*)

Food Item	Moisture Content, % x_{wo}	Protein, % x_p	Fat, % x_f	Carbohydrate Total, % x_c	Carbohydrate Fiber, % x_{fb}	Ash, % x_a	Initial Freezing Point, °C	Specific Heat Above Freezing, kJ/(kg·K)	Specific Heat Below Freezing kJ/(kg·K)	Latent Heat of Fusion, kJ/kg
Currants, European black	81.96	1.40	0.41	15.38	0.00	0.86	–1.0	3.71	1.95	274
red and white	83.95	1.40	0.20	13.80	4.30	0.66	–1.0	3.85	1.98	280
Dates, cured	22.50	1.97	0.45	73.51	7.50	1.58	–15.7	2.31	2.30	75
Figs, fresh	79.11	0.75	0.30	19.18	3.30	0.66	–2.4	3.70	2.25	264
dried	28.43	3.05	1.17	65.35	9.30	2.01	—	2.51	4.13	95
Gooseberries	87.87	0.88	0.58	10.18	4.30	0.49	–1.1	3.95	1.96	293
Grapefruit	90.89	0.63	0.10	8.08	1.10	0.31	–1.1	3.96	1.89	304
Grapes, American	81.30	0.63	0.35	17.15	1.00	0.57	–1.6	3.71	2.07	272
European type	80.56	0.66	0.58	17.77	1.00	0.44	–2.1	3.70	2.16	269
Lemons	87.40	1.20	0.30	10.70	4.70	0.40	–1.4	3.94	2.02	292
Limes	88.26	0.70	0.20	10.54	2.80	0.30	–1.6	3.93	2.03	295
Mangos	81.71	0.51	0.27	17.00	1.80	0.50	–0.9	3.74	1.95	273
Melons, casaba	92.00	0.90	0.10	6.20	0.80	0.80	–1.1	3.99	1.87	307
honeydew	89.66	0.46	0.10	9.18	0.60	0.60	–0.9	3.92	1.86	299
watermelon	91.51	0.62	0.43	7.18	0.50	0.26	–0.4	3.97	1.74	306
Nectarines	86.28	0.94	0.46	11.78	1.60	0.54	–0.9	3.86	1.90	288
Olives	79.99	0.84	10.68	6.26	3.20	2.23	–1.4	3.76	2.07	267
Oranges	82.30	1.30	0.30	15.50	4.50	0.60	–0.8	3.81	1.96	275
Peaches, fresh	87.66	0.70	0.90	11.10	2.00	0.46	–0.9	3.91	1.90	293
dried	31.80	3.61	0.76	61.33	8.20	2.50	—	2.57	3.49	106
Pears	83.81	0.39	0.40	15.11	2.40	0.28	–1.6	3.80	2.06	280
Persimmons	64.40	0.80	0.40	33.50	0.00	0.90	–2.2	3.26	2.29	215
Pineapples	86.50	0.39	0.43	12.39	1.20	0.29	–1.0	3.85	1.91	289
Plums	85.20	0.79	0.62	13.01	1.50	0.39	–0.8	3.83	1.90	285
Pomegranates	80.97	0.95	0.30	17.17	0.60	0.61	–3.0	3.70	2.30	270
Prunes, dried	32.39	2.61	0.52	62.73	7.10	1.76	—	2.56	3.50	108
Quinces	83.80	0.40	0.10	15.30	1.90	0.40	–2.0	3.79	2.13	280
Raisins, seedless	15.42	3.22	0.46	79.13	4.00	1.77	—	2.07	2.04	52
Raspberries	86.57	0.91	0.55	11.57	6.80	0.40	–0.6	3.96	1.91	289
Strawberries	91.57	0.61	0.37	7.02	2.30	0.43	–0.8	4.00	1.84	306
Tangerines	87.60	0.63	0.19	11.19	2.30	0.39	–1.1	3.90	1.93	293
Whole Fish										
Cod	81.22	17.81	0.67	0.0	0.0	1.16	–2.2	3.78	2.14	271
Haddock	79.92	18.91	0.72	0.0	0.0	1.21	–2.2	3.75	2.14	267
Halibut	77.92	20.81	2.29	0.0	0.0	1.36	–2.2	3.74	2.18	260
Herring, kippered	59.70	24.58	12.37	0.0	0.0	1.94	–2.2	3.26	2.27	199
Mackerel, Atlantic	63.55	18.60	13.89	0.0	0.0	1.35	–2.2	3.33	2.23	212
Perch	78.70	18.62	1.63	0.0	0.0	1.20	–2.2	3.71	2.15	263
Pollock, Atlantic	78.18	19.44	0.98	0.0	0.0	1.41	–2.2	3.70	2.15	261
Salmon, pink	76.35	19.94	3.45	0.0	0.0	1.22	–2.2	3.68	2.17	255
Tuna, bluefin	68.09	23.33	4.90	0.0	0.0	1.18	–2.2	3.43	2.19	227
Whiting	80.27	18.31	1.31	0.0	0.0	1.30	–2.2	3.77	2.15	268
Shellfish										
Clams	81.82	12.77	0.97	2.57	0.0	1.87	–2.2	3.76	2.13	273
Lobster, American	76.76	18.80	0.90	0.50	0.0	2.20	–2.2	3.64	2.15	256
Oysters	85.16	7.05	2.46	3.91	0.0	1.42	–2.2	3.83	2.12	284
Scallop, meat	78.57	16.78	0.76	2.36	0.0	1.53	–2.2	3.71	2.15	262
Shrimp	75.86	20.31	1.73	0.91	0.0	1.20	–2.2	3.65	2.16	253
Beef										
Brisket	55.18	16.94	26.54	0.0	0.0	0.80	—	3.19	2.33	184
Carcass, choice	57.26	17.32	24.05	0.0	0.0	0.81	–2.2	3.24	2.31	191
select	58.21	17.48	22.55	0.0	0.0	0.82	–1.7	3.25	2.24	194
Liver	68.99	20.00	3.85	5.82	0.0	1.34	–1.7	3.47	2.16	230
Ribs, whole (ribs 6-12)	54.54	16.37	26.98	0.0	0.0	0.77	—	3.16	2.32	182
Round, full cut, lean and fat	64.75	20.37	12.81	0.0	0.0	0.97	—	3.39	2.18	216
full cut, lean	70.83	22.03	4.89	0.0	0.0	1.07	—	3.52	2.12	237
Sirloin, lean	71.70	21.24	4.40	0.0	0.0	1.08	–1.7	3.53	2.11	239
Short loin, porterhouse steak, lean	69.59	20.27	8.17	0.0	0.0	1.01	—	3.49	2.14	232
T-bone steak, lean	69.71	20.78	7.27	0.0	0.0	1.27	—	3.49	2.14	233
Tenderloin, lean	68.40	20.78	7.90	0.0	0.0	1.04	—	3.45	2.14	228
Veal, lean	75.91	20.20	2.87	0.0	0.0	1.08	—	3.65	2.09	254

Table 3 Unfrozen Composition Data, Initial Freezing Point, and Specific Heats of Foods* (*Continued*)

Food Item	Moisture Content, % x_{wo}	Protein, % x_p	Fat, % x_f	Carbohydrate Total, % x_c	Carbohydrate Fiber, % x_{fb}	Ash, % x_a	Initial Freezing Point, °C	Specific Heat Above Freezing, kJ/(kg·K)	Specific Heat Below Freezing kJ/(kg·K)	Latent Heat of Fusion, kJ/kg
Pork										
Backfat	7.69	2.92	88.69	0.0	0.0	0.70	—	2.17	2.98	26
Bacon	31.58	8.66	57.54	0.09	0.0	2.13	—	2.70	2.70	105
Belly	36.74	9.34	53.01	0.0	0.0	0.49	—	2.80	3.37	123
Carcass	49.83	13.91	35.07	0.0	0.0	0.72	—	3.08	3.10	166
Ham, cured, whole, lean	68.26	22.32	5.71	0.05	0.0	3.66	—	3.47	2.22	228
country cured, lean	55.93	27.80	8.32	0.30	0.0	7.65	—	3.16	2.31	187
Shoulder, whole, lean	72.63	19.55	7.14	0.0	0.0	1.02	–2.2	3.59	2.20	243
Sausage										
Braunschweiger	48.01	13.50	32.09	3.13	0.0	3.27	—	3.01	2.40	160
Frankfurter	53.87	11.28	29.15	2.55	0.0	3.15	–1.7	3.15	2.31	180
Italian	51.08	14.25	31.33	0.65	0.0	2.70	—	3.10	2.37	171
Polish	53.15	14.10	28.72	1.63	0.0	2.40	—	3.14	2.36	178
Pork	44.52	11.69	40.29	1.02	0.0	2.49	—	2.95	2.43	149
Smoked links	39.30	22.20	31.70	2.10	0.0	4.70	—	2.82	2.45	131
Poultry Products										
Chicken	65.99	18.60	15.06	0.0	0.0	0.79	–2.8	4.34	3.32	220
Duck	48.50	11.49	39.34	0.0	0.0	0.68	—	3.06	2.45	162
Turkey	70.40	20.42	8.02	0.0	0.0	0.88	—	3.53	2.28	235
Egg										
White	87.81	10.52	0.0	1.03	0.0	0.64	–0.6	3.91	1.81	293
dried	14.62	76.92	0.04	4.17	0.0	4.25	—	2.29	2.10	49
Whole	75.33	12.49	10.02	1.22	0.0	0.94	–0.6	3.63	1.95	252
dried	3.10	47.35	40.95	4.95	0.0	3.65	—	2.04	2.00	10
Yolk	48.81	16.76	30.87	1.78	0.0	1.77	–0.6	3.05	2.25	163
salted	50.80	14.00	23.00	1.60	0.0	10.60	–17.2	3.01	3.79	170
sugared	51.25	13.80	22.75	10.80	0.0	1.40	–3.9	3.07	2.54	171
Lamb										
Composite of cuts, lean	73.42	20.29	5.25	0.0	0.0	1.06	–1.9	3.60	2.14	245
Leg, whole, lean	74.11	20.56	4.51	0.0	0.0	1.07	—	3.62	2.14	248
Dairy Products										
Butter	17.94	0.85	81.11	0.06	0.0	0.04	—	2.40	2.65	60
Cheese										
Camembert	51.80	19.80	24.26	0.46	0.0	3.68	—	3.10	3.34	173
Cheddar	36.75	24.90	33.14	1.28	0.0	3.93	–12.9	2.77	3.07	123
Cottage, uncreamed	79.77	17.27	0.42	1.85	0.0	0.69	–1.2	3.73	1.99	266
Cream	53.75	7.55	34.87	2.66	0.0	1.17	—	3.16	2.91	180
Gouda	41.46	24.94	27.44	2.22	0.0	3.94	—	2.87	2.77	138
Limburger	48.42	20.05	27.25	0.49	0.0	3.79	–7.4	3.03	2.82	162
Mozzarella	54.14	19.42	21.60	2.22	0.0	2.62	—	3.15	2.46	181
Parmesan, hard	29.16	35.75	25.83	3.22	0.0	6.04	—	2.58	2.94	97
Processed American	39.16	22.15	31.25	1.30	0.0	5.84	–6.9	2.80	2.75	131
Roquefort	39.38	21.54	30.64	2.00	0.0	6.44	–16.3	2.80	3.36	132
Swiss	37.21	28.43	27.45	3.38	0.0	3.53	–10.0	2.78	2.88	124
Cream										
Half and half	80.57	2.96	11.50	4.30	0.0	0.67	—	3.73	2.16	269
Table	73.75	2.70	19.31	3.66	0.0	0.58	–2.2	3.59	2.21	246
Heavy whipping	57.71	2.05	37.00	2.79	0.0	0.45	—	3.25	2.32	193
Ice Cream										
Chocolate	55.70	3.80	11.0	28.20	1.20	1.00	–5.6	3.11	2.75	186
Strawberry	60.00	3.20	8.40	27.60	0.30	0.70	–5.6	3.19	2.74	200
Vanilla	61.00	3.50	11.00	23.60	0.0	0.90	–5.6	3.22	2.74	204
Milk										
Canned, condensed, sweetened	27.16	7.91	8.70	54.40	0.0	1.83	–15.0	2.35	—	91
Evaporated	74.04	6.81	7.56	10.04	0.0	1.55	–1.4	3.56	2.08	247
Skim	90.80	3.41	0.18	4.85	0.0	0.76	—	3.95	1.78	303
Skim, dried	3.16	36.16	0.77	51.98	0.0	7.93	—	1.80	—	11
Whole	87.69	3.28	3.66	4.65	0.0	0.72	–0.6	3.89	1.81	293
dried	2.47	26.32	26.71	38.42	0.0	6.08	—	1.85	—	8
Whey, acid, dried	3.51	11.73	0.54	73.45	0.0	10.77	—	1.68	—	12
sweet, dried	3.19	12.93	1.07	74.46	0.0	8.35	—	1.69	—	11

Table 3 Unfrozen Composition Data, Initial Freezing Point, and Specific Heats of Foods* (*Continued*)

Food Item	Moisture Content, % x_{wo}	Protein, % x_p	Fat, % x_f	Carbohydrate: Total, % x_c	Carbohydrate: Fiber, % x_{fb}	Ash, % x_a	Initial Freezing Point, °C	Specific Heat Above Freezing, kJ/(kg·K)	Specific Heat Below Freezing kJ/(kg·K)	Latent Heat of Fusion, kJ/kg
Nuts, Shelled										
Almonds	4.42	19.95	52.21	20.40	10.90	3.03	—	2.20	—	15
Filberts	5.42	13.04	62.64	15.30	6.10	3.61	—	2.09	—	18
Peanuts, raw	6.5	25.80	49.24	16.14	8.50	2.33	—	2.23	—	22
dry roasted with salt	1.55	23.68	49.66	21.51	8.00	3.60	—	2.08	—	5
Pecans	4.82	7.75	67.64	18.24	7.60	1.56	—	2.17	—	16
Walnuts, English	3.65	14.29	61.87	18.34	4.80	1.86	—	2.09	—	12
Candy										
Fudge, vanilla	10.90	1.10	5.40	82.30	0.0	0.40	—	1.90	—	36
Marshmallows	16.40	1.80	0.20	81.30	0.10	0.30	—	2.02	—	55
Milk chocolate	1.30	6.90	30.70	59.20	3.40	1.50	—	1.83	—	4
Peanut brittle	1.80	7.50	19.10	69.30	2.00	1.50	—	1.77	—	6
Juice and Beverages										
Apple juice, unsweetened	87.93	0.06	0.11	11.68	0.10	0.22	—	3.87	1.78	294
Grapefruit juice, sweetened	87.38	0.58	0.09	11.13	0.10	0.82	—	3.85	1.78	292
Grape juice, unsweetened	84.12	0.56	0.08	14.96	0.10	0.29	—	3.77	1.82	281
Lemon juice	92.46	0.40	0.29	6.48	0.40	0.36	—	3.99	1.73	309
Lime juice, unsweetened	92.52	0.25	0.23	6.69	0.40	0.31	—	3.99	1.73	309
Orange juice	89.01	0.59	0.14	9.85	0.20	0.41	–0.4	3.90	1.76	297
Pineapple juice, unsweetened	85.53	0.32	0.08	13.78	0.20	0.30	—	3.81	1.81	286
Prune juice	81.24	0.61	0.03	17.45	1.00	0.68	—	3.71	1.87	271
Tomato juice	93.90	0.76	0.06	4.23	0.40	1.05	—	4.03	1.71	314
Cranberry-apple juice drink	82.80	0.10	0.0	17.10	0.10	0.0	—	3.73	1.84	277
Cranberry-grape juice drink	85.60	0.20	0.10	14.00	0.10	0.10	—	3.81	1.80	286
Fruit punch drink	88.00	0.0	0.0	11.90	0.10	0.10	—	3.87	1.78	294
Club soda	99.90	0.0	0.0	0.0	0.0	0.10	—	4.17	1.63	334
Cola	89.40	0.0	0.0	10.40	0.0	0.10	—	3.90	1.76	299
Cream soda	86.70	0.0	0.0	13.30	0.0	0.10	—	3.83	1.79	290
Ginger ale	91.20	0.0	0.0	8.70	0.0	0.0	—	3.95	1.73	305
Grape soda	88.80	0.0	0.0	11.20	0.0	0.10	—	3.89	1.77	297
Lemon-lime soda	89.50	0.0	0.0	10.40	0.0	0.10	—	3.90	1.76	299
Orange soda	87.60	0.0	0.0	12.30	0.0	0.10	—	3.86	1.78	293
Root beer	89.30	0.0	0.0	10.60	0.0	0.10	—	3.90	1.76	298
Chocolate milk, 2% fat	83.58	3.21	2.00	10.40	0.50	0.81	—	3.78	1.83	279
Miscellaneous										
Honey	17.10	0.30	0.0	82.40	0.20	0.20	—	2.03	—	57
Maple syrup	32.00	0.00	0.20	67.20	0.0	0.60	—	2.41	—	107
Popcorn, air-popped	4.10	12.00	4.20	77.90	15.10	1.80	—	2.04	—	14
oil-popped	2.80	9.00	28.10	57.20	10.00	2.90	—	1.99	—	9
Yeast, baker's, compressed	69.00	8.40	1.90	18.10	8.10	1.80	—	3.55	2.17	230

*Composition data from USDA (1996). Initial freezing point data from Table 1 in Chapter 30 of the 1993 *ASHRAE Handbook—Fundamentals*. Specific heats calculated from equations in this chapter. Latent heat of fusion obtained by multiplying water content expressed in decimal form by 334 kJ/kg, the heat of fusion of water (Table 1 in Chapter 30 of the 1993 *ASHRAE Handbook—Fundamentals*).

