Related Commercial Resources

CHAPTER 9

THERMAL PROPERTIES OF FOODS

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 300°F (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 ($-40 \le t \le 300$°F)

Thermal Property	Food Component	Thermal Property Model
Thermal conductivity, Btu/(h·ft·°F)	Protein	$k = 9.0535 \times 10^{-2} + 4.1486 \times 10^{-4}t - 4.8467 \times 10^{-7}t^2$
	Fat	$k = 1.0722 \times 10^{-1} - 8.6581 \times 10^{-5}t - 3.1652 \times 10^{-8}t^2$
	Carbohydrate	$k = 1.0133 \times 10^{-1} + 4.9478 \times 10^{-4}t - 7.7238 \times 10^{-7}t^2$
	Fiber	$k = 9.2499 \times 10^{-2} + 4.3731 \times 10^{-4}t - 5.6500 \times 10^{-7}t^2$
	Ash	$k = 1.7553 \times 10^{-1} + 4.8292 \times 10^{-4}t - 5.1839 \times 10^{-7}t^2$
Thermal diffusivity, ft^2/h	Protein	$\alpha = 2.3170 \times 10^{-3} + 1.1364 \times 10^{-5}t - 1.7516 \times 10^{-8}t^2$
	Fat	$\alpha = 3.8358 \times 10^{-3} - 2.4128 \times 10^{-7}t - 4.5790 \times 10^{-10}t^2$
	Carbohydrate	$\alpha = 2.7387 \times 10^{-3} + 1.3198 \times 10^{-5}t - 2.7769 \times 10^{-8}t^2$
	Fiber	$\alpha = 2.4818 \times 10^{-3} + 1.2873 \times 10^{-5}t - 2.6553 \times 10^{-8}t^2$
	Ash	$\alpha = 4.5565 \times 10^{-3} + 8.9716 \times 10^{-6}t - 1.4644 \times 10^{-8}t^2$
Density, lb/ft^3	Protein	$\rho = 8.3599 \times 10^{1} - 1.7979 \times 10^{-2}t$
	Fat	$\rho = 5.8246 \times 10^{1} - 1.4482 \times 10^{-2}t$
	Carbohydrate	$\rho = 1.0017 \times 10^{2} - 1.0767 \times 10^{-2}t$
	Fiber	$\rho = 8.2280 \times 10^{1} - 1.2690 \times 10^{-2}t$
	Ash	$\rho = 1.5162 \times 10^{2} - 9.7329 \times 10^{-3}t$
Specific heat, Btu/(lb·°F)	Protein	$c_p = 4.7442 \times 10^{-1} + 1.6661 \times 10^{-4}t - 9.6784 \times 10^{-8}t^2$
	Fat	$c_p = 4.6730 \times 10^{-1} + 2.1815 \times 10^{-4}t - 3.5391 \times 10^{-7}t^2$
	Carbohydrate	$c_p = 3.6114 \times 10^{-1} + 2.8843 \times 10^{-4}t - 4.3788 \times 10^{-7}t^2$
	Fiber	$c_p = 4.3276 \times 10^{-1} + 2.6485 \times 10^{-4}t - 3.4285 \times 10^{-7}t^2$
	Ash	$c_p = 2.5266 \times 10^{-1} + 2.6810 \times 10^{-4}t - 2.7141 \times 10^{-7}t^2$

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 ($-40 \le t \le 300$°F)

	Thermal Property	Thermal Property Model
Water	Thermal conductivity, Btu/(h·ft·°F)	$k_w = 3.1064 \times 10^{-1} + 6.4226 \times 10^{-4} t - 1.1955 \times 10^{-6} t^2$
	Thermal diffusivity, ft²/h	$\alpha_w = 4.6428 \times 10^{-3} + 1.5289 \times 10^{-5} t - 2.8730 \times 10^{-8} t^2$
	Density, lb/ft³	$\rho_w = 6.2174 \times 10^{1} + 4.7425 \times 10^{-3} t - 7.2397 \times 10^{-8} t^2$
	Specific heat, Btu/(lb·°F) (For temperature range of –40 to 32°F)	$c_w = 1.0725 - 5.3992 \times 10^{-3} t + 7.3361 \times 10^{-5} t^2$
	Specific heat, Btu/(lb·°F) (For temperature range of 32 to 300°F)	$c_w = 9.9827 \times 10^{-1} - 3.7879 \times 10^{-5} t + 4.0347 \times 10^{-7} t^2$
Ice	Thermal conductivity, Btu/(h·ft·°F)	$k_{ice} = 1.3652 - 3.1648 \times 10^{-3} t + 1.8108 \times 10^{-5} t^2$
	Thermal diffusivity, ft²/h	$\alpha_{ice} = 5.0909 \times 10^{-2} - 2.0371 \times 10^{-4} t + 1.1366 \times 10^{-6} t^2$
	Density, lb/ft³	$\rho_{ice} = 5.7385 \times 10^{1} - 4.5333 \times 10^{-3} t$
	Specific heat, Btu/(lb·°F)	$c_{ice} = 4.6677 \times 10^{-1} + 8.0636 \times 10^{-4} t$

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}:

$$x_{ice} = \frac{x_s R T_o^2 (t_f - t)}{M_s L_o (t_f - 32)(t - 32)} \tag{1}$$

where

x_s = mass fraction of solids in food
M_s = relative molecular mass of soluble solids, lb_m/mol
R = universal gas constant = 1.986 Btu/lb mol·°R
T_o = freezing point of water = 491.7°R
L_o = latent heat of fusion of water at 491.7°R = 143.4 Btu/lb
t_f = initial freezing point of food, °F
t = food temperature, °F

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

$$M_s = \frac{x_s R T_o^2}{-L_o (x_{wo} - x_b)(t_f - 32)} \tag{2}$$

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):

$$x_{ice} = (x_{wo} - x_b)\left(1 - \frac{t_f - 32}{t - 32}\right) \tag{4}$$

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:

$$x_{ice} = \frac{1.105 x_{wo}}{1 + \dfrac{0.7138}{\ln[1 + (t_f - t)/1.8]}} \tag{5}$$