Example 1. A 150 kg beef carcass is to be frozen to –20°C. What are the masses of the frozen and unfrozen water at –20°C?

Solution:

From Table 3, the mass fraction of water in the beef carcass is 0.58 and the initial freezing point for the beef carcass is –1.7°C. Using Equation (5), the mass fraction of ice is

$$x_{ice} = \frac{1.105 \times 0.58}{1 + \dfrac{0.7138}{\ln(-1.7 + 20 + 1)}} = 0.52$$

The mass fraction of unfrozen water is

$$x_u = x_{wo} - x_{ice} = 0.58 - 0.52 = 0.06$$

The mass of frozen water at –20°C is

$$x_{ice} \times 150 \text{ kg} = 0.52 \times 150 = 78 \text{ kg}$$

The mass of unfrozen water at –20°C is

$$x_u \times 150 \text{ kg} = 0.06 \times 150 = 9 \text{ kg}$$

DENSITY

Modeling the density of foods and beverages requires knowledge of the food porosity, as well as the mass fraction and density of the food components. The density ρ of foods and beverages can be calculated accordingly:

$$\rho = \frac{(1 - \varepsilon)}{\sum x_i / \rho_i} \tag{6}$$

where ε is the porosity, x_i is the mass fraction of the food constituents, and ρ_i is the density of the food constituents. The porosity ε is required to model the density of granular foods stored in bulk, such as grains and rice. For other foods, the porosity is zero.

SPECIFIC HEAT

Specific heat is a measure of the energy required to change the temperature of a food by one degree. Therefore, the specific heat of foods or beverages can be used to calculate the heat load imposed on the refrigeration equipment by the cooling or freezing of foods and beverages. In unfrozen foods, specific heat becomes slightly lower as the temperature rises from 0°C to 20°C. For frozen foods, there is a large decrease in specific heat as the temperature decreases. Table 3 lists experimentally determined values of the specific heats for various foods above and below freezing.

Unfrozen Food

The specific heat of a food, at temperatures above its initial freezing point, can be obtained from the mass average of the specific heats of the food components. Thus, the specific heat of an unfrozen food c_u may be determined as follows:

$$c_u = \sum c_i x_i \tag{7}$$

where c_i is the specific heat of the individual food components and x_i is the mass fraction of the food components.

A simpler model for the specific heat of an unfrozen food is presented by Chen (1985). If detailed composition data are not available, the following expression for specific heat of an unfrozen food can be used:

$$c_u = 4.19 - 2.30x_s - 0.628x_s^3 \tag{8}$$

where c_u is the specific heat of the unfrozen food in kJ/(kg·K) and x_s is the mass fraction of the solids in the food.

Frozen Food

Below the food's freezing point, the sensible heat from temperature change and the latent heat from the fusion of water must be considered. Because latent heat is not released at a constant temperature, but rather over a range of temperatures, an apparent specific heat must be used to account for both the sensible and latent heat effects. A common method to predict the apparent specific heat of foods is (Schwartzberg 1976)

$$c_a = c_u + (x_b - x_{wo})\Delta c + E x_s \left(\frac{RT_o^2}{M_w t^2} - 0.8\Delta c \right) \tag{9}$$

where

c_a = apparent specific heat
c_u = specific heat of food above initial freezing point
x_b = mass fraction of bound water
x_{wo} = mass fraction of water above initial freezing point
0.8 = constant
Δc = difference between specific heats of water and ice = $c_w - c_{ice}$
E = ratio of relative molecular masses of water M_w and food solids M_s ($E = M_w/M_s$)
R = universal gas constant = 8.314 kJ/(kg mol·K)
T_o = freezing point of water = 273.2 K
M_w = relative molecular mass, kg/kmol
t = food temperature, °C

The specific heat of the food above the freezing point may be estimated with Equation (7) or (8).

Schwartzberg (1981) developed an alternative method for determining the apparent specific heat of a food below the initial freezing point, as follows:

$$c_a = c_f + (x_{wo} - x_b)\left[\frac{L_o(t_o - t_f)}{t_o - t} \right] \tag{10}$$

where

c_f = specific heat of fully frozen food (typically at –40°C)
t_o = freezing point of water = 0°C
t_f = initial freezing point of food, °C
t = food temperature, °C
L_o = latent heat of fusion of water = 333.6 kJ/kg

Experimentally determined values of the specific heat of fully frozen foods are given in Table 3.

A slightly simpler apparent specific heat model, which is similar in form to that of Schwartzberg (1976), was developed by Chen (1985). Chen's model is an expansion of Siebel's equation (Siebel 1892) for specific heat and has the following form:

$$c_a = 1.55 + 1.26x_s + \frac{x_s R T_o^2}{M_s t^2} \tag{11}$$

where

c_a = apparent specific heat, kJ/(kg·K)
x_s = mass fraction of solids
R = universal gas constant
T_o = freezing point of water = 273.2 K
M_s = relative molecular mass of soluble solids in food
t = food temperature, °C

If the relative molecular mass of the soluble solids is unknown, Equation (2) may be used to estimate the molecular mass. Substituting Equation (2) into Equation (11) yields

$$c_a = 1.55 + 1.26x_s - \frac{(x_{wo} - x_b)L_o t_f}{t^2} \tag{12}$$

Example 2. One hundred fifty kilograms of lamb meat is to be cooled from 10°C to 0°C. Using the specific heat, determine the amount of heat that must be removed from the lamb.

Solution:

From Table 3, the composition of lamb is given as follows:

x_{wo} = 0.7742 x_f = 0.0525
x_p = 0.2029 x_a = 0.0106

Evaluate the specific heat of lamb at an average temperature of (0 + 10)/2 = 5°C. From Tables 1 and 2, the specific heat of the food constituents may be determined as follows:

$$c_w = 4.1762 - 9.0864 \times 10^{-5}(5) + 5.4731 \times 10^{-6}(5)^2 = 4.1759 \text{ kJ/(kg·K)}$$

$$c_p = 2.0082 + 1.2089 \times 10^{-3}(5) - 1.3129 \times 10^{-6}(5)^2 = 2.0142 \text{ kJ/(kg·K)}$$

$$c_f = 1.9842 + 1.4733 \times 10^{-3}(5) - 4.8008 \times 10^{-6}(5)^2 = 1.9914 \text{ kJ/(kg·K)}$$

$$c_a = 1.0926 + 1.8896 \times 10^{-3}(5) - 3.6817 \times 10^{-6}(5)^2 = 1.1020 \text{ kJ/(kg·K)}$$

The specific heat of lamb can be calculated with Equation (7):

$$c = \sum c_i x_i = (4.1759)(0.7342) + (2.0142)(0.2029) + (1.9914)(0.0525) + (1.1020)(0.0106)$$

$$c = 3.59 \text{ kJ/(kg·K)}$$

The heat to be removed from the lamb is thus

$$Q = mc\Delta T = 150 \times 3.59\ (10 - 0) = 5390 \text{ kJ}$$

ENTHALPY

The change in a food's enthalpy can be used to estimate the energy that must be added or removed to effect a temperature change. Above the freezing point, enthalpy consists of sensible energy; below the freezing point, enthalpy consists of both sensible and latent energy. Enthalpy may be obtained from the definition of constant-pressure specific heat:

$$c_p = \left(\frac{\partial H}{\partial T} \right)_p \tag{13}$$

where c_p is constant pressure specific heat, H is enthalpy, and T is temperature. Mathematical models for enthalpy may be obtained by integrating expressions of specific heat with respect to temperature.

Unfrozen Food

For foods at temperatures above their initial freezing point, enthalpy may be obtained by integrating the corresponding expression for specific heat above the freezing point. Thus, the enthalpy H of an unfrozen food may be determined by integrating Equation (7) as follows:

$$H = \sum H_i x_i = \sum \int c_i x_i \, dT \tag{14}$$

where H_i is the enthalpy of the individual food components and x_i is the mass fraction of the food components.

In Chen's (1985) method, the enthalpy of an unfrozen food may be obtained by integrating Equation (8):

$$H = H_f + (t - t_f)(4.19 - 2.30x_s - 0.628x_s^3) \tag{15}$$

where

H = enthalpy of food, kJ/kg
H_f = enthalpy of food at initial freezing temperature, kJ/kg
t = temperature of food, °C
t_f = initial freezing temperature of food, °C
x_s = mass fraction of food solids

The enthalpy at initial freezing point H_f may be estimated by evaluating either Equation (17) or (18) at the initial freezing temperature of the food, as discussed in the following section.

Frozen Foods

For foods below the initial freezing point, mathematical expressions for enthalpy may be obtained by integrating the apparent specific heat models. Integration of Equation (9) between a reference temperature T_r and food temperature T leads to the following expression for the enthalpy of a food (Schwartzberg 1976):

$$H = (T - T_r) \times \left\{ c_u + (x_b - x_{wo})\Delta c + Ex_s\left[\frac{RT_o^2}{18(T_o - T_r)(T_o - T)} - 0.8\,\Delta c\right]\right\} \tag{16}$$

Generally, the reference temperature T_r is taken to be 233.2 K (–40°C), at which point the enthalpy is defined to be zero.

By integrating Equation (11) between reference temperature T_r and food temperature T, Chen (1985) obtained the following expression for enthalpy below the initial freezing point:

$$H = (t - t_r)\left(1.55 + 1.26x_s + \frac{x_s R T_o^2}{M_s t t_r}\right) \tag{17}$$

where

H = enthalpy of food
R = universal gas constant
T_o = freezing point of water = 273.2 K

Substituting Equation (2) for the relative molecular mass of the soluble solids M_s simplifies Chen's method as follows:

$$H = (t - t_r)\left[1.55 + 1.26\,x_s - \frac{(x_{wo} - x_b)L_o t_f}{t_r t}\right] \tag{18}$$

As an alternative to the enthalpy models developed by integration of specific heat equations, Chang and Tao (1981) developed empirical correlations for the enthalpy of foods. Their enthalpy correlations are given as functions of water content, initial and final temperatures, and food type (meat, juice, or fruit/vegetable). The correlations at a reference temperature of –45.6°C have the following form:

$$H = H_f\left[y\bar{T} + (1 - y)\bar{T}^{\,z}\right] \tag{19}$$

where

H = enthalpy of food, kJ/kg
H_f = enthalpy of food at initial freezing temperature, kJ/kg
$\bar{T}$ = reduced temperature, $\bar{T} = (T - T_r)/(T_f - T_r)$
T_r = reference temperature (zero enthalpy) = 227.6 K (–45.6°C)
y, z = correlation parameters

By performing regression analysis on experimental data available in the literature, Chang and Tao (1981) developed the following correlation parameters y and z used in Equation (19):

Meat Group:

$$\begin{aligned} y &= 0.316 - 0.247(x_{wo} - 0.73) - 0.688(x_{wo} - 0.73)^2 \\ z &= 22.95 + 54.68(y - 0.28) - 5589.03(y - 0.28)^2 \end{aligned} \tag{20}$$

Fruit, Vegetable, and Juice Group:

$$\begin{aligned} y &= 0.362 + 0.0498(x_{wo} - 0.73) - 3.465(x_{wo} - 0.73)^2 \\ z &= 27.2 - 129.04(y - 0.23) - 481.46(y - 0.23)^2 \end{aligned} \tag{21}$$

They also developed correlations to estimate the initial freezing temperature T_f for use in Equation (19). These correlations give T_f as a function of water content:

Meat Group:

$$T_f = 271.18 + 1.47x_{wo} \tag{22}$$

Fruit/Vegetable Group:

$$T_f = 287.56 - 49.19x_{wo} + 37.07x_{wo}^2 \tag{23}$$

Juice Group:

$$T_f = 120.47 + 327.35x_{wo} - 176.49x_{wo}^2 \tag{24}$$

In addition, the enthalpy of the food at its initial freezing point is required in Equation (19). Chang and Tao (1981) suggest the following correlation for determining the food's enthalpy at its initial freezing point H_f:

$$H_f = 9.79246 + 405.096x_{wo} \tag{25}$$

Table 4 presents experimentally determined values for the enthalpy of some frozen foods at a reference temperature of –40°C as well as the percentage of unfrozen water in these foods.

Example 3. A 150 kg beef carcass is to be frozen to a temperature of –20°C. The initial temperature of the beef carcass is 10°C. How much heat must be removed from the beef carcass during this process?

Solution:

From Table 3, the mass fraction of water in the beef carcass is 0.5821, the mass fraction of protein in the beef carcass is 0.1748, and the initial freezing point of the beef carcass is –1.7°C. The mass fraction of solids in the beef carcass is

$$x_s = 1 - x_{wo} = 1 - 0.5821 = 0.4179$$

The mass fraction of bound water is given by Equation (3):

$x_b = 0.4x_p = 0.4 \times 0.1748 = 0.0699$

The enthalpy of the beef carcass at –20°C is given by Equation (18) for frozen foods:

$$H_{-20} = [-20 - (-40)]\left[1.55 + (1.26)(0.4179) - \frac{(0.5821 - 0.0699)(333.6)(-1.7)}{(-40)(-20)}\right] = 48.79 \text{ kJ/kg}$$

The enthalpy of the beef carcass at the initial freezing point is determined by evaluating Equation (18) at the initial freezing point:

$$H_f = [-1.7 - (-40)]\left[1.55 + (1.26)(0.4179) - \frac{(0.5821 - 0.0699)(333.6)(-1.7)}{(-40)(-1.7)}\right] = 243.14 \text{ kJ/kg}$$

The enthalpy of the beef carcass at 10°C is given by Equation (15) for unfrozen foods:

$$H_{10} = 243.14 + [10 - (-1.7)] \times [4.19 - (2.30)(0.4179) - (0.628)(0.4179)^3] = 280.38 \text{ kJ/kg}$$

Thus, the amount of heat removed during the freezing process is

$$Q = m\Delta H = m(H_{10} - H_{-20}) = 150(280.38 - 48.79) = 34{,}700 \text{ kJ}$$

THERMAL CONDUCTIVITY

Thermal conductivity relates the conduction heat transfer rate to the temperature gradient. A food's thermal conductivity depends on factors such as composition, structure, and temperature. Early work in the modeling of thermal conductivity of foods and beverages includes Eucken's adaption of Maxwell's equation (Eucken 1940). This model is based on the thermal conductivity of dilute dispersions of small spheres in a continuous phase:

$$k = k_c \frac{1 - [1 - a(k_d/k_c)]b}{1 + (a - 1)b} \qquad (26)$$

where

k = conductivity of mixture
k_c = conductivity of continuous phase
k_d = conductivity of dispersed phase
$a = 3k_c/(2k_c + k_d)$
$b = V_d/(V_c + V_d)$
V_d = volume of dispersed phase
V_c = volume of continuous phase

In an effort to account for the different structural features of foods, Kopelman (1966) developed thermal conductivity models for homogeneous and fibrous foods. Differences in thermal conductivity parallel and perpendicular to the food fibers are accounted for in Kopelman's fibrous food thermal conductivity models.

For an isotropic, two-component system composed of continuous and discontinuous phases, in which thermal conductivity is independent of direction of heat flow, Kopelman (1966) developed the following expression for thermal conductivity k:

$$k = k_c\left[\frac{1 - L^2}{1 - L^2(1 - L)}\right] \qquad (27)$$

where k_c is the thermal conductivity of the continuous phase and L^3 is the volume fraction of the discontinuous phase. In Equation (27), thermal conductivity of the continuous phase is assumed to be much larger than that of the discontinuous phase. However, if the opposite if true, the following expression is used to calculate the thermal conductivity of the isotropic mixture:

$$k = k_c\left[\frac{1 - M}{1 - M(1 - L)}\right] \qquad (28)$$

where $M = L^2(1 - k_d/k_c)$ and k_d is the thermal conductivity of the discontinuous phase.

For an anisotropic, two-component system in which thermal conductivity depends on the direction of heat flow, such as in fibrous food materials, Kopelman (1966) developed two expressions for thermal conductivity. For heat flow parallel to food fibers, thermal conductivity $k_=$ is

$$k_= = k_c\left[1 - N^2\left(1 - \frac{k_d}{k_c}\right)\right] \qquad (29)$$

where N^2 is the volume fraction of the discontinuous phase. If the heat flow is perpendicular to the food fibers, then thermal conductivity $k_\perp$ is

$$k_\perp = k_c\left[\frac{1 - P}{1 - P(1 - N)}\right] \qquad (30)$$

where $P = N(1 - k_d/k_c)$.

Levy (1981) introduced a modified version of the Maxwell-Eucken equation. Levy's expression for the thermal conductivity of a two-component system is as follows:

$$k = \frac{k_2[(2 + \Lambda) + 2(\Lambda - 1)F_1]}{(2 + \Lambda) - (\Lambda - 1)F_1} \qquad (31)$$

where Λ is the thermal conductivity ratio ($\Lambda = k_1/k_2$), and k_1 and k_2 are the thermal conductivities of components 1 and 2, respectively. The parameter F_1 introduced by Levy is given as follows:

$$F_1 = 0.5\left\{\left(\frac{2}{\sigma} - 1 + 2R_1\right) - \left[\left(\frac{2}{\sigma} - 1 + 2R_1\right)^2 - \frac{8R_1}{\sigma}\right]^{0.5}\right\} \qquad (32)$$

where

$$\sigma = \frac{(\Lambda - 1)^2}{(\Lambda + 1)^2 + (\Lambda/2)} \qquad (33)$$

and R_1 is the volume fraction of component 1, or

$$R_1 = \left[1 + \left(\frac{1}{x_1} - 1\right)\left(\frac{\rho_1}{\rho_2}\right)\right]^{-1} \qquad (34)$$

Here, x_1 is the mass fraction of component 1, ρ_1 is the density of component 1, and ρ_2 is the density of component 2.

To use Levy's method, follow these steps:

1. Calculate thermal conductivity ratio Λ
2. Determine volume fraction of constituent 1 using Equation (34)
3. Evaluate σ using Equation (33)
4. Determine F_1 using Equation (32)
5. Evaluate thermal conductivity of two-component system using Equation (31)

When foods consist of more than two distinct phases, the previously mentioned methods for the prediction of thermal conductivity must be applied successively to obtain the thermal conductivity of

Table 4 Enthalpy of Frozen Foods

Food	Water Content, % by mass		Temperature, °C –40	–30	–20	–18	–16	–14	–12	–10	–9	–8	–7	–6	–5	–4	–3	–2	–1	0
Fruits and Vegetables																				
Applesauce	82.8	Enthalpy, kJ/kg	0	23	51	58	65	73	84	95	102	110	120	132	152	175	210	286	339	343
		% water unfrozen	—	6	9	10	12	14	17	19	21	23	27	30	37	44	57	82	100	—
Asparagus, peeled	92.6	Enthalpy, kJ/kg	0	19	40	45	50	55	61	69	73	77	83	90	99	108	123	155	243	381
		% water unfrozen	—	—	—	—	—	5	6	—	7	8	10	12	15	17	20	29	58	100
Bilberries	85.1	Enthalpy, kJ/kg	0	21	45	50	57	64	73	82	87	94	101	110	125	140	167	218	348	352
		% water unfrozen	—	—	—	7	8	9	11	14	15	17	18	21	25	30	38	57	100	—
Carrots	87.5	Enthalpy, kJ/kg	0	21	46	51	57	64	72	81	87	94	102	111	124	139	166	218	357	361
		% water unfrozen	—	—	—	7	8	9	11	14	15	17	18	20	24	29	37	53	100	—
Cucumbers	95.4	Enthalpy, kJ/kg	0	18	39	43	47	51	57	64	67	70	74	79	85	93	104	125	184	390
		% water unfrozen	—	—	—	—	—	—	—	—	5	—	—	—	—	11	14	20	37	100
Onions	85.5	Enthalpy, kJ/kg	0	23	50	55	62	71	81	91	97	105	115	125	141	163	196	263	349	353
		% water unfrozen	—	5	8	10	12	14	16	18	19	20	23	26	31	38	49	71	100	—
Peaches, without stones	85.1	Enthalpy, kJ/kg	0	23	50	57	64	72	82	93	100	108	118	129	146	170	202	274	348	352
		% water unfrozen	—	5	8	9	11	13	16	18	20	22	25	28	33	40	51	75	100	—
Pears, Bartlett	83.8	Enthalpy, kJ/kg	0	23	51	57	64	73	83	95	101	109	120	132	150	173	207	282	343	347
		% water unfrozen	—	6	9	10	12	14	17	19	21	23	26	29	35	43	54	80	100	—
Plums, without stones	80.3	Enthalpy, kJ/kg	0	25	57	65	74	84	97	111	119	129	142	159	182	214	262	326	329	333
		% water unfrozen	—	8	14	16	18	20	23	27	29	33	37	42	50	61	78	100	—	—
Raspberries	82.7	Enthalpy, kJ/kg	0	20	47	53	59	65	75	85	90	97	105	115	129	148	174	231	340	344
		% water unfrozen	—	—	7	8	9	10	13	16	17	18	20	23	27	33	42	61	100	—
Spinach	90.2	Enthalpy, kJ/kg	0	19	40	44	49	54	60	66	70	74	79	86	94	103	117	145	224	371
		% water unfrozen	—	—	—	—	—	—	6	7	—	—	9	11	13	16	19	28	53	100
Strawberries	89.3	Enthalpy, kJ/kg	0	20	44	49	54	60	67	76	81	88	95	102	114	127	150	191	318	367
		% water unfrozen	—	—	5	—	6	7	9	11	12	14	16	18	20	24	30	43	86	100
Sweet cherries, without stones	77.0	Enthalpy, kJ/kg	0	26	58	66	76	87	100	114	123	133	149	166	190	225	276	317	320	324
		% water unfrozen	—	9	15	17	19	21	26	29	32	36	40	47	55	67	86	100	—	—
Tall peas	75.8	Enthalpy, kJ/kg	0	23	51	56	64	73	84	95	102	111	121	133	152	176	212	289	319	323
		% water unfrozen	—	6	10	12	14	16	18	21	23	26	28	33	39	48	61	90	100	—
Tomato pulp	92.9	Enthalpy, kJ/kg	0	20	42	47	52	57	63	71	75	81	87	93	103	114	131	166	266	382
		% water unfrozen	—	—	—	—	5	—	6	7	8	10	12	14	16	18	24	33	65	100
Fish and Meat																				
Cod	80.3	Enthalpy, kJ/kg	0	19	42	47	53	59	66	74	79	84	89	96	105	118	137	177	298	323
		% water unfrozen	10	10	11	12	12	13	14	16	17	18	19	21	23	27	34	48	92	100
Haddock	83.6	Enthalpy, kJ/kg	0	19	42	47	53	59	66	73	77	82	88	95	104	116	136	177	307	337
		% water unfrozen	8	8	9	10	11	11	12	13	14	15	16	18	20	24	31	44	90	100
Perch	79.1	Enthalpy, kJ/kg	0	19	41	46	52	58	65	72	76	81	86	93	101	112	129	165	284	318
		% water unfrozen	10	10	11	12	12	13	14	15	16	17	18	20	22	26	32	44	87	100
Beef, lean, fresh[a]	74.5	Enthalpy, kJ/kg	0	19	42	47	52	58	65	72	76	81	88	95	105	113	138	180	285	304
		% water unfrozen	10	10	11	12	13	14	15	16	17	18	20	22	24	31	40	55	95	100
lean, dried	26.1	Enthalpy, kJ/kg	0	19	42	47	53	62	66	70	72	74	—	79	—	84	—	89	—	93
		% water unfrozen	96	96	97	98	99	100	—	—	—	—	—	—	—	—	—	—	—	—
Eggs																				
White	86.5	Enthalpy, kJ/kg	0	18	39	43	48	53	58	65	68	72	75	81	87	96	109	134	210	352
		% water unfrozen	—	—	10	—	—	—	—	13	—	—	—	18	20	23	28	40	82	100
Yolk	50.0	Enthalpy, kJ/kg	0	18	39	43	48	53	59	65	68	71	75	80	85	91	99	113	155	228
		% water unfrozen	—	—	—	—	—	—	—	16	—	—	—	—	21	22	27	34	60	100
	40.0	Enthalpy, kJ/kg	0	19	40	45	50	56	62	68	72	76	80	85	92	99	109	128	182	191
		% water unfrozen	20	—	—	22	—	24	—	27	28	29	31	33	35	38	45	58	94	100
Whole, with shell[b]	66.4	Enthalpy, kJ/kg	0	17	36	40	45	50	55	61	64	67	71	75	81	88	98	117	175	281
Bread																				
White	37.3	Enthalpy, kJ/kg	0	17	35	39	44	49	56	67	75	83	93	104	117	124	128	131	134	137
Whole wheat	42.4	Enthalpy, kJ/kg	0	17	36	41	48	56	66	78	86	95	106	119	135	150	154	157	160	163

Source: Adapted from Dickerson (1968) and Riedel (1951, 1956, 1957a, 1957b, 1959).
[a]Data for chicken, veal, and venison nearly matched data for beef of same water content (Riedel 1957a, 1957b)
[b]Calculated for mass composition of 58% white (86.5% water) and 32% yolk (50% water).

the food product. For example, in the case of frozen food, the thermal conductivity of the ice and liquid water mix is calculated first by using one of the earlier methods mentioned. The resulting thermal conductivity of the ice/water mix is then combined successively with the thermal conductivity of each remaining food constituent to determine the thermal conductivity of the food product.

Numerous researchers have proposed using parallel and perpendicular (or series) thermal conductivity models based on analogies with electrical resistance (Murakami and Okos 1989). The parallel model is the sum of the thermal conductivities of the food constituents multiplied by their volume fractions:

$$k = \sum x_i^v k_i \tag{35}$$

where x_i^v is the volume fraction of constituent i. The volume fraction of constituent i can be found from the following equation:

$$x_i^v = \frac{x_i/\rho_i}{\sum(x_i/\rho_i)} \tag{36}$$

The perpendicular model is the reciprocal of the sum of the volume fractions divided by their thermal conductivities:

$$k = \frac{1}{\sum(x_i^v/k_i)} \tag{37}$$

These two models have been found to predict the upper and lower bounds of the thermal conductivity of most foods.

Tables 5 and 6 list the thermal conductivities for many foods (Qashou et al. 1972). Data in these tables have been averaged, interpolated, extrapolated, selected, or rounded off from the original research data. Tables 5 and 6 also include ASHRAE research data on foods of low and intermediate moisture content (Sweat 1985).

Example 4. Determine the thermal conductivity and density of lean pork shoulder meat at –40°C. Use both the parallel and perpendicular thermal conductivity models.

Solution:

From Table 3, the composition of lean pork shoulder meat is:

$$x_{wo} = 0.7263 \qquad x_f = 0.0714$$
$$x_p = 0.1955 \qquad x_a = 0.0102$$

In addition, the initial freezing point of lean pork shoulder meat is –2.2°C. Because the pork's temperature is below the initial freezing point, the fraction of ice in the pork must be determined. Using Equation (4), the ice fraction becomes

$$x_{ice} = (x_{wo} - x_b)\left(1 - \frac{t_f}{t}\right) = (x_{wo} - 0.4x_p)\left(1 - \frac{t_f}{t}\right)$$
$$= [0.7263 - (0.4)(0.1955)]\left(1 - \frac{-2.2}{-40}\right) = 0.6125$$

The mass fraction of unfrozen water is then

$$x_w = x_{wo} - x_{ice} = 0.7263 - 0.6125 = 0.1138$$

Using the equations in Tables 1 and 2, the density and thermal conductivity of the food constituents are calculated at the given temperature –40°C:

$$\rho_w = 9.9718 \times 10^2 + 3.1439 \times 10^{-3}(-40) - 3.7574 \times 10^{-3}(-40)^2$$
$$= 991.04 \text{ kg/m}^3$$

$$\rho_{ice} = 9.1689 \times 10^2 - 1.3071 \times 10^{-1}(-40)$$
$$= 922.12 \text{ kg/m}^3$$

$$\rho_p = 1.3299 \times 10^3 - 5.1840 \times 10^{-1}(-40)$$
$$= 1350.6 \text{ kg/m}^3$$

$$\rho_f = 9.2559 \times 10^2 - 4.1757 \times 10^{-1}(-40)$$
$$= 942.29 \text{ kg/m}^3$$

$$\rho_a = 2.4238 \times 10^3 - 2.8063 \times 10^{-1}(-40)$$
$$= 2435.0 \text{ kg/m}^3$$

$$k_w = 5.7109 \times 10^{-1} + 1.7625 \times 10^{-3}(-40) - 6.7036 \times 10^{-6}(-40)^2$$
$$= 0.4899 \text{ W/(m·K)}$$

$$k_{ice} = 2.2196 - 6.2489 \times 10^{-3}(-40) + 1.0154 \times 10^{-4}(-40)^2$$
$$= 2.632 \text{ W/(m·K)}$$

$$k_p = 1.7881 \times 10^{-1} + 1.1958 \times 10^{-3}(-40) - 2.7178 \times 10^{-6}(-40)^2$$
$$= 0.1266 \text{ W/(m·K)}$$

$$k_f = 1.8071 \times 10^{-1} - 2.7604 \times 10^{-3}(-40) - 1.7749 \times 10^{-7}(-40)^2$$
$$= 0.2908 \text{ W/(m·K)}$$

$$k_a = 3.2962 \times 10^{-1} + 1.4011 \times 10^{-3}(-40) - 2.9069 \times 10^{-6}(-40)^2$$
$$= 0.2689 \text{ W/(m·K)}$$

Using Equation (6), the density of lean pork shoulder meat at –40°C can be determined:

$$\sum\frac{x_i}{\rho_i} = \frac{0.6125}{922.12} + \frac{0.1138}{991.04} + \frac{0.1955}{1350.6} + \frac{0.0714}{942.29} + \frac{0.0102}{2435.0}$$
$$= 1.0038 \times 10^{-3}$$

$$\rho = \frac{1 - \varepsilon}{\sum x_i/p_i} = \frac{1 - 0}{1.0038 \times 10^{-3}} = 996 \text{ kg/m}^3$$

Using Equation (36), the volume fractions of the constituents can be found:

$$x_{ice}^v = \frac{x_{ice}/\rho_{ice}}{\sum x_i/\rho_i} = \frac{0.6125/922.12}{1.0038 \times 10^{-3}} = 0.6617$$

$$x_w^v = \frac{x_w/\rho_w}{\sum x_i/p_i} = \frac{0.1138/991.04}{1.0038 \times 10^{-3}} = 0.1144$$

$$x_p^v = \frac{x_p/\rho_p}{\sum x_i/p_i} = \frac{0.1955/1350.6}{1.0038 \times 10^{-3}} = 0.1442$$

$$x_f^v = \frac{x_f/\rho_f}{\sum x_i/p_i} = \frac{0.0714/942.29}{1.0038 \times 10^{-3}} = 0.0755$$

$$x_a^v = \frac{x_a/\rho_a}{\sum x_i/p_i} = \frac{0.0102/2435.0}{1.0038 \times 10^{-3}} = 0.0042$$

Using the parallel model, Equation (35), the thermal conductivity becomes

$$k = \sum x_i^v k_i = (0.6617)(2.632) + (0.1144)(0.4899)$$
$$+ (0.1442)(0.1266) + (0.0755)(0.2908) + (0.0042)(0.2689)$$
$$k = 1.84 \text{ W/(m·K)}$$

Using the perpendicular model, Equation (37), the thermal conductivity becomes

$$k = \frac{1}{\sum x_i^v/k_i} = \left(\frac{0.6617}{2.632} + \frac{0.1144}{0.4899} + \frac{0.1442}{0.1266} + \frac{0.0755}{0.2908} + \frac{0.0042}{0.2689}\right)^{-1}$$
$$k = 0.527 \text{ W/(m·K)}$$