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, °F	Specific Heat Above Freezing, Btu/lb·°F	Specific Heat Below Freezing Btu/lb·°F	Latent Heat of Fusion, Btu/lb
Vegetables										
Artichokes, globe	84.94	3.27	0.15	10.51	5.40	1.13	29.8	0.93	0.48	122
Jerusalem	78.01	2.00	0.01	17.44	1.60	2.54	27.5	0.87	0.54	112
Asparagus	92.40	2.28	0.20	4.54	2.10	0.57	30.9	0.96	0.43	133
Beans, snap	90.27	1.82	0.12	7.14	3.40	0.66	30.7	0.95	0.44	130
lima	70.24	6.84	0.86	20.16	4.90	1.89	30.9	0.84	0.49	101
Beets	87.58	1.61	0.17	9.56	2.80	1.08	30.0	0.93	0.46	126
Broccoli	90.69	2.98	0.35	5.24	3.00	0.92	30.9	0.96	0.43	130
Brussels sprouts	86.00	3.38	0.30	8.96	3.80	1.37	30.6	0.93	0.46	123
Cabbage	92.15	1.44	0.27	5.43	2.30	0.71	30.4	0.96	0.44	132
Carrots	87.79	1.03	0.19	10.14	3.00	0.87	29.5	0.94	0.48	126
Cauliflower	91.91	1.98	0.21	5.20	2.50	0.71	30.6	0.96	0.44	132
Celeriac	88.00	1.50	0.30	9.20	1.80	1.00	30.4	0.93	0.45	126
Celery	94.64	0.75	0.14	3.65	1.70	0.82	31.1	0.97	0.42	136
Collards	90.55	1.57	0.22	7.11	3.60	0.55	30.6	0.96	0.44	130
Corn, sweet, yellow	75.96	3.22	1.18	19.02	2.70	0.62	30.9	0.86	0.47	109
Cucumbers	96.01	0.69	0.13	2.76	0.80	0.41	31.1	0.98	0.41	138
Eggplant	92.03	1.02	0.18	6.07	2.50	0.71	30.6	0.96	0.44	132
Endive	93.79	1.25	0.20	3.35	3.10	1.41	31.8	0.97	0.40	135
Garlic	58.58	6.36	0.50	33.07	2.10	1.50	30.6	0.76	0.52	84
Ginger, root	81.67	1.74	0.73	15.09	2.00	0.77	—	0.90	0.46	117
Horseradish	78.66	9.40	1.40	8.28	2.00	2.26	28.8	0.88	0.51	113
Kale	84.46	3.30	0.70	10.01	2.00	1.53	31.1	0.91	0.44	121
Kohlrabi	91.00	1.70	0.10	6.20	3.60	1.00	30.2	0.96	0.45	131
Leeks	83.00	1.50	0.30	14.15	1.80	1.05	30.7	0.90	0.46	119
Lettuce, iceberg	95.89	1.01	0.19	2.09	1.40	0.48	31.6	0.98	0.39	138
Mushrooms	91.81	2.09	0.42	4.65	1.20	0.89	30.4	0.95	0.44	132
Okra	89.58	2.00	0.10	7.63	3.20	0.70	28.8	0.95	0.49	129
Onions	89.68	1.16	0.16	8.63	1.80	0.37	30.4	0.94	0.45	129
dehydrated flakes	3.93	8.95	0.46	83.28	9.20	3.38	—	—	—	6
Parsley	87.71	2.97	0.79	6.33	3.30	2.20	30.0	0.94	0.46	126
Parsnips	79.53	1.20	0.30	17.99	4.90	0.98	30.4	0.89	0.48	114
Peas, green	78.86	5.42	0.40	14.46	5.10	0.87	30.9	0.90	0.47	113
Peppers, freeze-dried	2.00	17.90	3.00	68.70	21.30	8.40	—	—	—	3
sweet, green	92.19	0.89	0.19	6.43	1.80	0.30	30.7	0.96	0.43	132
Potatoes, main crop	78.96	2.07	0.10	17.98	1.60	0.89	30.9	0.88	0.46	113
sweet	72.84	1.65	0.30	24.28	3.00	0.95	29.7	0.83	0.50	104
Pumpkins	91.60	1.00	0.10	6.50	0.50	0.80	30.6	0.95	0.43	132
Radishes	94.84	0.60	0.54	3.59	1.60	0.54	30.7	0.97	0.42	136
Rhubarb	93.61	0.90	0.20	4.54	1.80	0.76	30.4	0.97	0.44	135
Rutabaga	89.66	1.20	0.20	8.13	2.50	0.81	30.0	0.94	0.46	129
Salsify (vegetable oyster)	77.00	3.30	0.20	18.60	3.30	0.90	30.0	0.87	0.49	110
Spinach	91.58	2.86	0.35	3.50	2.70	1.72	31.5	0.96	0.42	132
Squash, summer	94.20	0.94	0.24	4.04	1.90	0.58	31.1	0.97	0.42	135
winter	87.78	0.80	0.10	10.42	1.50	0.90	30.6	0.93	0.45	126
Tomatoes, mature green	93.00	1.20	0.20	5.10	1.10	0.50	30.9	0.96	0.42	134
ripe	93.76	0.85	0.33	4.64	1.10	0.42	31.1	0.97	0.43	135
Turnip	91.87	0.90	0.10	6.23	1.80	0.70	30.0	0.96	0.45	132
greens	91.07	1.50	0.30	5.73	3.20	1.40	31.6	0.96	0.42	131
Watercress	95.11	2.30	0.10	1.29	1.50	1.20	31.5	0.97	0.40	137
Yams	69.60	1.53	0.17	27.89	4.10	0.82	—	0.83	0.49	100
Fruits										
Apples, fresh	83.93	0.19	0.36	15.25	2.70	0.26	30.0	0.91	0.47	120
dried	31.76	0.93	0.32	65.89	8.70	1.10	—	0.61	0.68	46
Apricots	86.35	1.40	0.39	11.12	2.40	0.75	30.0	0.92	0.47	124
Avocados	74.27	1.98	15.32	7.39	5.00	1.04	31.5	0.88	0.47	107
Bananas	74.26	1.03	0.48	23.43	2.40	0.80	30.6	0.85	0.48	107
Blackberries	85.64	0.72	0.39	12.76	5.30	0.48	30.6	0.93	0.46	123
Blueberries	84.61	0.67	0.38	14.13	2.70	0.21	29.1	0.91	0.49	122
Cantaloupes	89.78	0.88	0.28	8.36	0.80	0.71	29.8	0.94	0.46	129
Cherries, sour	86.13	1.00	0.30	12.18	1.60	0.40	28.9	0.92	0.49	124
sweet	80.76	1.20	0.96	16.55	2.30	0.53	28.8	0.89	0.51	116
Cranberries	86.54	0.39	0.20	12.68	4.20	0.19	30.4	0.93	0.46	124