Table 5 Thermal Conductivity of Foods

Food [a]	Thermal Conductivity W/(m·K)	Temperature, °C	Water Content, % by mass	Reference [b]	Remarks
Fruits, Vegetables					
Apples	0.418	8	—	Gane (1936)	Tasmanian French crabapple, whole fruit; 140 g
dried	0.219	23	41.6	Sweat (1985)	Density = 0.86 g/cm^3
Apple juice	0.559	20	87	Riedel (1949)	Refractive index at 20°C = 1.35
	0.631	80	87		
	0.504	20	70		Refractive index at 20°C = 1.38
	0.564	80	70		
	0.389	20	36		Refractive index at 20°C = 1.45
	0.435	80	36		
Applesauce	0.549	29	—	Sweat (1974)	
Apricots, dried	0.375	23	43.6	Sweat (1985)	Density = 1.32 g/cm^3
Beans, runner	0.398	9	—	Smith et al. (1952)	Density = 0.75 g/cm^3; machine sliced, scalded, packed in slab
Beets	0.601	28	87.6	Sweat (1974)	
Broccoli	0.385	–6	—	Smith et al. (1952)	Density = 0.56 g/cm^3; heads cut and scalded
Carrots	0.669	–16	—	Smith et al. (1952)	Density = 0.6 g/cm^3; scraped, sliced and scalded
pureed	1.26	–8	—	Smith et al. (1952)	Density = 0.89 g/cm^3; slab
Currants, black	0.310	–17	—	Smith et al. (1952)	Density = 0.64 g/cm^3
Dates	0.337	23	34.5	Sweat (1985)	Density = 1.32 g/cm^3
Figs	0.310	23	40.4	Sweat (1985)	Density = 1.24 g/cm^3
Gooseberries	0.276	–15	—	Smith et al. (1952)	Density = 0.58 g/cm^3; mixed sizes
Grapefruit juice vesicle	0.462	30	—	Bennett et al. (1964)	Marsh, seedless
Grapefruit rind	0.237	28	—	Bennett et al. (1964)	Marsh, seedless
Grape, green, juice	0.567	20	89	Riedel (1949)	Refractive index at 20°C = 1.35
	0.639	80	89		
	0.496	20	68		Refractive index at 20°C = 1.38
	0.554	80	68		
	0.396	20	37		Refractive index at 20°C = 1.45
	0.439	80	37		
	0.439	25	—	Turrell and Perry (1957)	Eureka
Grape jelly	0.391	20	42.0	Sweat (1985)	Density = 1.32 g/cm^3
Nectarines	0.585	8.6	82.9	Sweat (1974)	
Onions	0.575	8.6	—	Saravacos (1965)	
Orange juice vesicle	0.435	30	—	Bennett et al. (1964)	Valencia
Orange rind	0.179	30	—	Bennett et al. (1964)	Valencia
Peas	0.480	–13	—	Smith et al. (1952)	Density = 0.70 g/cm^3; shelled and scalded
	0.395	–3	—		
	0.315	7	—		
Peaches, dried	0.361	23	43.4	Sweat (1985)	Density = 1.26 g/cm^3
Pears	0.595	8.7	—	Sweat (1974)	
Pear juice	0.550	20	85	Riedel (1949)	Refractive index at 20°C = 1.36
	0.629	80	85		
	0.475	20	60		Refractive index at 20°C = 1.40
	0.532	80	60		
	0.402	20	39		Refractive index at 20°C = 1.44
	0.446	80	39		
Plums	0.247	–16	—	Smith et al. (1952)	Density = 0.61 g/cm^3; 40 mm dia.; 50 mm long
Potatoes, mashed	1.09	–13	—	Smith et al. (1952)	Density = 0.97 g/cm^3; tightly packed slab
Potato salad	0.479	2	—	Dickerson and Read (1968)	Density = 1.01 g/cm^3
Prunes	0.375	23	42.9	Sweat (1985)	Density = 1.22 g/cm^3
Raisins	0.336	23	32.2	Sweat (1985)	Density = 1.38 g/cm^3
Strawberries	1.10	–14	—	Smith et al. (1952)	Mixed sizes, density = 0.80 g/cm^3, slab
	0.96	–15	—		Mixed sizes in 57% sucrose syrup, slab
Strawberry jam	0.338	20	41.0	Sweat (1985)	Density = 1.31 g/cm^3
Squash	0.502	8	—	Gane (1936)	
Meat and Animal By-Products					
Beef, lean =[a]	0.506	3	75	Lentz (1961)	Sirloin; 0.9% fat
	1.42	–15	75		
	0.430	20	79	Hill et al. (1967)	1.4% fat
	1.43	–15	79		
	0.400	6	76.5	Hill (1966), Hill et al. (1967)	2.4% fat
	1.36	–15	76.5		
⊥[a]	0.480	20	79	Hill et al. (1967)	Inside round; 0.8% fat
	1.35	–15	79		
	0.410	6	76	Hill (1966), Hill et al. (1967)	3% fat
	1.14	–15	76		
	0.471	3	74	Lentz (1961)	Flank; 3 to 4% fat
	1.12	–15	74		
ground	0.406	6	67	Qashou et al. (1970)	12.3% fat; density = 0.95 g/cm^3
	0.410	4	62		16.8% fat; density = 0.98 g/cm^3
	0.351	6	55		18% fat; density = 0.93 g/cm^3

Table 5 Thermal Conductivity of Foods (*Continued*)

Food [a]	Thermal Conductivity W/(m·K)	Temper-ature, °C	Water Content, % by mass	Reference [b]	Remarks
Beef ground (*continued*)	0.364	3	53		22% fat; density = 0.95 g/cm^3
Beef brain	0.496	35	77.7	Poppendick et al. (1965-1966)	12% fat; 10.3% protein; density = 1.04 g/cm^3
Beef fat	0.190	35	0.0	Poppendick et al. (1965-1966)	Melted 100% fat; density = 0.81 g/cm^3
	0.230	35	20		Density = 0.86 g/cm^3
⊥[a]	0.217	2	9	Lentz (1961)	89% fat
	0.287	–9	9		
Beef kidney	0.524	35	76.4	Poppendick et al. (1965-1966)	8.3% fat, 15.3% protein; density = 1.02 g/cm^3
Beef liver	0.488	35	72	Poppendick et al. (1965-1966)	7.2% fat, 20.6% protein
Beefstick	0.297	20	36.6	Sweat (1985)	Density = 1.05 g/cm^3
Bologna	0.421	20	64.7	Sweat (1985)	Density = 1.00 g/cm^3
Dog food	0.319	23	30.6	Sweat (1985)	Density = 1.24 g/cm^3
Cat food	0.326	23	39.7	Sweat (1985)	Density = 1.14 g/cm^3
Ham, country	0.480	20	71.8	Sweat (1985)	Density = 1.03 g/cm^3
Horse meat ⊥[a]	0.460	30	70	Griffiths and Cole (1948)	Lean
Lamb ⊥[a]	0.456	20	72	Hill et al. (1967)	8.7% fat
	1.12	–15	72		
=[a]	0.399	20	71	Hill et al. (1967)	9.6% fat
	1.27	–15	71		
Pepperoni	0.256	20	32.0	Sweat (1985)	Density = 1.06 g/cm^3
Pork fat	0.215	3	6	Lentz (1961)	93% fat
	0.218	–15	6		
Pork, lean =[a]	0.453	20	76	Hill et al. (1967)	6.7% fat
	1.42	–13	76		
⊥[a]	0.505	20	76	Hill et al. (1967)	6.7% fat
	1.30	–14	76		
lean flank	0.460	2.2	—	Lentz (1961)	3.4% fat
	1.22	–15	—		
lean leg =[a]	0.478	4	72	Lentz (1961)	6.1% fat
	1.49	–15	72		
⊥[a]	0.456	4	72	Lentz (1961)	6.1% fat
	1.29	–15	72		
Salami	0.311	20	35.6	Sweat (1985)	Density = 0.96 g/cm^3
Sausage	0.427	25	68	Nowrey and Woodams (1968),	Mixture of beef and pork; 16.1% fat, 12.2% protein
	0.385	25	62	Woodams (1965)	Mixture of beef and pork; 24.1% fat, 10.3% protein
Veal ⊥[a]	0.470	20	75	Hill et al. (1967)	2.1% fat
	1.38	–15	75		
=[a]	0.445	28	75	Hill et al. (1967)	2.1% fat
	1.46	–15	75		
Poultry and Eggs					
Chicken breast ⊥[a]	0.412	20	69 to 75	Walters and May (1963)	0.6% fat
with skin	0.366	20	58 to 74	Walters and May (1963)	0 to 30% fat
Turkey, breast ⊥[a]	0.496	3	74	Lentz (1961)	2.1% fat
	1.38	–15	74		
leg ⊥[a]	0.497	4	74	Lentz (1961)	3.4% fat
	1.23	–15	74		
breast = ⊥[a]	0.502	3	74	Lentz (1961)	2.1% fat
	1.53	–15	74		
Egg, white	0.558	36	88	Spells (1958, 1960-1961)	
whole	0.960	–8	—	Smith et al. (1952)	Density = 0.98 g/cm^3
yolk	0.420	31	50.6	Poppendick et al. (1965-1966)	32.7% fat; 16.7% protein, density = 1.02 g/cm^3
Fish and Sea Products					
Fish, cod ⊥[a]	0.534	3	83	Lentz (1961)	0.1% fat
	1.46	–15	83		
cod	0.560	1	—	Jason and Long (1955), Long (1955)	
	1.69	–15	—	Long (1955)	
Fish, herring	0.80	–19	—	Smith et al. (1952)	Density = 0.91 g/cm^3; whole and gutted
Fish, salmon ⊥[a]	0.531	3	67	Lentz (1961)	12% fat; *Salmo salar* from Gaspe peninsula
	1.24	–15	67		
	0.498	5	73	Lentz (1961)	5.4% fat; *Oncorhynchus tchawytscha* from
	1.13	–15	73		British Columbia
Seal blubber ⊥[a]	0.197	5	4.3	Lentz (1961)	95% fat
Whale blubber ⊥[a]	0.209	18	—	Griffiths and Cole (1948)	Density = 1.04 g/cm^3
Whale meat	0.649	32	—	Griffiths and Hickman (1951)	Density = 1.07 g/cm^3
	1.44	–9	—		
	1.28	–12	—	Smith et al. (1952)	0.51% fat; density = 1.00 g/cm^3
Dairy Products					
Butterfat	0.173	6	0.6	Lentz (1961)	
	0.179	–15	0.6		

Table 5 Thermal Conductivity of Foods (*Continued*)

Food[a]	Thermal Conductivity W/(m·K)	Temperature, °C	Water Content, % by mass	Reference[b]	Remarks
Butter	0.197	4	—	Hooper and Chang (1952)	
Buttermilk	0.569	20	89	Riedel (1949)	0.35% fat
Milk, whole	0.580	28	90	Leidenfrost (1959)	3% fat
	0.522	2	83	Riedel (1949)	3.6% fat
	0.550	20	83		
	0.586	50	83		
	0.614	80	83		
skimmed	0.538	2	90	Riedel (1949)	0.1% fat
	0.566	20	90		
	0.606	50	90		
	0.635	80	90		
evaporated	0.486	2	72	Riedel (1949)	4.8% fat
	0.504	20	72		
	0.542	50	72		
	0.565	80	72		
	0.456	2	62	Riedel (1949)	6.4% fat
	0.472	20	62		
	0.510	50	62		
	0.531	80	62		
	0.472	23	67	Leidenfrost (1959)	10% fat
	0.504	41	67		
	0.516	60	67		
	0.527	79	67		
	0.324	26	50	Leidenfrost (1959)	15% fat
	0.340	40	50		
	0.357	59	50		
	0.364	79	50		
Whey	0.540	2	90	Riedel (1949)	No fat
	0.567	20	90		
	0.630	50	90		
	0.640	80	90		
Sugar, Starch, Bakery Products, and Derivatives					
Sugar beet juice	0.550	25	79	Khelemskii and Zhadan (1964)	
	0.569	25	82		
Sucrose solution	0.535	0	90	Riedel (1949)	Cane or beet sugar solution
	0.566	20	90		
	0.607	50	90		
	0.636	80	90		
	0.504	0	80		
	0.535	20	80		
	0.572	50	80		
	0.600	80	80		
	0.473	0	70		
	0.501	20	70		
	0.536	50	70		
	0.563	80	70		
	0.443	0	60		
	0.470	20	60		
	0.502	50	60		
	0.525	80	60		
	0.413	0	50		
	0.437	20	50		
	0.467	50	93 to 80		
	0.490	80	93 to 80		
	0.382	0	40		
	0.404	20	40		
	0.434	50	40		
	0.454	80	40		
Glucose solution	0.539	2	89	Riedel (1949)	
	0.566	20	89		
	0.601	50	89		
	0.639	80	89		
	0.508	2	80		
	0.535	20	80		
	0.571	50	80		

Table 5 Thermal Conductivity of Foods (*Continued*)

Food [a]	Thermal Conductivity W/(m·K)	Temperature, °C	Water Content, % by mass	Reference[b]	Remarks
Glucose solution (*continued*)					
	0.599	80	80		
	0.478	2	70		
	0.504	20	70		
	0.538	50	70		
	0.565	80	70		
	0.446	2	60		
	0.470	20	60		
	0.501	50	60		
	0.529	80	60		
Corn syrup	0.562	25	—	Metzner and Friend (1959)	Density = 1.16 g/cm^3
	0.484	25	—		Density = 1.31 g/cm^3
	0.467	25	—		Density = 1.34 g/cm^3
Honey	0.502	2	80	Reidy (1968)	
	0.415	69	80		
Molasses syrup	0.346	30	23	Popov and Terentiev (1966)	
Cake, angel food	0.099	23	36.1	Sweat (1985)	Density = 0.15 g/cm^3, porosity: 88%
applesauce	0.079	23	23.7	Sweat (1985)	Density = 0.30 g/cm^3, porosity: 78%
carrot	0.084	23	21.6	Sweat (1985)	Density = 0.32 g/cm^3, porosity: 75%
chocolate	0.106	23	31.9	Sweat (1985)	Density = 0.34 g/cm^3, porosity: 74%
pound	0.131	23	22.7	Sweat (1985)	Density = 0.48 g/cm^3, porosity: 58%
yellow	0.110	23	25.1	Sweat (1985)	Density = 0.30 g/cm^3, porosity: 78%
white	0.082	23	32.3	Sweat (1985)	Density = 0.45 g/cm^3, porosity: 62%
Grains, Cereals, and Seeds					
Corn, yellow	0.140	32	0.9	Kazarian (1962)	Density = 0.75 g/cm^3
	0.159	32	14.7		Density = 0.75 g/cm^3
	0.172	32	30.2		Density = 0.68 g/cm^3
Flaxseed	0.115	32	—	Griffiths and Hickman (1951)	Density = 0.66 g/cm^3
Oats, white English	0.130	27	12.7	Oxley (1944)	
Sorghum	0.131	5	13	Miller (1963)	Hybrid Rs610 grain
	0.150		22		
Wheat, No. 1 northern hard spring	0.135	34	2	Moote (1953)	Values taken from plot of series of values given by authors
	0.149	—	7	Babbitt (1945)	
	0.155	—	10		
	0.168	—	14		
Wheat, soft white winter	0.121	31	5	Kazarian (1962)	Values taken from plot of series of values given by author; Density = 0.78 g/cm^3
	0.129	31	10		
	0.137	31	15		
Fats, Oils, Gums, and Extracts					
Gelatin gel	0.522	5	94 to 80	Lentz (1961)	Conductivity did not vary with concentration in range tested (6, 12, 20%)
	2.14	–15	94		6% gelatin concentration
	1.94	–15	88		12% gelatin concentration
	1.41	–15	80		20% gelatin concentration
Margarine	0.233	5	—	Hooper and Chang (1952)	Density = 1.00 g/cm^3
Oil, almond	0.176	4	—	Wachsmuth (1892)	Density = 0.92 g/cm^3
cod liver	0.170	35	—	Spells (1958), Spells (1960-1961)	
lemon	0.156	6	—	Weber (1880)	Density = 0.82 g/cm^3
mustard	0.170	25	—	Weber (1886)	Density = 1.02 g/cm^3
nutmeg	0.156	4	—	Wachsmuth (1892)	Density = 0.94 g/cm^3
olive	0.175	7	—	Weber (1880)	Density = 0.91 g/cm^3
olive	0.168	32	—	Kaye and Higgins (1928)	Density = 0.91 g/cm^3
	0.166	65	—		
	0.160	151	—		
	0.156	185	—		
peanut	0.168	4	—	Wachsmuth (1892)	Density = 0.92 g/cm^3
	0.169	25	—	Woodams (1965)	
rapeseed	0.160	20	—	Kondrat'ev (1950)	Density = 0.91 g/cm^3
sesame	0.176	4	—	Wachsmuth (1892)	Density = 0.92 g/cm^3

[a] ⊥ indicates heat flow perpendicular to grain structure, and = indicates heat flow parallel to grain structure.
[b] References quoted are those on which given data are based, although actual values in this table may have been averaged, interpolated, extrapolated, selected, or rounded off.

Table 6 Thermal Conductivity of Freeze-Dried Foods

Food	Thermal Conductivity, W/(m·K)	Temperature, °C	Pressure, Pa	Reference[b]	Remarks
Apple	0.0156	35	2.66	Harper (1960, 1962)	Delicious; 88% porosity; 5.1 tortuosity factor; measured in air
	0.0185	35	21.0		
	0.0282	35	187		
	0.0405	35	2880		
Peach	0.0164	35	6.0	Harper (1960, 1962)	Clingstone; 91% porosity; 4.1 tortuosity factor; measured in air
	0.0185	35	21.5		
	0.0279	35	187		
	0.0410	35	2670		
	0.0431	35	51000		
Pears	0.0186	35	2.13	Harper (1960, 1962)	97% porosity; measured in nitrogen
	0.0207	35	19.5		
	0.0306	35	187		
	0.0419	35	2150		
	0.0451	35	68900		
Beef =[a]	0.0382	35	1.46	Harper (1960, 1962)	Lean; 64% porosity; 4.4 tortuosity factor; measured in air
	0.0412	35	22.7		
	0.0532	35	238		
	0.0620	35	2700		
	0.0652	35	101 000		
Egg albumin gel	0.0393	41	101 000	Saravacos and Pilsworth (1965)	2% water content; measured in air
	0.0129	41	4.40	Saravacos and Pilsworth (1965)	Measured in air
Turkey =[a]	0.0287	—	5.33	Triebes and King (1966)	Cooked white meat; 68 to 72% porosity; measured in air
	0.0443	—	15.0		
	0.0706	—	467		
	0.0861	—	2130		
	0.0927	—	98 500		
⊥[a]	0.0170	—	5.60	Triebes and King (1966)	Cooked white meat; 68 to 72% porosity; measured in air
	0.0174	—	18.9		
	0.0221	—	133		
	0.0417	—	1250		
	0.0586	—	87 600		
Potato starch gel	0.0091	—	4.3	Saravacos and Pilsworth (1965)	Measured in air
	0.0144	—	181		
	0.0291	—	2210		
	0.0393	—	102 700		

[a]⊥ indicates heat flow perpendicular to grain structure, and = indicates heat flow parallel to grain structure.
[b]References quoted are those on which given data are based, although actual values in this table may have been averaged, interpolated, extrapolated, selected, or rounded off.

Example 5. Determine the thermal conductivity and density of lean pork shoulder meat at a temperature of –40°C. Use the isotropic model developed by Kopelman (1966).

Solution:

From Table 3, the composition of lean pork shoulder meat is

$x_{wo} = 0.7263$ $\quad x_f = 0.0714$

$x_p = 0.1955$ $\quad x_a = 0.0102$

In addition, the initial freezing point of lean pork shoulder is –2.2°C. Because the pork's temperature is below the initial freezing point, the fraction of ice within the pork must be determined. From Example 4, the ice fraction was found to be

$$x_{ice} = 0.6125$$

The mass fraction of unfrozen water is then

$$x_w = x_{wo} - x_{ice} = 0.7263 - 0.6125 = 0.1138$$

Using the equations in Tables 1 and 2, the density and thermal conductivity of the food constituents are c1alculated at the given temperature, –40°C (refer to Example 4):

$\rho_w = 991.04$ kg/m^3 $\quad k_w = 0.4899$ W/(m·K)

$\rho_{ice} = 922.12$ kg/m^3 $\quad k_{ice} = 2.632$ W/(m·K)

$\rho_p = 1350.6$ kg/m^3 $\quad k_p = 0.1266$ W/(m·K)

$\rho_f = 942.29$ kg/m^3 $\quad k_f = 0.2908$ W/(m·K)

$\rho_a = 2435.0$ kg/m^3 $\quad k_a = 0.2689$ W/(m·K)

Now, determine the thermal conductivity of the ice/water mixture. This requires the volume fractions of the ice and water:

$$x_w^v = \frac{x_w/\rho_w}{\sum \frac{x_i}{\rho_i}} = \frac{0.1138/991.04}{\frac{0.1138}{991.04} + \frac{0.6125}{922.12}} = 0.1474$$

$$x_{ice}^v = \frac{x_{ice}/\rho_{ice}}{\sum \frac{x_i}{\rho_i}} = \frac{0.6125/922.12}{\frac{0.1138}{991.04} + \frac{0.6125}{922.12}} = 0.8526$$

Note that the volume fractions calculated for the two-component ice/water mixture are different from those calculated in Example 4 for lean pork shoulder meat. Because the ice has the largest volume fraction in the two-component ice/water mixture, consider the ice to be the "continuous" phase. Then, L from Equation (27) becomes

$$L^3 = x_w^v = 0.1474$$

$$L^2 = 0.2790$$

$$L = 0.5282$$

Because $k_{ice} > k_w$ and the ice is the continuous phase, the thermal conductivity of the ice/water mixture is calculated using Equation (27):

$$k_{ice/water} = k_{ice}\left[\frac{1-L^2}{1-L^2(1-L)}\right]$$

$$= 2.632\left[\frac{1-0.2790}{1-0.2790(1-0.5282)}\right] = 2.1853\ \text{W/(m·K)}$$

The density of the ice/water mixture then becomes

$$\rho_{ice/water} = x_w^v\rho_w + x_{ice}^v$$
$$= (0.1474)(991.04) + (0.8526)(922.12)$$
$$= 932.28\ \text{kg/m}^3$$

Next, find the thermal conductivity of the ice/water/protein mixture. This requires the volume fractions of the ice/water and the protein:

$$x_p^v = \frac{x_p/\rho_p}{\sum\frac{x_i}{\rho_i}} = \frac{0.1955/1350.6}{\frac{0.1955}{1350.6}+\frac{0.7263}{932.28}} = 0.1567$$

$$x_{ice/water}^v = \frac{x_{ice/water}/\rho_{ice/water}}{\sum\frac{x_i}{\rho_i}} = \frac{0.7263/932.28}{\frac{0.1955}{1350.6}+\frac{0.7263}{932.28}} = 0.8433$$

Note that these volume fractions are calculated based on a two-component system composed of ice/water as one constituent and protein as the other. Because protein has the smaller volume fraction, consider it to be the discontinuous phase.

$$L^3 = x_p^v = 0.1567$$
$$L^2 = 0.2907$$
$$L = 0.5391$$

Thus, the thermal conductivity of the ice/water/protein mixture becomes

$$k_{ice/water/protein} = k_{ice/water}\left[\frac{1-L^2}{1-L^2(1-L)}\right]$$

$$= 2.1853\left[\frac{1-0.2907}{1-0.2907(1-0.5391)}\right]$$

$$= 1.7898\ \text{W/(m·K)}$$

The density of the ice/water/protein mixture then becomes

$$\rho_{ice/water/protein} = x_{ice/water}^v\rho_{ice/water} + x_p^v\rho_p$$
$$= (0.8433)(932.28) + (0.1567)(1350.6)$$
$$= 997.83\ \text{kg/m}^3$$

Next, find the thermal conductivity of the ice/water/protein/fat mixture. This requires the volume fractions of the ice/water/protein and the fat:

$$x_f^v = \frac{x_f/\rho_f}{\sum\frac{x_i}{\rho_i}} = \frac{0.0714/942.29}{\frac{0.0714}{942.29}+\frac{0.9218}{997.83}} = 0.0758$$

$$x_{i/w/p}^v = \frac{x_{i/w/p}/\rho_{i/w/p}}{\sum\frac{x_i}{\rho_i}} = \frac{0.9218/997.83}{\frac{0.0714}{942.29}+\frac{0.9218}{997.83}} = 0.9242$$

$$L^3 = x_f^v = 0.0758$$
$$L^2 = 0.1791$$
$$L = 0.4232$$

Thus, the thermal conductivity of the ice/water/protein/fat mixture becomes

$$k_{i/w/p/f} = k_{i/w/p}\left[\frac{1-L^2}{1-L^2(1-L)}\right]$$

$$= 1.7898\left[\frac{1-0.1791}{1-0.1791(1-0.4232)}\right]$$

$$= 1.639\ \text{W/(m·K)}$$

The density of the ice/water/protein/fat mixture then becomes

$$\rho_{i/w/p/f} = x_{i/w/p}^v\rho_{i/w/p} + x_f^v\rho_f$$
$$= (0.9242)(997.83) + (0.0758)(942.29)$$
$$= 993.62\ \text{kg/m}^3$$

Finally, the thermal conductivity of the lean pork shoulder meat can be found. This requires the volume fractions of the ice/water/protein/fat and the ash:

$$x_a^v = \frac{x_a/\rho_a}{\sum\frac{x_i}{\rho_i}} = \frac{0.0102/2435.0}{\frac{0.0102}{2435.0}+\frac{0.9932}{993.62}} = 0.0042$$

$$x_{i/w/p/f}^v = \frac{\frac{x_{i/w/p/f}}{\rho_{i/w/p/f}}}{\sum\frac{x_i}{\rho_i}} = \frac{\frac{0.9932}{993.62}}{\frac{0.0102}{2435.0}+\frac{0.9932}{993.62}} = 0.9958$$

$$L^3 = x_a^v = 0.0042$$
$$L^2 = 0.0260$$
$$L = 0.1613$$

Thus, the thermal conductivity of the lean pork shoulder meat becomes

$$k_{pork} = k_{i/w/p/f}\left[\frac{1-L^2}{1-L^2(1-L)}\right]$$

$$= 1.639\left[\frac{1-0.0260}{1-0.0260(1-0.1613)}\right]$$

$$= 1.632\ \text{W/(m·K)}$$

The density of the lean pork shoulder meat then becomes

$$\rho_{pork} = x_{i/w/p/f}^v\rho_{i/w/p/f} + x_a^v\rho_a$$
$$= (0.9958)(993.62) + (0.0042)(2435.0)$$
$$= 999.7\ \text{kg/m}^3$$

THERMAL DIFFUSIVITY

For transient heat transfer, the important thermophysical property is thermal diffusivity α, which appears in the Fourier equation:

$$\frac{\partial T}{\partial\theta} = \alpha\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right] \tag{38}$$

where x, y, z are rectangular coordinates, T is temperature, and θ is time. Thermal diffusivity can be defined as follows:

$$\alpha = \frac{k}{\rho c} \tag{39}$$

where α is thermal diffusivity, k is thermal conductivity, ρ is density, and c is specific heat.

Experimentally determined values of food's thermal diffusivity are scarce. However, thermal diffusivity can be calculated using Equation (39), with appropriate values of thermal conductivity, specific heat, and density. A few experimental values are given in Table 7.

Table 7 Thermal Diffusivity of Foods

Food	Thermal Diffusivity, mm^2/s	Water Content, % by mass	Fat Content, % by mass	Apparent Density, kg/m^3	Temperature, °C	Reference
Fruits and Vegetables						
Apple, Red Delicious, whole[a]	0.14	85	—	840	0 to 30	Bennett et al. (1969)
dried	0.096	42	—	856	23	Sweat (1985)
Applesauce	0.11	37	—	—	5	Riedel (1969)
	0.11	37	—	—	65	Riedel (1969)
	0.12	80	—	—	5	Riedel (1969)
	0.14	80	—	—	65	Riedel (1969)
Apricots, dried	0.11	44	—	1323	23	Sweat (1985)
Bananas, flesh	0.12	76	—	—	5	Riedel (1969)
	0.14	76	—	—	65	Riedel (1969)
Cherries, flesh[b]	0.13	—	—	1050	0 to 30	Parker and Stout (1967)
Dates	0.10	35	—	1319	23	Sweat (1985)
Figs	0.096	40	—	1241	23	Sweat (1985)
Jam, strawberry	0.12	41	—	1310	20	Sweat (1985)
Jelly, grape	0.12	42	—	1320	20	Sweat (1985)
Peaches[b]	0.14	—	—	960	2 to 32	Bennett (1963)
dried	0.12	43	—	1259	23	Sweat (1985)
Potatoes, whole	0.13	—	—	1040 to 1070	0 to 70	Mathews and Hall (1968), Minh et al. (1969)
mashed, cooked	0.12	78	—	—	5	Riedel (1969)
	0.15	78	—	—	65	Riedel (1969)
Prunes	0.12	43	—	1219	23	Sweat (1985)
Raisins	0.11	32	—	1380	23	Sweat (1985)
Strawberries, flesh	0.13	92	—	—	5	Riedel (1969)
Sugar beets	0.13	—	—	—	0 to 60	Slavicek et al. (1962)
Meats						
Codfish	0.12	81	—	—	5	Riedel (1969)
	0.14	81	—	—	65	Riedel (1969)
Halibut[c]	0.15	76	1	1070	40 to 65	Dickerson and Read (1975)
Beef, chuck[d]	0.12	66	16	1060	40 to 65	Dickerson and Read (1975)
round[d]	0.13	71	4	1090	40 to 65	Dickerson and Read (1975)
tongue[d]	0.13	68	13	1060	40 to 65	Dickerson and Read (1975)
Beefstick	0.11	37	—	1050	20	Sweat (1985)
Bologna	0.13	65	—	1000	20	Sweat (1985)
Corned beef	0.11	65	—	—	5	Riedel (1969)
	0.13	65	—	—	65	Riedel (1969)
Ham, country	0.14	72	—	1030	20	Sweat (1985)
smoked	0.12	64	—	—	5	Riedel (1969)
smoked[d]	0.13	64	14	1090	40 to 65	Dickerson and Read (1975)
Pepperoni	0.093	32	—	1060	20	Sweat (1985)
Salami	0.13	36	—	960	20	Sweat (1985)
Cakes						
Angel food	0.26	36	—	147	23	Sweat (1985)
Applesauce	0.12	24	—	300	23	Sweat (1985)
Carrot	0.12	22	—	320	23	Sweat (1985)
Chocolate	0.12	32	—	340	23	Sweat (1985)
Pound	0.12	23	—	480	23	Sweat (1985)
Yellow	0.12	25	—	300	23	Sweat (1985)
White	0.10	32	—	446	23	Sweat (1985)

[a]Data apply only to raw whole apple.
[b]Freshly harvested.
[c]Stored frozen and thawed before test.
[d]Data apply only where juices exuded during heating remain in food samples.

HEAT OF RESPIRATION

All living foods respire. During respiration, sugar and oxygen combine to form CO_2, H_2O, and heat as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2667 \text{ kJ} \tag{40}$$

In most stored plant products, little cell development takes place, and the greater part of respiration energy is released as heat, which must be taken into account when cooling and storing these living commodities (Becker et al. 1996a). The rate at which this chemical reaction takes place varies with the type and temperature of the commodity.

Becker et al. (1996b) developed correlations that relate a commodity's rate of carbon dioxide production to its temperature. The carbon dioxide production rate can then be related to the commodity's heat generation rate from respiration. The resulting correlation gives the commodity's respiratory heat generation rate W in W/kg as a function of temperature t in °C:

$$W = \frac{10.7f}{3600}\left(\frac{9t}{5} + 32\right)^g \tag{41}$$

The respiration coefficients f and g for various commodities are given in Table 8.

Table 8 Commodity Respiration Coefficients

Commodity	Respiration Coefficients		Commodity	Respiration Coefficients	
	f	g		f	g
Apples	5.6871×10^{-4}	2.5977	Onions	3.668×10^{-4}	2.538
Blueberries	7.2520×10^{-5}	3.2584	Oranges	2.8050×10^{-4}	2.6840
Brussels sprouts	0.0027238	2.5728	Peaches	1.2996×10^{-5}	3.6417
Cabbage	6.0803×10^{-4}	2.6183	Pears	6.3614×10^{-5}	3.2037
Carrots	0.050018	1.7926	Plums	8.608×10^{-5}	2.972
Grapefruit	0.0035828	1.9982	Potatoes	0.01709	1.769
Grapes	7.056×10^{-5}	3.033	Rutabagas (swedes)	1.6524×10^{-4}	2.9039
Green peppers	3.5104×10^{-4}	2.7414	Snap beans	0.0032828	2.5077
Lemons	0.011192	1.7740	Sugar beets	8.5913×10^{-3}	1.8880
Lima beans	9.1051×10^{-4}	2.8480	Strawberries	3.6683×10^{-4}	3.0330
Limes	2.9834×10^{-8}	4.7329	Tomatoes	2.0074×10^{-4}	2.8350

Source: Becker et al. (1996b).