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, °F	Specific Heat Above Freezing, Btu/lb·°F	Specific Heat Below Freezing Btu/lb·°F	Latent Heat of Fusion, Btu/lb
Currants, European black	81.96	1.40	0.41	15.38	0.00	0.86	30.2	0.89	0.47	118
red and white	83.95	1.40	0.20	13.80	4.30	0.66	30.2	0.92	0.47	120
Dates, cured	22.50	1.97	0.45	73.51	7.50	1.58	3.7	0.55	0.55	32
Figs, fresh	79.11	0.75	0.30	19.18	3.30	0.66	27.7	0.88	0.54	113
dried	28.43	3.05	1.17	65.35	9.30	2.01	—	0.60	0.98	41
Gooseberries	87.87	0.88	0.58	10.18	4.30	0.49	30.0	0.94	0.47	126
Grapefruit	90.89	0.63	0.10	8.08	1.10	0.31	30.0	0.95	0.45	131
Grapes, American	81.30	0.63	0.35	17.15	1.00	0.57	29.1	0.89	0.49	117
European type	80.56	0.66	0.58	17.77	1.00	0.44	28.2	0.88	0.52	116
Lemons	87.40	1.20	0.30	10.70	4.70	0.40	29.5	0.94	0.48	126
Limes	88.26	0.70	0.20	10.54	2.80	0.30	29.1	0.94	0.48	127
Mangos	81.71	0.51	0.27	17.00	1.80	0.50	30.4	0.89	0.47	117
Melons, casaba	92.00	0.90	0.10	6.20	0.80	0.80	30.0	0.95	0.45	132
honeydew	89.66	0.46	0.10	9.18	0.60	0.60	30.4	0.94	0.44	129
watermelon	91.51	0.62	0.43	7.18	0.50	0.26	31.3	0.95	0.42	132
Nectarines	86.28	0.94	0.46	11.78	1.60	0.54	30.4	0.92	0.45	124
Olives	79.99	0.84	10.68	6.26	3.20	2.23	29.5	0.90	0.49	115
Oranges	82.30	1.30	0.30	15.50	4.50	0.60	30.6	0.91	0.47	118
Peaches, fresh	87.66	0.70	0.90	11.10	2.00	0.46	30.4	0.93	0.45	126
dried	31.80	3.61	0.76	61.33	8.20	2.50	—	0.61	0.83	46
Pears	83.81	0.39	0.40	15.11	2.40	0.28	29.1	0.91	0.49	120
Persimmons	64.40	0.80	0.40	33.50	0.00	0.90	28.0	0.78	0.55	92
Pineapples	86.50	0.39	0.43	12.39	1.20	0.29	30.2	0.92	0.46	124
Plums	85.20	0.79	0.62	13.01	1.50	0.39	30.6	0.91	0.45	123
Pomegranates	80.97	0.95	0.30	17.17	0.60	0.61	26.6	0.88	0.55	116
Prunes, dried	32.39	2.61	0.52	62.73	7.10	1.76	—	0.61	0.84	46
Quinces	83.80	0.40	0.10	15.30	1.90	0.40	28.4	0.91	0.51	120
Raisins, seedless	15.42	3.22	0.46	79.13	4.00	1.77	—	0.49	0.49	22
Raspberries	86.57	0.91	0.55	11.57	6.80	0.40	30.9	0.95	0.46	124
Strawberries	91.57	0.61	0.37	7.02	2.30	0.43	30.6	0.96	0.44	132
Tangerines	87.60	0.63	0.19	11.19	2.30	0.39	30.0	0.93	0.46	126
Whole Fish										
Cod	81.22	17.81	0.67	0.0	0.0	1.16	28.0	0.90	0.51	117
Haddock	79.92	18.91	0.72	0.0	0.0	1.21	28.0	0.90	0.51	115
Halibut	77.92	20.81	2.29	0.0	0.0	1.36	28.0	0.89	0.52	112
Herring, kippered	59.70	24.58	12.37	0.0	0.0	1.94	28.0	0.78	0.54	86
Mackerel, Atlantic	63.55	18.60	13.89	0.0	0.0	1.35	28.0	0.80	0.53	91
Perch	78.70	18.62	1.63	0.0	0.0	1.20	28.0	0.89	0.51	113
Pollock, Atlantic	78.18	19.44	0.98	0.0	0.0	1.41	28.0	0.88	0.51	112
Salmon, pink	76.35	19.94	3.45	0.0	0.0	1.22	28.0	0.88	0.52	110
Tuna, bluefin	68.09	23.33	4.90	0.0	0.0	1.18	28.0	0.82	0.52	98
Whiting	80.27	18.31	1.31	0.0	0.0	1.30	28.0	0.90	0.51	115
Shellfish										
Clams	81.82	12.77	0.97	2.57	0.0	1.87	28.0	0.90	0.51	117
Lobster, American	76.76	18.80	0.90	0.50	0.0	2.20	28.0	0.87	0.51	110
Oysters	85.16	7.05	2.46	3.91	0.0	1.42	28.0	0.91	0.51	122
Scallop, meat	78.57	16.78	0.76	2.36	0.0	1.53	28.0	0.89	0.51	113
Shrimp	75.86	20.31	1.73	0.91	0.0	1.20	28.0	0.87	0.52	109
Beef										
Brisket	55.18	16.94	26.54	0.0	0.0	0.80	—	0.76	0.56	79
Carcass, choice	57.26	17.32	24.05	0.0	0.0	0.81	28.0	0.77	0.55	82
select	58.21	17.48	22.55	0.0	0.0	0.82	28.9	0.78	0.54	83
Liver	68.99	20.00	3.85	5.82	0.0	1.34	28.9	0.83	0.52	99
Ribs, whole (ribs 6-12)	54.54	16.37	26.98	0.0	0.0	0.77	—	0.75	0.55	78
Round, full cut, lean and fat	64.75	20.37	12.81	0.0	0.0	0.97	—	0.81	0.52	93
full cut, lean	70.83	22.03	4.89	0.0	0.0	1.07	—	0.84	0.51	102
Sirloin, lean	71.70	21.24	4.40	0.0	0.0	1.08	28.9	0.84	0.50	103
Short loin, porterhouse steak, lean	69.59	20.27	8.17	0.0	0.0	1.01	—	0.83	0.51	100
T-bone steak, lean	69.71	20.78	7.27	0.0	0.0	1.27	—	0.83	0.51	100
Tenderloin, lean	68.40	20.78	7.90	0.0	0.0	1.04	—	0.82	0.51	98
Veal, lean	75.91	20.20	2.87	0.0	0.0	1.08	—	0.87	0.50	109

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, °F	Specific Heat Above Freezing, Btu/lb·°F	Specific Heat Below Freezing Btu/lb·°F	Latent Heat of Fusion, Btu/lb
Pork										
Backfat	7.69	2.92	88.69	0.0	0.0	0.70	—	0.52	0.71	11
Bacon	31.58	8.66	57.54	0.09	0.0	2.13	—	0.64	0.64	45
Belly	36.74	9.34	53.01	0.0	0.0	0.49	—	0.67	0.80	53
Carcass	49.83	13.91	35.07	0.0	0.0	0.72	—	0.74	0.74	71
Ham, cured, whole, lean	68.26	22.32	5.71	0.05	0.0	3.66	—	0.83	0.53	98
country cured, lean	55.93	27.80	8.32	0.30	0.0	7.65	—	0.75	0.55	80
Shoulder, whole, lean	72.63	19.55	7.14	0.0	0.0	1.02	28.0	0.86	0.53	104
Sausage										
Braunschweiger	48.01	13.50	32.09	3.13	0.0	3.27	—	0.72	0.57	69
Frankfurter	53.87	11.28	29.15	2.55	0.0	3.15	28.9	0.75	0.55	77
Italian	51.08	14.25	31.33	0.65	0.0	2.70	—	0.74	0.57	74
Polish	53.15	14.10	28.72	1.63	0.0	2.40	—	0.75	0.56	77
Pork	44.52	11.69	40.29	1.02	0.0	2.49	—	0.70	0.58	64
Smoked links	39.30	22.20	31.70	2.10	0.0	4.70	—	0.67	0.59	56
Poultry Products										
Chicken	65.99	18.60	15.06	0.0	0.0	0.79	27.0	1.04	0.79	95
Duck	48.50	11.49	39.34	0.0	0.0	0.68	—	0.73	0.59	70
Turkey	70.40	20.42	8.02	0.0	0.0	0.88	—	0.84	0.54	101
Egg										
White	87.81	10.52	0.0	1.03	0.0	0.64	30.9	0.93	0.43	126
dried	14.62	76.92	0.04	4.17	0.0	4.25	—	0.55	0.50	21
Whole	75.33	12.49	10.02	1.22	0.0	0.94	30.9	0.87	0.47	108
dried	3.10	47.35	40.95	4.95	0.0	3.65	—	0.49	0.48	4
Yolk	48.81	16.76	30.87	1.78	0.0	1.77	30.9	0.73	0.54	70
salted	50.80	14.00	23.00	1.60	0.0	10.60	1.0	0.72	0.91	73
sugared	51.25	13.80	22.75	10.80	0.0	1.40	25.0	0.73	0.61	74
Lamb										
Composite of cuts, lean	73.42	20.29	5.25	0.0	0.0	1.06	28.6	0.86	0.51	105
Leg, whole, lean	74.11	20.56	4.51	0.0	0.0	1.07	—	0.86	0.51	107
Dairy Products										
Butter	17.94	0.85	81.11	0.06	0.0	0.04	—	0.57	0.63	26
Cheese										
Camembert	51.80	19.80	24.26	0.46	0.0	3.68	—	0.74	0.80	74
Cheddar	36.75	24.90	33.14	1.28	0.0	3.93	8.8	0.66	0.73	53
Cottage, uncreamed	79.77	17.27	0.42	1.85	0.0	0.69	29.8	0.89	0.48	114
Cream	53.75	7.55	34.87	2.66	0.0	1.17	—	0.75	0.70	77
Gouda	41.46	24.94	27.44	2.22	0.0	3.94	—	0.69	0.66	59
Limburger	48.42	20.05	27.25	0.49	0.0	3.79	18.7	0.72	0.67	70
Mozzarella	54.14	19.42	21.60	2.22	0.0	2.62	—	0.75	0.59	78
Parmesan, hard	29.16	35.75	25.83	3.22	0.0	6.04	—	0.62	0.70	42
Processed American	39.16	22.15	31.25	1.30	0.0	5.84	19.6	0.67	0.66	56
Roquefort	39.38	21.54	30.64	2.00	0.0	6.44	2.7	0.67	0.80	57
Swiss	37.21	28.43	27.45	3.38	0.0	3.53	14.0	0.66	0.69	53
Cream										
Half and half	80.57	2.96	11.50	4.30	0.0	0.67	—	0.89	0.52	116
Table	73.75	2.70	19.31	3.66	0.0	0.58	28.0	0.86	0.53	106
Heavy whipping	57.71	2.05	37.00	2.79	0.0	0.45	—	0.78	0.55	83
Ice Cream										
Chocolate	55.70	3.80	11.0	28.20	1.20	1.00	21.9	0.74	0.66	80
Strawberry	60.00	3.20	8.40	27.60	0.30	0.70	21.9	0.76	0.65	86
Vanilla	61.00	3.50	11.00	23.60	0.0	0.90	21.9	0.77	0.65	88
Milk										
Canned, condensed, sweetened	27.16	7.91	8.70	54.40	0.0	1.83	5.0	0.56	—	39
Evaporated	74.04	6.81	7.56	10.04	0.0	1.55	29.5	0.85	0.50	106
Skim	90.80	3.41	0.18	4.85	0.0	0.76	—	0.94	0.43	130
dried	3.16	36.16	0.77	51.98	0.0	7.93	—	0.43	—	5
Whole	87.69	3.28	3.66	4.65	0.0	0.72	30.9	0.93	0.43	126
dried	2.47	26.32	26.71	38.42	0.0	6.08	—	0.44	—	3
Whey, acid, dried	3.51	11.73	0.54	73.45	0.0	10.77	—	0.40	—	5
sweet, dried	3.19	12.93	1.07	74.46	0.0	8.35	—	0.40	—	5