Fruits, vegetables, flowers, bulbs, florists' greens, and nursery stock are storage commodities with significant heats of respiration. Dry plant products, such as seeds and nuts, have very low respiration rates. Young, actively growing tissues, such as asparagus, broccoli, and spinach, have high rates of respiration, as do immature seeds such as green peas and sweet corn. Fast-developing fruits, such as strawberries, raspberries, and blackberries, have much higher respiration rates than do fruits that are slow to develop, such as apples, grapes, and citrus fruits.

In general, most vegetables, other than root crops, have a high initial respiration rate for the first one or two days after harvest. Within a few days, the respiration rate quickly lowers to the equilibrium rate (Ryall and Lipton 1972).

Fruits that do not ripen during storage, such as citrus fruits and grapes, have fairly constant rates of respiration. Those that ripen in storage, such as apples, peaches, and avocados, increase in respiration rate. At low storage temperatures, around 0°C, the rate of respiration rarely increases because no ripening takes place. However, if fruits are stored at higher temperatures (10°C to 15°C), the respiration rate increases because of ripening and then decreases. Soft fruits, such as blueberries, figs, and strawberries, decrease in respiration with time at 0°C. If they become infected with decay organisms, however, respiration increases.

Table 9 lists the heats of respiration as a function of temperature for a variety of commodities, and Table 10 shows the change in respiration rate with time. Most commodities in Table 9 have a low and a high value for heat of respiration at each temperature. When no range is given, the value is an average for the specified temperature and may be an average of the respiration rates for many days.

When using Table 9, select the lower value for estimating the heat of respiration at equilibrium storage, and use the higher value for calculating the heat load for the first day or two after harvest, including precooling and short-distance transport. In storage of fruits between 0°C and 5°C, the increase in respiration rate caused by ripening is slight. However, for fruits such as mangoes, avocados, or bananas, significant ripening occurs at temperatures above 10°C and the higher rates listed in Table 9 should be used. Vegetables such as onions, garlic, and cabbage can increase heat production after a long storage period.

TRANSPIRATION OF FRESH FRUITS AND VEGETABLES

The most abundant constituent in fresh fruits and vegetables is water, which exists as a continuous liquid phase in the fruit or vegetable. Some of this water is lost through transpiration, which involves the transport of moisture through the skin, evaporation, and convective mass transport of the moisture to the surroundings (Becker et al. 1996b).

The rate of transpiration in fresh fruits and vegetables affects product quality. Moisture transpires continuously from commodities during handling and storage. Some moisture loss is inevitable and can be tolerated. However, under many conditions, enough moisture may be lost to cause shriveling. The resulting loss in mass not only affects appearance, texture, and flavor of the commodity, but also reduces the salable mass (Becker et al. 1996a).

Many factors affect the rate of transpiration from fresh fruits and vegetables. Moisture loss is driven by a difference in water vapor pressure between the product surface and the environment. Becker and Fricke (1996a) state that the product surface may be assumed to be saturated, and thus the water vapor pressure at the commodity surface is equal to the water vapor saturation pressure evaluated at the product's surface temperature. However, they also report that dissolved substances in the moisture of the commodity tend to lower the vapor pressure at the evaporating surface slightly.

Evaporation at the product surface is an endothermic process that cools the surface, thus lowering the vapor pressure at the surface and reducing transpiration. Respiration within the fruit or vegetable, on the other hand, tends to increase the product's temperature, thus raising the vapor pressure at the surface and increasing transpiration. Furthermore, the respiration rate is itself a function of the commodity's temperature (Gaffney et al. 1985). In addition, factors such as surface structure, skin permeability, and airflow also effect the transpiration rate (Sastry et al. 1978).

Becker et al. (1996c) performed a numerical, parametric study to investigate the influence of bulk mass, airflow rate, skin mass transfer coefficient, and relative humidity on the cooling time and moisture loss of a bulk load of apples. They found that relative humidity and skin mass transfer coefficient had little effect on cooling time, whereas bulk mass and airflow rate were of primary importance. Moisture loss varied appreciably with relative humidity, airflow rate, and skin mass transfer coefficient; bulk mass had little effect. Increased airflow resulted in a decrease in moisture loss; increased airflow reduces cooling time, which quickly reduces the vapor pressure deficit, thus lowering the transpiration rate.

The driving force for transpiration is a difference in water vapor pressure between the surface of a commodity and the surrounding air. Thus, the basic form of the transpiration model is as follows:

$$\dot{m} = k_t(p_s - p_a) \tag{42}$$

where $\dot{m}$ is the transpiration rate expressed as the mass of moisture transpired per unit area of commodity surface per unit time. This rate may also be expressed per unit mass of commodity rather than per unit area of commodity surface. The transpiration coefficient k_t is the mass of moisture transpired per unit area of commodity, per unit water vapor pressure deficit, per unit time. It may also be expressed per unit mass of commodity rather than per unit area of commodity

Table 9 Heat of Respiration for Fresh Fruits and Vegetables at Various Temperatures[a]

	Heat of Respiration (mW/kg)						
Commodity	**0°C**	**5°C**	**10°C**	**15°C**	**20°C**	**25°C**	**Reference**
Apples							
Yellow, transparent	20.4	35.9	—	106.2	166.8	—	Wright et al. (1954)
Delicious	10.2	15.0	—	—	—	—	Lutz and Hardenburg (1968)
Golden Delicious	10.7	16.0	—	—	—	—	Lutz and Hardenburg (1968)
Jonathan	11.6	17.5	—	—	—	—	Lutz and Hardenburg (1968)
McIntosh	10.7	16.0	—	—	—	—	Lutz and Hardenburg (1968)
Early cultivars	9.7-18.4	15.5-31.5	41.2-60.6	53.6-92.1	58.2-121.2	—	IIR (1967)
Late cultivars	5.3-10.7	13.6-20.9	20.4-31.0	27.6-58.2	43.6-72.7	—	IIR (1967)
Average of many cultivars	6.8-12.1	15.0-21.3	—	40.3-91.7	50.0-103.8	—	Lutz and Hardenburg (1968)
Apricots	15.5-17.0	18.9-26.7	33.0-55.8	63.0-101.8	87.3-155.2	—	Lutz and Hardenburg (1968)
Artichokes, globe	67.4-133.4	94.6-178.0	16.2-291.5	22.9-430.2	40.4-692.0	—	Rappaport and Watada (1958), Sastry et al. (1978)
Asparagus	81.0-237.6	162.0-404.5	318.1-904.0	472.3-971.4	809.4-1484.0	—	Lipton (1957), Sastry et al. (1978)
Avocados	*[b]	*[b]	—	183.3-465.6	218.7-1029.1	—	Biale (1960), Lutz and Hardenburg (1968)
Bananas							
Green	*[b]	*[b]	†[b]	59.7-130.9	87.3-155.2	—	IIR (1967)
Ripening	*[b]	*[b]	†[b]	37.3-164.9	97.0-242.5	—	IIR (1967)
Beans							
Lima, unshelled	31.0-89.2	58.2-106.7	—	296.8-369.5	393.8-531.5	—	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
shelled	52.4-103.8	86.3-180.9	—	—	627.0-801.1	—	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
Snap	*[b]	101.4-103.8	162.0-172.6	252.2-276.4	350.6-386.0	—	Ryall and Lipton (1972), Watada and Morris (1966)
Beets, red, roots	16.0-21.3	27.2-28.1	34.9-40.3	50.0-68.9	—	—	Ryall and Lipton (1972), Smith (1957)
Berries							
Blackberries	46.6-67.9	84.9-135.8	155.2-281.3	208.5-431.6	388.0-581.9	—	IIR (1967)
Blueberries	6.8-31.0	27.2-36.4	—	101.4-183.3	153.7-259.0	—	Lutz and Hardenburg (1968)
Cranberries	*[b]	12.1-13.6	—	—	32.5-53.8	—	Anderson et al. (1963), Lutz and Hardenburg (1968)
Gooseberries	20.4-25.7	36.4-40.3	—	64.5-95.5	—	—	Lutz and Hardenburg (1968), Smith (1966)
Raspberries	52.4-74.2	91.7-114.4	82.4-164.9	243.9-300.7	339.5-727.4	—	Haller et al. (1941), IIR (1967), Lutz and Hardenburg (1968)
Strawberries	36.4-52.4	48.5-98.4	145.5-281.3	210.5-273.5	303.1-581.0	501.4-625.6	IIR (1967), Lutz and Hardenburg (1968), Maxie et al. (1959)
Broccoli, sprouting	55.3-63.5	102.3-474.8	—	515.0-1008.2	824.9-1011.1	1155.2-1661.0	Morris (1947), Lutz and Hardenburg (1968), Scholz et al. (1963)
Brussels sprouts	45.6-71.3	95.5-144.0	187.2-250.7	283.2-316.7	267.2-564.0	—	Sastry et al. (1978), Smith (1957)
Cabbage							
Penn State[c]	11.6	28.1-30.1	—	66.4-94.1	—	—	Van den Berg and Lentz (1972)
White, winter	14.5-24.2	21.8-41.2	36.4-53.3	58.2-80.0	106.7-121.2	—	IIR (1967)
spring	28.1-40.3	52.4-63.5	86.3-98.4	159.1-167.7	—	—	Sastry et al. (1978), Smith (1957)
Red, early	22.8-29.1	46.1-50.9	70.3-824.2	109.1-126.1	164.9-169.7	—	IIR (1967)
Savoy	46.1-63.0	75.2-87.3	155.2-181.9	259.5-293.4	388.0-436.5	—	IIR (1967)
Carrots, roots							
Imperator, Texas	45.6	58.2	93.1	117.4	209.0	—	Scholz et al. (1963)
Main crop, United Kingdom	10.2-20.4	17.5-35.9	29.1-46.1	86.8-196.4 at 18°C	—	—	Smith(1957)
Nantes, Canada[d]	9.2	19.9	—	64.0-83.9	—	—	Van den Berg and Lentz (1972)
Cauliflower							
Texas	52.9	60.6	100.4	136.8	238.1	—	Scholz et al. (1963)
United Kingdom	22.8-71.3	58.2-81.0	121.2-144.5	199.8-243.0	—	—	Smith (1957)
Celery							
New York, white	21.3	32.5	—	110.6	191.6	—	Lutz and Hardenburg (1968)
United Kingdom	15.0-21.3	27.2-37.8	58.2-81.0	115.9-124.1 at 18°C	—	—	Smith(1957)
Utah, Canada[e]	15.0	26.7	—	88.3	—	—	Van den Berg and Lentz (1972)
Cherries							
Sour	17.5-39.3	37.8-39.3	—	81.0-148.4	115.9-148.4	157.6-210.5	Hawkins (1929), Lutz and Hardenburg (1968)

Table 9 Heat of Respiration for Fresh Fruits and Vegetables at Various Temperatures[a] (*Continued*)

	Heat of Respiration (mW/kg)						
Commodity	**0°C**	**5°C**	**10°C**	**15°C**	**20°C**	**25°C**	**Reference**
Sweet	12.1-16.0	28.1-41.7	—	74.2-133.4	83.4-94.6	—	Gerhardt et al. (1942), Lutz and Hardenburg (1968), Micke et al. (1965)
Corn, sweet with husk, Texas	126.1	230.4	332.2	483.0	855.5	1207.5	Scholz et al. (1963)
Cucumbers, California	*[b]	*[b]	68.4-85.8 at 13°C	71.3-98.4	92.1-142.6	—	Eaks and Morris (1956)
Figs, Mission	—	23.5-39.3	65.5-68.4	145.5-187.7	168.8-281.8	252.2-281.8	Claypool and Ozbek (1952), Lutz and Hardenburg (1968)
Garlic	8.7-32.5	17.5-28.6	27.2-28.6	32.5-81.0	29.6-53.8	—	Mann and Lewis (1956), Sastry et al. (1978)
Grapes							
Labrusca, Concord	8.2	16.0	—	47.0	97.0	114.4	Lutz (1938), Lutz and Hardenburg (1968)
Vinifera, Emperor	3.9-6.8	9.2-17.5	2.42	29.6-34.9	—	74.2-89.2	Lutz and Hardenburg (1968), Pentzer et al. (1933)
Thompson seedless	5.8	14.1	22.8	—	—	—	Wright et al. (1954)
Ohanez	3.9	9.7	21.3	—	—	—	Wright et al. (1954)
Grapefruit							
California Marsh	*[b]	*[b]	*[b]	34.9	52.4	64.5	Haller et al. (1945)
Florida	*[b]	*[b]	*[b]	37.8	47.0	56.7	Haller et al. (1945)
Horseradish	24.2	32.0	78.1	97.0	132.4	—	Sastry et al. (1978)
Kiwifruit	8.3	19.6	38.9	—	51.9-57.3	—	Saravacos and Pilsworth (1965)
Kohlrabi	29.6	48.5	93.1	145.5	—	—	Sastry et al. (1978)
Leeks	28.1-48.5	58.2-86.3	159.1-202.2	245.4-346.7	—	—	Sastry et al. (1978), Smith (1957)
Lemons, California, Eureka	*[b]	*[b]	*[b]	47.0	67.4	77.1	Haller et al. (1945)
Lettuce							
Head, California	27.2-50.0	39.8-59.2	81.0-118.8	114.4-121.2	178.0	—	Sastry et al. (1978)
Texas	31.0	39.3	64.5	106.7	168.8	2.4 at 27°C	Lutz and Hardenburg, (1968), Watt and Merrill (1963)
Leaf, Texas	68.4	86.8	116.9	186.7	297.8	434.5	Scholz et al. (1963)
Romaine, Texas	—	61.6	105.2	131.4	203.2	321.5	Scholz et al. (1963)
Limes, Persian	*[b]	*[b]	7.8-17.0	17.5-31.0	20.4-55.3	44.6-134.8	Lutz and Hardenburg (1968)
Mangoes	*[b]	*[b]	—	133.4	222.6-449.1	356.0	Gore (1911), Karmarkar and Joshe (1941b), Lutz and Hardenburg (1968)
Melons							
Cantaloupes	*[b]	25.7-29.6	46.1	99.9-114.4	132.4-191.6	184.8-211.9	Lutz and Hardenburg (1968), Sastry et al. (1978), Scholz et al. (1963)
Honeydew	—	*[b]	23.8	34.9-47.0	59.2-70.8	78.1-102.3	Lutz and Hardenburg (1968), Pratt and Morris (1958), Scholz (1963)
Watermelon	*[b]	*[b]	22.3	—	51.4-74.2	—	Lutz and Hardenburg (1968), Scholz et al. (1963)
Mint[l]	23.8-44.5	89.0	225.6-270.1	311.6-403.6	492.7-673.7	762.7-940.8	Hruschka and Want (1979)
Mushrooms	83.4-129.5	210.5	—	—	782.2-938.9	—	Lutz and Hardenburg (1968), Smith (1964)
Nuts (kind not specified)	2.4	4.8	9.7	9.7	14.5	—	IIR (1967)
Okra, Clemson	*[b]	—	259.0	432.6	774.5	1024 at 29°C	Scholz et al. (1963)
Olives, Manzanillo	*[b]	*[b]	—	64.5-115.9	114.4-145.5	121.2-180.9	Maxie et al. (1959)
Onions							
Dry, Autumn Spice[f]	6.8-9.2	10.7-19.9	—	14.7-28.1	—	—	Van den Berg and Lentz (1972)
White Bermuda	8.7	10.2	21.3	33.0	50.0	83.4 at 27°C	Scholz et al. (1963)
Green, New Jersey	31.0-65.9	51.4-202.2	107.2-174.6	195.9-288.6	231.6-460.8	290.0-622.2	Lutz and Hardenburg (1968)
Oranges							
Florida	9.2	18.9	36.4	62.1	89.2	105.2 at 27°C	Haller et al. (1945)
California, w. navel	*[b]	18.9	40.3	67.4	81.0	107.7	Haller et al. (1945)
California, Valencia	*[b]	13.6	34.9	37.8	52.4	62.1	Haller et al. (1945)
Papayas	*[b]	*[b]	33.5	44.6-64.5	—	115.9-291.0	Jones (1942), Pantastico (1974)
Parsley[l]	98.0-136.5	195.9-252.3	388.8-486.7	427.4-661.9	581.7-756.8	914.1-1012.0	Hruschka and Want (1979)

Table 9 Heat of Respiration for Fresh Fruits and Vegetables at Various Temperatures[a] (*Continued*)

Commodity	Heat of Respiration (mW/kg) 0°C	5°C	10°C	15°C	20°C	25°C	Reference
Parsnips							
United Kingdom	34.4-46.1	26.2-51.9	60.6-78.1	95.5-127.1	—	—	Smith (1957)
Canada, Hollow Crown[g]	10.7-24.2	18.4-45.6	—	64.0-137.2	—	—	Van den Berg and Lentz (1972)
Peaches							
Elberta	11.2	19.4	46.6	101.8	181.9	266.7 at 27°C	Haller et al. (1932)
Several cultivars	12.1-18.9	18.9-27.2	—	98.4-125.6	175.6-303.6	241.5-361.3	Lutz and Hardenburg (1968)
Peanuts							
Cured[h]	0.05 at 1.7°C					0.5 at 30°C	Thompson et al. (1951)
Not cured, Virginia Bunch[i]						42.0 at 30°C	Schenk (1959, 1961)
Dixie Spanish						24.5 at 30°C	Schenk (1959, 1961)
Pears							
Bartlett	9.2-20.4	15.0-29.6	—	44.6-178.0	89.2-207.6	—	Lutz and Hardenburg (1968)
Late ripening	7.8-10.7	17.5-41.2	23.3-55.8	82.4-126.1	97.0-218.2	—	IIR (1967)
Early ripening	7.8-14.5	21.8-46.1	21.9-63.0	101.8-160.0	116.4-266.7	—	IIR (1967)
Peas							
Green-in-pod	90.2-138.7	163.4-226.5	—	530.1-600.4	728.4-1072.2	1018.4-1118.3	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
shelled	140.2-224.1	234.7-288.7	—	—	1035-1630	—	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
Peppers, sweet	*[b]	*[b]	42.7	67.9	130.0	—	Scholz et al. (1963)
Persimmons		17.5		34.9-41.7	59.2-71.3	86.3-118.8	Gore (1911), Lutz and Hardenburg (1968)
Pineapple							
Mature green	*[b]	*[b]	165	38.3	71.8	105.2 at 27°C	Scholz et al. (1963)
Ripening	*[b]	*[b]	22.3	53.8	118.3	185.7	Scholz et al. (1963)
Plums, Wickson	5.8-8.7	11.6-26.7	26.7-33.9	35.4-36.9	53.3-77.1	82.9-210.5	Claypool and Allen (1951)
Potatoes							
California white, rose							
immature	*[b]	34.9	41.7-62.1	41.7-91.7	53.8-133.7		Sastry et al. (1978)
mature	*[b]	17.5-20.4	19.7-29.6	19.7-34.9	19.7-47.0		Sastry et al. (1978)
very mature	*[b]	15.0-20.4	20.4	20.4-29.6	27.2-35.4		Sastry et al. (1978)
Katahdin, Canada[j]	*[b]	11.6-12.6		23.3-30.1			Van den Berg and Lentz (1972)
Kennebec	*[b]	10.7-12.6		12.6-26.7			Van den Berg and Lentz (1972)
Radishes							
With tops	43.2-51.4	56.7-62.1	91.7-109.1	207.6-230.8	368.1-404.5	469.4-571.8	Lutz and Hardenburg (1968)
Topped	16.0-17.5	22.8-24.2	44.6-97.0	82.4-97.0	141.6-145.5	199.8-225.5	Lutz and Hardenburg (1968)
Rhubarb, topped	24.2-39.3	32.5-53.8		91.7-134.8	118.8-168.8		Hruschka (1966)
Rutabaga, Laurentian, Canada[k]	5.8-8.2	14.1-15.1		31.5-46.6			Van den Berg and Lentz (1972)
Spinach							
Texas		136.3	328.3	530.5	682.3		Scholz et al. (1963)
United Kingdom, summer	34.4-63.5	81.0-95.5	173.6-222.6		549.0-641.6 at 18°C		Smith (1957)
winter	51.9-75.2	86.8-186.7	202.2-306.5		578.1-722.6 at 18°C		Smith (1957)
Squash							
Summer, yellow, straight-neck	†[b]	†[b]	103.8-109.1	222.6-269.6	252.2-288.6		Lutz and Hardenburg (1968)
Winter butternut	*[b]	*[b]	—	—	—	219.7-362.3	Lutz and Hardenburg (1968)
Sweet Potatoes							
Cured, Puerto Rico	*[b]	*[b]	†[b]	47.5-65.5			Lewis and Morris (1956)
Yellow Jersey	*[b]	*[b]	†[b]	65.5-68.4			Lewis and Morris (1956)
Noncured	*[b]	*[b]	*[b]	84.9		160.5-217.3	Lutz and Hardenburg (1968)
Tomatoes							
Texas, mature green	*[b]	*[b]	*[b]	60.6	102.8	126.6 at 27°C	Scholz et al. (1963)
ripening	*[b]	*[b]	*[b]	79.1	120.3	143.1 at 27°C	Scholz et al. (1963)
California, mature green	*[b]	*[b]	*[b]		71.3-103.8	88.7-142.6	Workman and Pratt (1957)

Table 9 Heat of Respiration for Fresh Fruits and Vegetables at Various Temperatures[a] (*Continued*)

	Heat of Respiration (mW/kg)						
Commodity	**0°C**	**5°C**	**10°C**	**15°C**	**20°C**	**25°C**	**Reference**
Turnip, roots	25.7	28.1-29.6		63.5-71.3	71.3-74.2	—	Lutz and Hardenburg (1968)
Watercress[l]	44.5	133.6	270.1-359.1	403.6-581.7	896.3-1032.8	1032.9-1300.0	Hruschka and Want (1979)

[a]Column headings indicate temperatures at which respiration rates were determined, within 1 K, except where the actual temperatures are given.
[b]The symbol * denotes a chilling temperature. The symbol † denotes the temperature is borderline, not damaging to some cultivars if exposure is short.
[c]Rates are for 30 to 60 days and 60 to 120 days storage, the longer storage having the higher rate, except at 0°C, where they were the same.
[d]Rates are for 30 to 60 days and 120 to 180 days storage, respiration increasing with time only at 15°C.
[e]Rates are for 30 to 60 days storage.
[f]Rates are for 30 to 60 days and 120 to 180 days storage; rates increased with time at all temperatures as dormancy was lost.
[g]Rates are for 30 to 60 days and 120 to 180 days; rates increased with time at all temperatures.
[h]Shelled peanuts with about 7% moisture. Respiration after 60 hours curing was almost negligible, even at 30°C.
[i]Respiration for freshly dug peanuts, not cured, with about 35-40% moisture. During curing, peanuts in the shell were dried-about 5-6% moisture, and in roasting are dried further-about 2% moisture.
[j]Rates are for 30-60 days and 120-180 days with rate declining with time at 5°C but increasing at 15°C as sprouting started.
[k]Rates are for 30-60 days and 120-180 days; rates increased with time, especially at 15°C where sprouting occurred.
[l]Rates are for 1 day after harvest.

Table 10 Change in Respiration Rates with Time

		Heat of Respiration, mW/kg of Produce		
Commodity	**Days in Storage**	**0°C**	**5°C**	**Reference**
Apples, Grimes	7	8.7	38.8 at 10°C	Harding (1929)
	30	8.7	51.9	
	80	8.7	32.5	
Artichokes, globe	1	133.3	177.9	Rappaport and Watada (1958)
	4	74.2	103.8	
	16	44.6	77.1	
Asparagus, Martha Washington	1	237.6	31.2	Lipton (1957)
	3	116.9	193.0	
	16	82.9	89.2	
Beans, lima, in pod	2	88.7	106.7	Tewfik and Scott (1954)
	4	59.6	85.8	
	6	52.4	78.6	
Blueberries, Blue Crop	1	21.3	—	
	2	7.9	—	
		17.0	—	
Broccoli, Waltham 29	1	—	216.7	
	4	—	130.4	
	8	—	97.9	
Corn, sweet, in husk	1	152.3	—	Scholz et al. (1963)
	2	109.1	—	
	4	91.2	—	
Figs, Mission	1	38.8	—	Claypool and Ozbek (1952)
	2	35.4		
	12	35.4	—	
Garlic	10	11.6	26.7	Mann and Lewis (1956)
	30	17.9	44.6	
	180	41.7	97.9	
Lettuce, Great Lakes	1	50.4	59.2	Pratt et al. (1954)
	5	26.7	0.4	
	10	23.8	44.6	
Olives, Manzanillo	1	—	115.9 at 15°C	Maxie et al. (1960)
	5	—	85.8	
	10	—	65.5	
Onions, red	1	4.8	—	Karmarkar and Joshe (1941a)
	30	7.3	—	
	120	9.7	—	
Plums, Wickson	2	5.8	11.6	Claypool and Allen (1951)
	6	5.8	20.8	
	18	8.7	26.7	
Potatoes	2	—	17.9	
	6	—	23.8	
	10	—	20.8	
Strawberries, Shasta	1	52.1	84.9	Maxie et al. (1959)
	2	39.3	91.2	
	5	39.3	97.9	
Tomatoes, Pearson, mature green	5	—	95.0 at 20°C	Workman and Pratt (1957)
	15	—	82.9	
	20	—	71.3	

surface. The quantity $(p_s - p_a)$ is the water vapor pressure deficit. The water vapor pressure at the commodity surface p_s is the water vapor saturation pressure evaluated at the commodity surface temperature; the water vapor pressure in the surrounding air p_a is a function of the relative humidity of the air.

In its simplest form, the transpiration coefficient k_t is considered to be constant for a particular commodity. Table 11 lists values for the transpiration coefficients k_t of various fruits and vegetables (Sastry et al. 1978). Because of the many factors that influence transpiration rate, not all the values in Table 11 are reliable. They are to be used primarily as a guide or as a comparative indication of various commodity transpiration rates obtained from the literature.

Fockens and Meffert (1972) modified the simple transpiration coefficient to model variable skin permeability and to account for airflow rate. Their modified transpiration coefficient takes the following form:

$$k_t = \frac{1}{\dfrac{1}{k_a} + \dfrac{1}{k_s}} \tag{43}$$

where k_a is the air film mass transfer coefficient and k_s is the skin mass transfer coefficient. The variable k_a describes the convective mass transfer that occurs at the surface of the commodity and is a function of airflow rate. The variable k_s describes the skin's diffusional resistance to moisture migration.

The air film mass transfer coefficient k_a can be estimated by using the Sherwood-Reynolds-Schmidt correlations (Becker et al. 1996b). The Sherwood number is defined as follows:

Table 11 Transpiration Coefficients for Fruits and Vegetables

Commodity and Variety	Transpiration Coefficient, ng/(kg·s·Pa)
Apples	
Jonathan	35
Golden Delicious	58
Bramley's seedling	42
Average for all varieties	**42**
Brussels Sprouts	
Unspecified	3300
Average for all varieties	**6150**
Cabbage	
Penn State ballhead	
trimmed	271
untrimmed	404
Mammoth	
trimmed	240
Average for all varieties	**223**
Carrots	
Nantes	1648
Chantenay	1771
Average for all varieties	**1207**
Celery	
Unspecified varieties	2084
Average for all varieties	**1760**
Grapefruit	
Unspecified varieties	31
Marsh	55
Average for all varieties	**81**
Grapes	
Emperor	79
Cardinal	100
Thompson	204
Average for all varieties	**123**
Leeks	
Musselburgh	1040
Average for all varieties	**790**
Lemons	
Eureka	
dark green	227
yellow	140
Average for all varieties	**186**
Lettuce	
Unrivalled	8750
Average for all varieties	**7400**
Onions	
Autumn Spice	
uncured	96
cured	44
Sweet White Spanish	
cured	123
Average for all varieties	**60**
Oranges	
Valencia	58
Navel	104
Average for all varieties	**117**
Parsnips	
Hollow Crown	1930
Peaches	
Redhaven	
hard mature	917
soft mature	1020
Elberta	274
Average for all varieties	**572**
Pears	
Passe Crassane	80
Beurre Clairgeau	81
Average for all varieties	**69**
Plums	
Victoria	
unripe	198
ripe	115
Wickson	124
Average for all varieties	**136**
Potatoes	
Manona	
mature	25
Kennebec	
uncured	171
cured	60
Sebago	
uncured	158
cured	38
Average for all varieties	**44**
Rutabagas	
Laurentian	469
Tomatoes	
Marglobe	71
Eurocross BB	116
Average for all varieties	**140**

Note: Sastry et al. (1978) gathered these data as part of a literature review. Averages reported are the average of all published data found by Sastry et al. for each commodity. Specific varietal data were selected because they considered them highly reliable.

$$\mathrm{Sh} = \frac{k'_a d}{\delta} \tag{44}$$

where k'_a is the air film mass transfer coefficient, d is the commodity's diameter, and δ is the coefficient of diffusion of water vapor in air. For convective mass transfer from a spherical fruit or vegetable, Becker and Fricke (1996b) recommend using the following Sherwood-Reynolds-Schmidt correlation, which was taken fromGeankoplis (1978):

$$\mathrm{Sh} = 2.0 + 0.552\,\mathrm{Re}^{0.53}\mathrm{Sc}^{0.33} \tag{45}$$

Re is the Reynolds number (Re = $u\,d/\nu$) and Sc is the Schmidt number (Sc = ν/δ), where u is the free stream air velocity and ν is the kinematic viscosity of air. The driving force for k'_a is concentration. However, the driving force in the transpiration model is vapor pressure. Thus, the following conversion from concentration to vapor pressure is required:

$$k_a = \frac{1}{R_{wv} T} k'_a \tag{46}$$

where R_{wv} is the gas constant for water vapor and T is the absolute mean temperature of the boundary layer.

The skin mass transfer coefficient k_s, which describes the resistance to moisture migration through the skin of a commodity, is based on the fraction of the product surface covered by pores. Although it is difficult to theoretically determine the skin mass transfer coefficient, experimental determination has been performed by Chau et al. (1987) and Gan and Woods (1989). These experimental values of k_s are given in Table 12, along with estimated values of k_s for grapes,

Table 12 Commodity Skin Mass Transfer Coefficient

	Skin Mass Transfer Coefficient k_s, μg/(m²·s·Pa)			
Commodity	Low	Mean	High	Standard Deviation
Apples	0.111	0.167	0.227	0.03
Blueberries	0.955	2.19	3.39	0.64
Brussels sprouts	9.64	13.3	18.6	2.44
Cabbage	2.50	6.72	13.0	2.84
Carrots	31.8	156.	361.	75.9
Grapefruit	1.09	1.68	2.22	0.33
Grapes	—	0.4024	—	—
Green peppers	0.545	2.159	4.36	0.71
Lemons	1.09	2.08	3.50	0.64
Lima beans	3.27	4.33	5.72	0.59
Limes	1.04	2.22	3.48	0.56
Onions	—	0.8877	—	—
Oranges	1.38	1.72	2.14	0.21
Peaches	1.36	14.2	45.9	5.2
Pears	0.523	0.686	1.20	0.149
Plums	—	1.378	—	—
Potatoes	—	0.6349	—	—
Rutabagas (swedes)	—	116.6	—	—
Snap beans	3.46	5.64	10.0	1.77
Sugar beets	9.09	33.6	87.3	20.1
Strawberries	3.95	13.6	26.5	4.8
Tomatoes	0.217	1.10	2.43	0.67

Source: Becker and Fricke (1996a)

onions, plums, potatoes, and rutabagas. Note that three values of skin mass transfer coefficient are tabulated for most commodities. These values correspond to the spread of the experimental data.

SURFACE HEAT TRANSFER COEFFICIENT

Although the surface heat transfer coefficient is not a thermal property of a food or beverage, it is needed to design heat transfer equipment for processing foods and beverages where convection is involved. Newton's law of cooling defines the surface heat transfer coefficient h as follows:

$$q = hA(t_s - t) \tag{47}$$

where q is the heat transfer rate, t_s is the surface temperature of the food, t is the surrounding fluid temperature, and A is the surface area of the food through which the heat transfer occurs.

The surface heat transfer coefficient h depends on the velocity of the surrounding fluid, product geometry, orientation, surface roughness, and packaging, as well as other factors. Therefore, for most applications h must be determined experimentally. Researchers have generally reported their findings as correlations, which give the Nusselt number as a function of the Reynolds number and the Prandtl number.

Experimentally determined values of the surface heat transfer coefficient are given in Table 13. The following guidelines are important for using the table:

- Use a Nusselt-Reynolds-Prandtl correlation or a value of the surface heat transfer coefficient that applies to the Reynolds number called for in the design.
- Avoid extrapolations.
- Use data for the same heat transfer medium, including temperature and temperature difference, that are similar to the design conditions. The proper characteristic length and fluid velocity, either free stream or interstitial, should be used in calculating the Reynolds and Nusselt numbers.