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, °F	Specific Heat Above Freezing, Btu/lb·°F	Specific Heat Below Freezing Btu/lb·°F	Latent Heat of Fusion, Btu/lb
Nuts, Shelled										
Almonds	4.42	19.95	52.21	20.40	10.90	3.03	—	0.53	—	6
Filberts	5.42	13.04	62.64	15.30	6.10	3.61	—	0.50	—	8
Peanuts, raw	6.50	25.80	49.24	16.14	8.50	2.33	—	0.53	—	9
dry roasted with salt	1.55	23.68	49.66	21.51	8.00	3.60	—	0.50	—	2
Pecans	4.82	7.75	67.64	18.24	7.60	1.56	—	0.52	—	7
Walnuts, English	3.65	14.29	61.87	18.34	4.80	1.86	—	0.50	—	5
Candy										
Fudge, vanilla	10.90	1.10	5.40	82.30	0.0	0.40	—	0.45	—	15
Marshmallows	16.40	1.80	0.20	81.30	0.10	0.30	—	0.48	—	24
Milk chocolate	1.30	6.90	30.70	59.20	3.40	1.50	—	0.44	—	2
Peanut brittle	1.80	7.50	19.10	69.30	2.00	1.50	—	0.42	—	3
Juice and Beverages										
Apple juice, unsweetened	87.93	0.06	0.11	11.68	0.10	0.22	—	0.92	0.43	126
Grapefruit juice, sweetened	87.38	0.58	0.09	11.13	0.10	0.82	—	0.92	0.43	126
Grape juice, unsweetened	84.12	0.56	0.08	14.96	0.10	0.29	—	0.90	0.43	121
Lemon juice	92.46	0.40	0.29	6.48	0.40	0.36	—	0.95	0.41	133
Lime juice, unsweetened	92.52	0.25	0.23	6.69	0.40	0.31	—	0.95	0.41	133
Orange juice	89.01	0.59	0.14	9.85	0.20	0.41	31.3	0.93	0.42	128
Pineapple juice, unsweetened	85.53	0.32	0.08	13.78	0.20	0.30	—	0.91	0.43	123
Prune juice	81.24	0.61	0.03	17.45	1.00	0.68	—	0.89	0.45	117
Tomato juice	93.90	0.76	0.06	4.23	0.40	1.05	—	0.96	0.41	135
Cranberry-apple juice drink	82.80	0.10	0.0	17.10	0.10	0.0	—	0.89	0.44	119
Cranberry-grape juice drink	85.60	0.20	0.10	14.00	0.10	0.10	—	0.91	0.43	123
Fruit punch drink	88.00	0.0	0.0	11.90	0.10	0.10	—	0.92	0.43	126
Club soda	99.90	0.0	0.0	0.0	0.0	0.10	—	1.00	0.39	144
Cola	89.40	0.0	0.0	10.40	0.0	0.10	—	0.93	0.42	129
Cream soda	86.70	0.0	0.0	13.30	0.0	0.10	—	0.91	0.43	125
Ginger ale	91.20	0.0	0.0	8.70	0.0	0.0	—	0.94	0.41	131
Grape soda	88.80	0.0	0.0	11.20	0.0	0.10	—	0.93	0.42	128
Lemon-lime soda	89.50	0.0	0.0	10.40	0.0	0.10	—	0.93	0.42	129
Orange soda	87.60	0.0	0.0	12.30	0.0	0.10	—	0.92	0.43	126
Root beer	89.30	0.0	0.0	10.60	0.0	0.10	—	0.93	0.42	128
Chocolate milk, 2% fat	83.58	3.21	2.00	10.40	0.50	0.81	—	0.90	0.44	120
Miscellaneous										
Honey	17.10	0.30	0.0	82.40	0.20	0.20	—	0.48	—	25
Maple syrup	32.00	0.00	0.20	67.20	0.0	0.60	—	0.58	—	46
Popcorn, air-popped	4.10	12.00	4.20	77.90	15.10	1.80	—	0.49	—	6
oil-popped	2.80	9.00	28.10	57.20	10.00	2.90	—	0.48	—	4
Yeast, baker's, compressed	69.00	8.40	1.90	18.10	8.10	1.80	—	0.85	0.52	100

*Composition data from USDA (1996). Initial freezing point data from Table 1 in Chapter 30 of the 1993 *ASHRAE Handbook—Fundamentals* and USDA (1968). Specific heats calculated from equations in this chapter. Latent heat of fusion obtained by multiplying water content expressed in decimal form by 144 Btu/lb, the heat of fusion of water (Table 1 in Chapter 30 of the 1993 *ASHRAE Handbook—Fundamentals*).

Example 1. A 300 lb beef carcass is to be frozen to 0°F. What are the masses of the frozen and unfrozen water at 0°F?