Evaluation of Thermophysical Property Models

Numerous composition-based thermophysical property models have been developed, and selecting appropriate ones from those available can be challenging. Becker and Fricke (1999) and Fricke and Becker (2001, 2002) quantitatively evaluated selected thermophysical property models by comparison to a comprehensive experimental thermophysical property data set compiled from the literature. They found that for ice fraction prediction, the equation by Chen (1985) performed best, followed closely by that of Tchigeov (1979). For apparent specific heat capacity, the model of Schwartzberg (1976) performed best, and for specific enthalpy prediction, the Chen (1985) equation gave the best results. Finally, for thermal conductivity, the model by Levy (1981) performed best.

Table 13 Surface Heat Transfer Coefficients for Food Products

1	2	3	4	5	6	7	8	9	10
Product	**Shape and Length, mm[a]**	**Transfer Medium**	**Δt and/or Temp. t of Medium, °C**	**Velocity of Medium, m/s**	**Reynolds Number Range[b]**	**h, W/(m²·K)**	**Nu-Re-Pr Correlation[c]**	**Reference**	**Comments**
Apple	Spherical	Air	t = 27	0.0	N/A	11.1	N/A	Kopelman et al. (1966)	N/A indicates that data were not reported in original article
Jonathan	52			0.39		17.0			
				0.91		27.3			
				2.0		45.3			
				5.1		53.4			
	58			0.0		11.2			
				0.39		17.0			
				0.91		27.8			
				2.0		44.8			
				5.1		54.5			
	62			0.0		11.4			
				0.39		15.9			
				0.91		26.1			
				2.0		39.2			
				5.1		50.5			
Red Delicious	63	Air	Δt = 22.8, t = –0.6	1.5	N/A	27.3	N/A	Nicholas et al. (1964)	Thermocouples at center of fruit
				4.6		56.8			
	72			1.5		14.2			
				4.6		36.9			
	76			0.0		10.2			
				1.5		22.7			
				3.0		32.9			
				4.6		34.6			
	57	Water	Δt = 25.6, t = 0	0.27		90.9			
	70					79.5			
	75					55.7			
Beef carcass	64.5 kg*	Air	t = –19.5	1.8	N/A	21.8	N/A	Fedorov et al. (1972)	*For size indication
	85 kg*			0.3		10.0			
patties	Slab	Air	t = –32 to –28	2.8 to 6.0	2000 to 7500	N/A	$Nu = 1.37 Re^{0.282} Pr^{0.3}$	Becker and Fricke (2004)	Unpackaged patties. Characteristic dimension is patty thickness. 7 points in correlation.
Cake	Cylinder or brick	Air	t = –40 to 0	2.1 to 3.0	4000 to 80 000	N/A	$Nu = 0.00156 Re^{0.960} Pr^{0.3}$	Becker and Fricke (2004)	Packaged and unpackaged. Characteristic dimension is cake height. 29 points in correlation.

Table 13 Surface Heat Transfer Coefficients for Food Products (*Continued*)

1	2	3	4	5	6	7	8	9	10
Product	**Shape and Length, mm[a]**	**Transfer Medium**	**Δt and/or Temp. t of Medium, °C**	**Velocity of Medium, m/s**	**Reynolds Number Range[b]**	**h, W/(m²·K)**	**Nu-Re-Pr Correlation[c]**	**Reference**	**Comments**
Cheese	Brick	Air	t = –34 to 2	3.0	6000 to 30 000	N/A	$Nu = 0.0987 Re^{0.560} Pr^{0.3}$	Becker and Fricke (2004)	Packaged and unpackaged. Characteristic dimension is minimum dimension. 7 points in correlation.
Cucumbers	Cylinder 38	Air	t = 4	1.00 1.25 1.50 1.75 2.00	N/A	18.2 19.9 21.3 23.1 26.6	$Nu = 0.291 Re^{0.592} Pr^{0.333}$	Dincer (1994)	Diameter = 38 mm Length = 160 mm
Eggs, Jifujitori	34	Air	Δt = 45	2 to 8	6000 to 15 000	N/A	$Nu = 0.46 Re^{0.56} \pm 1.0\%$	Chuma et al. (1970)	5 points in correlation
Leghorn	44	Air	Δt = 45	2 to 8	8000 to 25 000	N/A	$Nu = 0.71 Re^{0.55} \pm 1.0\%$	Chuma et al. (1970)	5 points in correlation
Entrees	Brick	Air	t = –38 to 0	2.8 to 5.0	5000 to 20 000	N/A	$Nu = 1.31 Re^{0.280} Pr^{0.3}$	Becker and Fricke (2004)	Packaged. Characteristic dimension is minimum dimension. 42 points in correlation.
Figs	Spherical 47	Air	t = 4	1.10 1.50 1.75 2.50	N/A	23.8 26.2 27.4 32.7	$Nu = 1.560 Re^{0.426} Pr^{0.333}$	Dincer (1994)	
Fish, Pike, perch, sheatfish	N/A	Air	N/A	0.97 to 6.6	5000 to 35 000	N/A	$Nu = 4.5 Re^{0.28} \pm 10\%$	Khatchaturov (1958)	32 points in correlation
Fillets	N/A	Air	t = –40 to –28	2.7 to 7.0	1000 to 25 000	N/A	$Nu = 0.0154 Re^{0.818} Pr^{0.3}$	Becker and Fricke (2004)	Packaged and unpackaged. Characteristic dimension is minimum dimension. 28 points in correlation.
Grapes	Cylinder 11	Air	t = 4	1.00 1.25 1.50 1.75 2.00	N/A	30.7 33.8 37.8 40.7 42.3	$Nu = 0.291 Re^{0.592} Pr^{0.333}$	Dincer (1994)	Diameter = 11 mm Length = 22 mm
Hams, Boneless Processed	G^* = 0.4 to 0.45 * G = Geometrical factor for shrink-fitted plastic bag	Air	Δt = 132 t = 150	N/A	1000 to 86 000	N/A	$Nu = 0.329 Re^{0.564}$	Clary et al. (1968) $G = 1/4 + 3/(8A^2) + 3/(8B^2)$ $A = a/Z$, $B = b/Z$ A = characteristic length = 0.5 min. dist. ⊥ to airflow a = minor axis b = major axis Correlation on 18 points Recalc with min. distance ⊥ to airflow Calculated Nu with 1/2 char. length	
	N/A	Air	t = –23.3 t = –48.3 t = –51.1 t = –56.7 t = –62.2	0.61	N/A	20.39 20.44 19.70 19.99 18.17	N/A	Van den Berg and Lentz (1957)	38 points total Values are averages
Meat	Slabs 23	Air	t = 0	0.56 1.4 3.7	N/A	10.6 20.0 35.0	N/A	Radford et al. (1976)	
Oranges, grapefruit, tangelos, bulk packed	Spheroids 58 80 53	Air	Δt = 39 to 31 t = –9	0.11 to 0.33	35 000 to 135 000	*66.4	$Nu = 5.05 Re^{0.333}$	Bennett et al. (1966) Bins 1070 × 1070 × 400 mm. 36 points in correlation. Random packaging. Interstitial velocity. *Average for oranges	
	Spheroids 77 107	Air	Δt = 32.7 t = 0	0.05 to 2.03	180 to 18 000	N/A	$Nu = 1.17 Re^{0.529}$	Baird and Gaffney (1976)	20 points in correlation Bed depth: 670 mm
Peas Fluidized bed	Spherical N/A	Air	t = –26 to –37	1.5 to 7.2 ±0.3	1000 to 4000	N/A	$Nu = 3.5 \times 10^{-4} Re^{1.5}$	Kelly (1965)	Bed: 50 mm deep
Bulk packed	Spherical N/A	Air	t = –26 to –37	1.5 to 7.2 ±0.3	1000 to 6000	N/A	$Nu = 0.016 Re^{0.95}$	Kelly (1965)	

Table 13 Surface Heat Transfer Coefficients for Food Products (*Continued*)

1	2	3	4	5	6	7	8	9	10
Product	**Shape and Length, mm[a]**	**Transfer Medium**	**Δt and/or Temp. t of Medium, °C**	**Velocity of Medium, m/s**	**Reynolds Number Range[b]**	**h, W/(m²·K)**	**Nu-Re-Pr Correlation[c]**	**Reference**	**Comments**
Pears	Spherical 60	Air	$t = 4$	1.00 1.25 1.50 1.75 2.00	N/A	12.6 14.2 15.8 16.1 19.5	$Nu = 1.560 Re^{0.426} Pr^{0.333}$	Dincer (1994)	
Pizza	Slab	Air	$t = -34$ to -26	3.0 to 3.8	3000 to 12 000	N/A	$Nu = 0.00517 Re^{0.891} Pr^{0.3}$	Fricke and Becker (2004)	Packaged and unpackaged. Characteristic dimension is pizza thickness. 12 points in correlation.
Potatoes Pungo, bulk packed	Ellipsoid N/A N/A	Air	$t = 4.4$	0.66 1.23 1.36	3000 to 9000	*14.0 19.1 20.2	$Nu = 0.364 Re^{0.558} Pr^{1/3}$ (at top of bin)	Minh et al. (1969) Use interstitial velocity to calculate Re Bin is 760 × 510 × 230 mm *Each h value is average of 3 reps with airflow from top to bottom	
Patties, fried	Slab	Air	$t = -32$ to -28	2.3 to 3.5	1000 to 6000	N/A	$Nu = 0.00313 Re^{1.06} Pr^{0.3}$	Becker and Fricke (2004)	Unpackaged. Characteristic dimension is patty thickness. 8 points in correlation.
Poultry Chickens, turkeys	1.18 to 9.43 kg*	**	$\Delta t = 17.8$	***	N/A	420 to 473	N/A	Lentz (1969)	Vacuum packaged *To give indications of size. **$CaCl_2$ Brine, 26% by mass ***Moderately agitated Chickens 1.1 to 2.9 kg Turkeys 5.4 to 9.5 kg
Chicken breast	N/A	Air	$t = -34$ to -2	1.0 to 3.0	1000 to 11 000	N/A	$Nu = 0.0378 Re^{0.837} Pr^{0.3}$	Becker and Fricke (2004)	Unpackaged. Characteristic dimension is minimum dimension. 22 points in correlation.
Sausage	Cylinder	Air	$t = -40$ to -13	2.7 to 3.0	4500 to 25 000	N/A	$Nu = 7.14 Re^{0.170} Pr^{0.3}$	Becker and Fricke (2004)	Unpackaged. Characteristic dimension is sausage diameter. 14 points in correlation.
Soybeans	Spherical 65	Air	N/A	6.8	1200 to 4600	N/A	$Nu = 1.07 Re^{0.64}$	Otten (1974)	8 points in correlation Bed depth: 32 mm
Squash	Cylinder 46	Water	0.5 1.0 1.5	0.05	N/A	272 205 166	N/A	Dincer (1993)	Diameter = 46 mm Length = 155 mm
Tomatoes	Spherical 70	Air	$t = 4$	1.00 1.25 1.50 1.75 2.00	N/A	10.9 13.1 13.6 14.9 17.3	$Nu = 1.560 Re^{0.426} Pr^{0.333}$	Dincer (1994)	
Karlsruhe substance	Slab 75	Air	$\Delta t = 53$ $t = 38$	N/A	N/A	16.4	N/A	Cleland and Earle (1976)	Packed in aluminum foil and brown paper
Milk Container	Cylinder 70 × 100 70 × 150 70 × 250	Air	$\Delta t = 5.3$	N/A	$Gr = 10^6$ to 5×10^7	N/A	$Nu = 0.754 Gr^{0.264}$	Leichter et al. (1976)	Emissivity = 0.7 300 points in correlation L = characteristic length. All cylinders 70 mm dia.
Acrylic	Ellipsoid 76 (minor axis) G = 0.297 to 1.0	Air	$\Delta t = 44.4$	2.1 to 8.0	12 000 to 50 000	N/A	$Nu = a Re^b$ $a = 0.32 - 0.22G$ $b = 0.44 + 0.23G$	Smith et al. (1971) $G = 1/4 + 3/(8A^2) + 3/(8B^2)$ A = minor length/char. length B = major length/char. length Char. length = 0.5 × minor axis Use twice char. length to calculate Re	
	Spherical 76	Air	$t = -4.4$	0.66 1.23 1.36 1.73	3700 to 10 000	15.0* 14.5 22.2 21.4	$Nu = 2.58 Re^{0.303} Pr^{1/3}$	Minh et al. (1969)	Random packed Interstitial velocity used to calculate Re Bin dimensions: 760 × 455 × 610 mm *Values for top of bin

[a]Characteristic length is used in Reynolds number and illustrated in the Comments column (10) where appropriate.
[b]Characteristic length is given in column 2; free stream velocity is used, unless specified otherwise in the Comments column (10).
[c]Nu = Nusselt number, Re = Reynolds number, Gr = Grashof number, Pr = Prandtl number.

SYMBOLS

a = parameter in Equation (26): $a = 3k_c/(2k_c + k_d)$
A = surface area
b = parameter in Equation (26): $b = V_d/(V_c + V_d)$
c = specific heat
c_a = apparent specific heat
c_f = specific heat of fully frozen food
c_i = specific heat of ith food component
c_p = constant-pressure specific heat
c_u = specific heat of unfrozen food
d = commodity diameter
E = ratio of relative molecular masses of water and solids: $E = M_w/M_s$
f = respiration coefficient given in Table 8
F_1 = parameter given by Equation (32)
g = respiration coefficient given in Table 8
Gr = Grashof number
h = surface heat transfer coefficient
H = enthalpy
H_f = enthalpy at initial freezing temperature
H_i = enthalpy of ith food component
k = thermal conductivity
k_1 = thermal conductivity of component 1
k_2 = thermal conductivity of component 2
k_a' = air film mass transfer coefficient (driving force: vapor pressure)
k_a = air film mass transfer coefficient (driving force: concentration)
k_c = thermal conductivity of continuous phase
k_d = thermal conductivity of discontinuous phase
k_i = thermal conductivity of the ith component
k_s = skin mass transfer coefficient
k_t = transpiration coefficient
$k_=$ = thermal conductivity parallel to food fibers
$k_\perp$ = thermal conductivity perpendicular to food fibers
L^3 = volume fraction of discontinuous phase
L_o = latent heat of fusion of water at 0°C = 333.6 kJ/kg
m = mass
$\dot{m}$ = transpiration rate
M = parameter in Equation (28) = $L^2(1 - k_d/k_c)$
M_s = relative molecular mass of soluble solids
M_w = relative molecular mass of water
Nu = Nusselt number
N^2 = volume fraction of discontinuous phase
P = parameter in Equation (30) = $N(1 - k_d/k_c)$
Pr = Prandtl number
p_a = water vapor pressure in air
p_s = water vapor pressure at commodity surface
q = heat transfer rate
Q = heat transfer
R = universal gas constant = 8.314 kJ/(kg mol·K)
R_1 = volume fraction of component 1
Re = Reynolds number
R_{wv} = universal gas constant for water vapor
Sc = Schmidt number
Sh = Sherwood number
t = food temperature, °C
t_f = initial freezing temperature of food, °C
t_r = reference temperature = −40°C
t_s = surface temperature, °C
t_∞ = ambient temperature, °C
T = food temperature, K
T_f = initial freezing point of food, K
T_o = freezing point of water; T_o = 233.2 K
T_r = reference temperature = 233.2 K
$\bar{T}$ = reduced temperature
u_∞ = free stream air velocity
V_c = volume of continuous phase
V_d = volume of discontinuous phase
W = rate of heat generation from respiration, W/kg
x_1 = mass fraction of component 1
x_a = mass fraction of ash
x_b = mass fraction of bound water
x_c = mass fraction of carbohydrate
x_f = mass fraction of fat
x_{fb} = mass fraction of fiber
x_i = mass fraction of ith food component
x_{ice} = mass fraction of ice
x_p = mass fraction of protein
x_s = mass fraction of solids
x_{wo} = mass fraction of water in unfrozen food
x_i^v = volume fraction of ith food component
y = correlation parameter in Equation (19)
z = correlation parameter in Equation (19)

Greek

α = thermal diffusivity
δ = diffusion coefficient of water vapor in air
Δc = difference in specific heats of water and ice = $c_{water} - c_{ice}$
ΔH = enthalpy difference
Δt = temperature difference
ε = porosity
θ = time
Λ = thermal conductivity ratio = k_1/k_2
ν = kinematic viscosity
ρ = density of food
ρ_1 = density of component 1
ρ_2 = density of component 2
ρ_i = density of ith food component
σ = parameter given by Equation (33)

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