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 28.9°F. Using Equation (5), the mass fraction of ice is

$$x_{ice} = \frac{1.105 \times 0.58}{1 + \dfrac{0.7138}{\ln[1 + (28.9 - 0)/1.8]}} = 0.51$$

The mass fraction of unfrozen water is

$$x_u = x_{wo} - x_{ice} = 0.58 - 0.51 = 0.07$$

The mass of frozen water at 0°F is

$$x_{ice} \times 300 \text{ lb} = 0.51 \times 300 = 153 \text{ lb}$$

The mass of unfrozen water at 0°F is

$$x_u \times 300 \text{ lb} = 0.07 \times 300 = 21 \text{ lb}$$

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 32°F to 68°F. 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:

$$c_u = 1.0 - 0.55x_s - 0.15x_s^3 \tag{8}$$

where c_u is the specific heat of the unfrozen food in Btu/lb·°F 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)

$$c_a = c_u + (x_b - x_{wo})\Delta c + Ex_s\left[\frac{RT_o^2}{M_w(t-32)^2} - 0.8\Delta c\right] \tag{9}$$

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 = 1.986 Btu/lb mol·°R
T_o = freezing point of water = 491.7°R
M_w = relative molecular weight, lb_m/mol
t = food temperature, °F

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°F)
t_o = freezing point of water = 32°F
t_f = initial freezing point of food, °F
t = food temperature, °F
L_o = latent heat of fusion of water = 143.4 Btu/lb

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:

$$c_a = 0.37 + 0.30x_s + \frac{x_s RT_o^2}{M_s(t-32)^2} \tag{11}$$

where

c_a = apparent specific heat, Btu/lb·°F
x_s = mass fraction of solids
R = universal gas constant
T_o = freezing point of water = 491.7°R
M_s = relative molecular mass of soluble solids in food
t = food temperature, °F

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

$$c_a = 0.37 + 0.30x_s - \frac{L_o(x_{wo} - x_b)(t_f - 32)}{(t-32)^2} \tag{12}$$

Example 2. Three hundred pounds of lamb meat is to be cooled from 50°F to 32°F. 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} = 0.7342 x_f = 0.0525
x_p = 0.2029 x_a = 0.0106

Evaluate the specific heat of lamb at an average temperature of (50 + 32)/2 = 41°F. From Tables 1 and 2, the specific heat of the food constituents may be determined as follows:

$$c_w = 9.9827 \times 10^{-1} - 3.7879 \times 10^{-5}(41) + 4.0347 \times 10^{-7}(41)^2 = 0.9974 \text{ Btu/lb}\cdot°\text{F}$$

$$c_p = 4.7442 \times 10^{-1} + 1.6661 \times 10^{-4}(41) - 9.6784 \times 10^{-8}(41)^2 = 0.4811 \text{ Btu/lb}\cdot°\text{F}$$

$$c_f = 4.6730 \times 10^{-1} + 2.1815 \times 10^{-4}(41) - 3.5391 \times 10^{-7}(41)^2 = 0.4756 \text{ Btu/lb}\cdot°\text{F}$$

$$c_a = 2.5266 \times 10^{-1} + 2.6810 \times 10^{-4}(41) - 2.7141 \times 10^{-7}(41)^2 = 0.2632 \text{ Btu/lb}\cdot°\text{F}$$

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

$$c = \sum c_i x_i = (0.9974)(0.7342) + (0.4811)(0.2029) + (0.4756)(0.0525) + (0.2632)(0.0106)$$

$$c = 0.858 \text{ Btu/lb}\cdot°\text{F}$$

The heat to be removed from the lamb is thus

$$Q = mc\Delta T = 300 \times 0.858(50 - 32) = 4630 \text{ Btu}$$

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):

$$H = H_f + (t - t_f)(1.0 - 0.55x_s - 0.15x_s^3) \tag{15}$$

where

H = enthalpy of food, Btu/lb
H_f = enthalpy of food at initial freezing temperature, Btu/lb
t = temperature of food, °F
t_f = initial freezing temperature of food, °F
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):

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

Generally, the reference temperature T_r is taken to be 419.7°R (–40°F), 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:

$$H = (t - t_r)\left[0.37 + 0.30\,x_s + \frac{x_s R T_o^2}{M_s(t - 32)(t_r - 32)} \right] \tag{17}$$

where

H = enthalpy of food
R = universal gas constant
T_o = freezing point of water = 491.7°R

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

$$H = (t - t_r)\left[0.37 + 0.30\,x_s - \frac{(x_{wo} - x_b)L_o(t_f - 32)}{(t_r - 32)(t - 32)} \right] \tag{18}$$

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 –50°F have the following form:

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

where

H = enthalpy of food, Btu/lb
H_f = enthalpy of food at initial freezing temperature, Btu/lb
$\bar{T}$ = reduced temperature, $\bar{T} = (T - T_r)/(T_f - T_r)$
T_r = reference temperature (zero enthalpy) = 409.7°R (–50°F)
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:

$$T_f = 488.12 + 2.65x_{wo} \tag{22}$$

Fruit/Vegetable Group:

$$T_f = 517.61 - 88.54x_{wo} + 66.73x_{wo}^2 \tag{23}$$

Juice Group:

$$T_f = 216.85 + 589.23x_{wo} - 317.68x_{wo}^2 \tag{24}$$

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:

$$H_f = 4.21 + 0.17416x_{wo} \tag{25}$$

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

Example 3. A 300 lb beef carcass is to be frozen to a temperature of 0°F. The initial temperature of the beef carcass is 50°F. 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 28.9°F. 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 0°F is given by Equation (18) for frozen foods:

$$H_0 = [0 - (-40)]\left[0.37 + 0.30 \times 0.4179 - \frac{(0.5821 - 0.0699)143.4(28.9 - 32)}{(-40 - 32)(0 - 32)}\right] = 23.77 \text{ Btu/lb}$$

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

$$H_f = [28.9 - (-40)]\left[0.37 + 0.30 \times 0.4179 - \frac{(0.5821 - 0.0699)143.4(28.9 - 32)}{(-40 - 32)(28.9 - 32)}\right] = 104.42 \text{ Btu/lb}$$

The enthalpy of the beef carcass at 50°F is given by Equation (15) for unfrozen foods:

$$\begin{aligned} H_{50} &= 104.42 + (50 - 28.9) \times [1 - 0.55(0.4179) - 0.15(0.4179)^3] \\ &= 120.44 \text{ Btu/lb} \end{aligned}$$

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

$$\begin{aligned} Q &= m\Delta H = m(H_{50} - H_0) \\ &= 300(120.44 - 23.77) = 29{,}000 \text{ Btu} \end{aligned}$$

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:

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

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:

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

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:

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

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

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

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

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

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:

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

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:

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

where

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

and R_1 is the volume fraction of component 1, or

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

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, °F −40	−20	−10	−5	0	5	10	15	18	20	22	24	26	28	30	32
Fruits and Vegetables																		
Applesauce	82.8	Enthalpy, Btu/lb	0	11	17	21	25	30	36	43	49	56	61	71	84	114	145	147
		% water unfrozen	—	5	7	9	11	14	17	20	25	28	33	41	52	76	100	—
Asparagus, peeled	92.6	Enthalpy, Btu/lb	0	8	14	16	19	22	26	30	34	37	40	44	51	63	101	162
		% water unfrozen	—	—	—	4	5	6	7	9	10	12	16	20	28	55	100	—
Bilberries	85.1	Enthalpy, Btu/lb	0	10	15	18	22	25	30	37	41	45	50	56	67	87	149	151
		% water unfrozen	—	—	5	6	7	9	11	14	17	19	22	27	35	50	100	—
Carrots	87.5	Enthalpy, Btu/lb	0	10	15	18	22	26	31	37	41	45	50	57	68	88	152	154
		% water unfrozen	—	—	5	6	7	9	11	14	17	19	22	27	35	50	100	—
Cucumbers	95.4	Enthalpy, Btu/lb	0	8	13	16	18	21	24	27	30	32	35	38	43	52	78	167
		% water unfrozen	—	—	—	—	—	—	—	—	6	7	8	9	12	18	36	100
Onions	85.5	Enthalpy, Btu/lb	0	10	16	20	24	28	34	40	46	52	57	66	79	105	149	151
		% water unfrozen	—	5	7	8	9	12	15	18	21	24	28	35	45	65	100	—
Peaches, without stones	85.1	Enthalpy, Btu/lb	0	10	16	20	24	28	34	42	47	53	59	67	81	108	148	150
		% water unfrozen	—	5	7	8	10	12	15	18	22	26	30	37	48	69	100	—
Pears, Bartlett	83.8	Enthalpy, Btu/lb	0	10	17	21	25	29	35	42	47	53	59	69	83	111	146	148
		% water unfrozen	—	6	8	9	10	12	15	19	23	27	31	38	49	72	100	—
Plums, without stones	80.3	Enthalpy, Btu/lb	0	12	19	24	28	33	40	50	57	64	73	85	113	139	141	143
		% water unfrozen	—	8	11	13	16	18	22	28	34	38	46	55	71	100	—	—
Raspberries	82.7	Enthalpy, Btu/lb	0	10	16	19	22	26	31	38	42	46	52	59	71	92	146	148
		% water unfrozen	—	4	6	7	8	9	12	15	18	21	24	30	39	56	100	—
Spinach	90.2	Enthalpy, Btu/lb	0	8	14	16	19	22	26	29	32	35	38	42	48	59	93	158
		% water unfrozen	—	—	—	—	—	—	5	7	9	10	11	14	18	25	50	100
Strawberries	89.3	Enthalpy, Btu/lb	0	9	15	18	21	25	29	34	39	41	45	51	60	77	127	158
		% water unfrozen	—	—	—	5	6	7	8	10	13	15	18	21	28	40	79	100
Sweet cherries, without stones	77.0	Enthalpy, Btu/lb	0	12	20	24	29	35	42	51	59	67	76	89	110	134	136	138
		% water unfrozen	—	9	12	14	17	20	25	32	38	43	50	62	80	100	—	—
Tall peas	75.8	Enthalpy, Btu/lb	0	10	17	21	25	30	36	43	49	54	61	70	86	114	137	139
		% water unfrozen	—	6	8	10	12	15	18	22	27	30	37	44	57	82	100	—
Tomato pulp	92.9	Enthalpy, Btu/lb	0	10	14	17	20	23	27	32	36	39	42	47	54	68	112	163
		% water unfrozen	—	—	—	—	—	5	6	8	10	12	14	18	22	31	62	100
Fish and Meat																		
Cod	80.3	Enthalpy, Btu/lb	0	10	15	18	21	24	28	33	36	39	43	48	56	73	123	139
		% water unfrozen	10	10	10	11	12	13	14	16	18	20	22	26	32	45	88	100
Haddock	83.6	Enthalpy, Btu/lb	0	9	15	18	21	24	28	33	36	39	43	48	56	73	127	145
		% water unfrozen	8	8	9	9	10	11	12	14	15	17	19	23	29	42	86	100
Perch	79.1	Enthalpy, Btu/lb	0	9	14	17	20	23	27	32	35	38	42	46	53	68	117	137
		% water unfrozen	10	10	11	11	12	13	14	16	17	19	21	24	30	41	83	100
Beef, lean, fresh[a]	74.5	Enthalpy, Btu/lb	0	9	15	18	21	24	27	32	35	38	42	48	57	74	119	131
		% water unfrozen	10	10	11	12	12	13	15	18	20	22	24	28	37	48	92	100
lean, dried	26.1	Enthalpy, Btu/lb	0	9	14	17	20	24	28	31	—	33	—	36	—	38	—	40
		% water unfrozen	96	96	96	97	98	99	100	—	—	—	—	—	—	—	—	—
Eggs																		
White	86.5	Enthalpy, Btu/lb	0	9	14	16	19	22	25	29	31	33	36	40	45	55	87	151
		% water unfrozen	—	—	—	—	—	—	—	—	10	12	13	14	17	22	48	100
Yolk	50.0	Enthalpy, Btu/lb	0	9	14	16	19	22	25	29	31	33	35	38	42	47	65	98
		% water unfrozen	—	—	—	—	—	—	—	—	—	—	20	23	27	32	66	100
	40.0	Enthalpy, Btu/lb	0	9	14	17	20	23	26	31	33	35	38	41	46	53	76	82
		% water unfrozen	20	—	—	—	24	—	27	—	30	—	34	38	43	54	89	100
Whole, with shell[b]	66.4	Enthalpy, Btu/lb	0	9	13	15	18	20	23	27	29	31	34	37	41	49	73	121
Bread																		
White	37.3	Enthalpy, Btu/lb	0	9	13	15	18	21	26	34	40	45	51	55	56	57	58	59
Whole wheat	42.4	Enthalpy, Btu/lb	0	9	13	15	18	22	27	36	43	48	55	62	67	68	69	70

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°F. Use both the parallel and perpendicular thermal conductivity models.

Solution:

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

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

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

In addition, the initial freezing point of lean pork shoulder meat is 28°F. 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

$$x_{ice} = (x_{wo} - x_b)\left(1 - \frac{t_f - 32}{t - 32}\right) = (x_{wo} - 0.4x_p)\left(1 - \frac{t_f - 32}{t - 32}\right)$$

$$= [0.7263 - (0.4)(0.1955)]\left(1 - \frac{28 - 32}{-40 - 32}\right) = 0.6121$$

The mass fraction of unfrozen water is then

$$x_w = x_{wo} - x_{ice} = 0.7263 - 0.6121 = 0.1142$$

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

$$\rho_w = 6.2174 \times 10^1 + 4.7425 \times 10^{-3}(-40) - 7.2397 \times 10^{-5}(-40)^2$$
$$= 61.868 \text{ lb/ft}^3$$

$$\rho_{ice} = 5.7385 \times 10^1 - 4.5333 \times 10^{-3}(-40)$$
$$= 57.566 \text{ lb/ft}^3$$

$$\rho_p = 8.3599 \times 10^1 - 1.7979 \times 10^{-2}(-40)$$
$$= 84.318 \text{ lb/ft}^3$$

$$\rho_f = 5.8246 \times 10^1 - 1.4482 \times 10^{-2}(-40)$$
$$= 58.825 \text{ lb/ft}^3$$

$$\rho_a = 1.5162 \times 10^2 - 9.7329 \times 10^{-3}(-40)$$
$$= 152.01 \text{ lb/ft}^3$$

$$k_w = 3.1064 \times 10^{-1} + 6.4226 \times 10^{-4}(-40) - 1.1955 \times 10^{-6}(-40)^2$$
$$= 0.2830 \text{ Btu/h·ft·°F}$$

$$k_{ice} = 1.3652 - 3.1648 \times 10^{-3}(-40) + 1.8108 \times 10^{-5}(-40)^2$$
$$= 1.521 \text{ Btu/h·ft·°F}$$

$$k_p = 9.0535 \times 10^{-2} + 4.1486 \times 10^{-4}(-40) - 4.8467 \times 10^{-7}(-40)^2$$
$$= 0.07317 \text{ Btu/h·ft·°F}$$

$$k_f = 1.3273 \times 10^{-1} - 8.8405 \times 10^{-4}(-40) - 3.1652 \times 10^{-8}(-40)^2$$
$$= 0.1680 \text{ Btu/h·ft·°F}$$

$$k_a = 1.7553 \times 10^{-1} + 4.8292 \times 10^{-4}(-40) - 5.1839 \times 10^{-7}(-40)^2$$
$$= 0.1554 \text{ Btu/h·ft·°F}$$

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

$$\sum\frac{x_i}{\rho_i} = \frac{0.6121}{57.566} + \frac{0.1142}{61.868} + \frac{0.1955}{84.318} + \frac{0.0714}{58.825} + \frac{0.0102}{152.01}$$
$$= 1.6078 \times 10^{-2}$$

$$\rho = \frac{1 - \varepsilon}{\sum x_i/p_i} = \frac{1 - 0}{1.6078 \times 10^{-2}} = 62.2 \text{ lb/ft}^3$$

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

$$x_{ice}^v = \frac{x_{ice}/\rho_{ice}}{\sum x_i/p_i} = \frac{0.6121/57.566}{1.6078 \times 10^{-2}} = 0.6613$$

$$x_w^v = \frac{x_w/\rho_w}{\sum x_i/p_i} = \frac{0.1142/61.868}{1.6078 \times 10^{-2}} = 0.1148$$

$$x_p^v = \frac{x_p/\rho_p}{\sum x_i/p_i} = \frac{0.1955/84.318}{1.6078 \times 10^{-2}} = 0.1442$$

$$x_f^v = \frac{x_f/\rho_f}{\sum x_i/p_i} = \frac{0.0714/58.825}{1.6078 \times 10^{-2}} = 0.0755$$

$$x_f^a = \frac{x_a/\rho_a}{\sum x_i/p_i} = \frac{0.0102/152.01}{1.6078 \times 10^{-2}} = 0.0042$$

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

$$k = \sum x_i^v k_i = (0.6613)(1.521) + (0.1148)(0.2830)$$
$$+ (0.1442)(0.0731) + (0.0755)(0.1680) + (0.0042)(0.1554)$$
$$k = 1.06 \text{ Btu/h·ft·°F}$$

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

$$k = \frac{1}{\sum x_i^v/k_i} = \left(\frac{0.6613}{1.521} + \frac{0.1148}{0.2830} + \frac{0.1442}{0.07317} + \frac{0.0755}{0.1680} + \frac{0.0042}{0.1554}\right)^{-1}$$
$$k = 0.304 \text{ Btu/h·ft·°F}$$

Table 5 Thermal Conductivity of Foods

Food[a]	Thermal Conductivity Btu/h·ft·°F	Temperature, °F	Water Content, % by mass	Reference[b]	Remarks
Fruits, Vegetables					
Apples	0.242	46.4	—	Gane (1936)	Tasmanian French crabapple, whole fruit; 0.3 lb
dried	0.127	73.4	41.6	Sweat (1985)	Density = 54 lb/ft^3
Apple juice	0.323	68	87	Riedel (1949)	Refractive index at 68°F = 1.35
	0.365	176	87		
	0.291	68	70		Refractive index at 68°F = 1.38
	0.326	176	70		
	0.225	68	36		Refractive index at 68°F = 1.45
	0.251	176	36		
Applesauce	0.317	84.2	—	Sweat (1974)	
Apricots, dried	0.217	73.4	43.6	Sweat (1985)	Density = 82 lb/ft^3
Beans, runner	0.230	48.2	—	Smith et al. (1952)	Density = 47 lb/ft^3; machine sliced, scalded, packed in slab
Beets	0.347	82.4	87.6	Sweat (1974)	
Broccoli	0.222	21.2	—	Smith et al. (1952)	Density = 35 lb/ft^3; heads cut and scalded
Carrots	0.387	3.2	—	Smith et al. (1952)	Density = 37 lb/ft^3; scraped, sliced and scalded
pureed	0.728	17.6	—	Smith et al. (1952)	Density = 56 lb/ft^3; slab
Currants, black	0.179	1.4	—	Smith et al. (1952)	Density = 40 lb/ft^3
Dates	0.195	73.4	34.5	Sweat (1985)	Density = 82 lb/ft^3
Figs	0.179	73.4	40.4	Sweat (1985)	Density = 77 lb/ft^3
Gooseberries	0.159	5	—	Smith et al. (1952)	Density = 36 lb/ft^3; mixed sizes
Grapefruit juice vesicle	0.267	86	—	Bennett et al. (1964)	Marsh, seedless
Grapefruit rind	0.137	82	—	Bennett et al. (1964)	Marsh, seedless
Grape, green, juice	0.328	68	89	Riedel (1949)	Refractive index at 68°F = 1.35
	0.369	176	89		
	0.287	68	68		Refractive index at 68°F = 1.38
	0.320	176	68		
	0.229	68	37		Refractive index at 20°C = 1.45
	0.254	176	37		
	0.254	77	—	Turrell and Perry (1957)	Eureka
Grape jelly	0.226	68	42.0	Sweat (1985)	Density = 82 lb/ft^3
Nectarines	0.338	47.5	82.9	Sweat (1974)	
Onions	0.332	47.5	—	Saravacos (1965)	
Orange juice vesicle	0.251	86	—	Bennett et al. (1964)	Valencia
Orange rind	0.103	86	—	Bennett et al. (1964)	Valencia
Peas	0.277	8.6	—	Smith et al. (1952)	Density = 44 lb/ft^3; shelled and scalded
	0.228	26.6	—		
	0.182	44.6	—		
Peaches, dried	0.209	73.4	43.4	Sweat (1985)	Density = 79 lb/ft^3
Pears	0.344	47.7	—	Sweat (1974)	
Pear juice	0.318	68	85	Riedel (1949)	Refractive index at 68°F = 1.36
	0.363	176	85		
	0.274	68	60		Refractive index at 68°F = 1.40
	0.307	176	60		
	0.232	68	39		Refractive index at 68°F = 1.44
	0.258	176	39		
Plums	0.143	3.2	—	Smith et al. (1952)	Density = 38 lb/ft^3; 1.57 in. dia.; 2.0 in. long
Potatoes, mashed	0.630	8.6	—	Smith et al. (1952)	Density = 61 lb/ft^3; tightly packed slab
Potato salad	0.277	35.6	—	Dickerson and Read (1968)	Density = 63 lb/ft^3
Prunes	0.217	73.4	42.9	Sweat (1985)	Density = 76 lb/ft^3
Raisins	0.194	73.4	32.2	Sweat (1985)	Density = 86 lb/ft^3
Strawberries	0.636	6.8	—	Smith et al. (1952)	Mixed sizes, density = 50 lb/ft^3, slab
	0.555	5	—		Mixed sizes in 57% sucrose syrup, slab
Strawberry jam	0.195	68	41.0	Sweat (1985)	Density = 82 lb/ft^3
Squash	0.290	46.4	—	Gane (1936)	
Meat and Animal By-Products					
Beef, lean =[a]	0.292	37.4	75	Lentz (1961)	Sirloin; 0.9% fat
	0.820	5	75		
	0.248	68	79	Hill et al. (1967)	1.4% fat
	0.826	5	79		
	0.231	42.8	76.5	Hill (1966), Hill et al. (1967)	2.4% fat
	0.786	5	76.5		
⊥[a]	0.277	68	79	Hill et al. (1967)	Inside round; 0.8% fat
	0.780	5	79		
	0.237	42.8	76	Hill (1966), Hill et al. (1967)	3% fat
	0.659	5	76		
	0.272	37.4	74	Lentz (1961)	Flank; 3 to 4% fat
	0.647	5	74		
ground	0.235	42.8	67	Qashou et al. (1970)	12.3% fat; density = 59 lb/ft^3
	0.237	39.2	62		16.8% fat; density = 61 lb/ft^3
	0.203	42.8	55		18% fat; density = 58 lb/ft^3

Table 5 Thermal Conductivity of Foods (*Continued*)

Food[a]	Thermal Conductivity Btu/h·ft·°F	Temperature, °F	Water Content, % by mass	Reference[b]	Remarks
Beef, ground (*continued*)	0.210	37.4	53		22% fat; density = 59 lb/ft^3
Beef brain	0.287	95	77.7	Poppendiek et al. (1965-1966)	12% fat; 10.3% protein; density = 63 lb/ft^3
Beef fat	0.110	95	0.0	Poppendiek et al. (1965-1966)	Melted 100% fat; density = 51 lb/ft^3
	0.133	95	20		Density = 54 lb/ft^3
⊥[a]	0.125	35.6	9	Lentz (1961)	89% fat
	0.166	15.8	9		
Beef kidney	0.303	95	76.4	Poppendiek et al. (1965-1966)	8.3% fat, 15.3% protein; density = 64 lb/ft^3
Beef liver	0.282	95	72	Poppendiek et al. (1965-1966)	7.2% fat, 20.6% protein
Beefstick	0.172	68	36.6	Sweat (1985)	Density = 66 lb/ft^3
Bologna	0.243	68	64.7	Sweat (1985)	Density = 62 lb/ft^3
Dog food	0.184	73.4	30.6	Sweat (1985)	Density = 77 lb/ft^3
Cat food	0.188	73.4	39.7	Sweat (1985)	Density = 71 lb/ft^3
Ham, country	0.277	68	71.8	Sweat (1985)	Density = 64 lb/ft^3
Horse meat ⊥[a]	0.266	86	70	Griffiths and Cole (1948)	Lean
Lamb ⊥[a]	0.263	68	72	Hill et al. (1967)	8.7% fat
	0.647	5	72		
=[a]	0.231	68	71	Hill et al. (1967)	9.6% fat
	0.734	5	71		
Pepperoni	0.148	68	32.0	Sweat (1985)	Density = 66 lb/ft^3
Pork fat	0.124	37.4	6	Lentz (1961)	93% fat
	0.126	5	6		
Pork, lean =[a]	0.262	68	76	Hill et al. (1967)	6.7% fat
	0.820	8.6	76		
⊥[a]	0.292	68	76	Hill et al. (1967)	6.7% fat
	0.751	6.8	76		
lean flank	0.266	36.0	—	Lentz (1961)	3.4% fat
	0.705	5	—		
lean leg =[a]	0.276	39.2	72	Lentz (1961)	6.1% fat
	0.861	5	72		
⊥[a]	0.263	39.2	72	Lentz (1961)	6.1% fat
	0.745	5	72		
Salami	0.180	68	35.6	Sweat (1985)	Density = 60 lb/ft^3
Sausage	0.247	77	68	Nowrey and Woodams (1968),	Mixture of beef and pork; 16.1% fat, 12.2% protein
	0.222	77	62	Woodams (1965)	Mixture of beef and pork; 24.1% fat, 10.3% protein
Veal ⊥[a]	0.272	68	75	Hill et al. (1967)	2.1% fat
	0.797	5	75		
=[a]	0.257	82.4	75	Hill et al. (1967)	2.1% fat
	0.844	5	75		
Poultry and Eggs					
Chicken breast ⊥[a]	0.238	68	69−75	Walters and May (1963)	0.6% fat
with skin	0.211	68	58−74	Walters and May (1963)	0−30% fat
Turkey, breast ⊥[a]	0.287	37.4	74	Lentz (1961)	2.1% fat
	0.797	5	74		
leg ⊥[a]	0.287	39.2	74	Lentz (1961)	3.4% fat
	0.711	5	74		
breast = ⊥[a]	0.290	37.4	74	Lentz (1961)	2.1% fat
	0.884	5	74		
Egg, white	0.322	96.8	88	Spells (1958, 1960-1961)	
whole	0.555	17.6	—	Smith et al. (1952)	Density = 61 lb/ft^3
yolk	0.243	87.8	50.6	Poppendiek et al. (1965-1966)	32.7% fat; 16.7% protein, density = 64 lb/ft^3
Fish and Sea Products					
Fish, cod	0.324	33.8	—	Jason and Long (1955), Long (1955)	
	0.976	5	—	Long (1955)	
⊥[a]	0.309	37.4	83	Lentz (1961)	0.1% fat
	0.844	5	83		
Fish, herring	0.462	-2.2	—	Smith et al. (1952)	Density = 57 lb/ft^3; whole and gutted
Fish, salmon ⊥[a]	0.307	37.4	67	Lentz (1961)	12% fat; *Salmo salar* from Gaspe peninsula
	0.716	5	67		
	0.288	41	73	Lentz (1961)	5.4% fat; *Oncorhynchus tchawytscha* from British Columbia
	0.653	5	73		
Seal blubber ⊥[a]	0.114	41	4.3	Lentz (1961)	95% fat
Whale blubber ⊥[a]	0.121	64.4	—	Griffiths and Cole (1948)	Density = 65 lb/ft^3
Whale meat	0.375	89.6	—	Griffiths and Hickman (1951)	Density = 67 lb/ft^3
	0.832	15.8	—		
	0.740	10.4	—	Smith et al. (1952)	0.51% fat; density = 62 lb/ft^3
Dairy Products					
Butterfat	0.100	42.8	0.6	Lentz (1961)	
	0.103	5	0.6		

Table 5 Thermal Conductivity of Foods (*Continued*)

Food[a]	Thermal Conductivity Btu/h·ft·°F	Temperature, °F	Water Content, % by mass	Reference[b]	Remarks
Butter	0.114	39.2	—	Hooper and Chang (1952)	
Buttermilk	0.329	68	89	Riedel (1949)	0.35% fat
Milk, whole	0.335	82.4	90	Leidenfrost (1959)	3% fat
	0.302	35.6	83	Riedel (1949)	3.6% fat
	0.318	68	83		
	0.339	122	83		
	0.355	176	83		
skimmed	0.311	35.6	90	Riedel (1949)	0.1% fat
	0.327	68	90		
	0.350	122	90		
	0.367	176	90		
evaporated	0.281	35.6	72	Riedel (1949)	4.8% fat
	0.291	68	72		
	0.313	122	72		
	0.326	176	72		
	0.263	35.6	62	Riedel (1949)	6.4% fat
	0.273	68	62		
	0.295	122	62		
	0.307	176	62		
	0.273	73.4	67	Leidenfrost (1959)	10% fat
	0.291	105.8	67		
	0.298	140	67		
	0.304	174.2	67		
	0.187	78.8	50	Leidenfrost (1959)	15% fat
	0.196	104	50		
	0.206	138.2	50		
	0.210	174.2	50		
Whey	0.312	35.6	90	Riedel (1949)	No fat
	0.328	68	90		
	0.364	122	90		
	0.370	176	90		
Sugar, Starch, Bakery Products, and Derivatives					
Sugar beet juice	0.318	77	79	Khelemskii and Zhadan (1964)	
	0.329	77	82		
Sucrose solution	0.309	32	90	Riedel (1949)	Cane or beet sugar solution
	0.327	68	90		
	0.351	122	90		
	0.367	176	90		
	0.291	32	80		
	0.309	68	80		
	0.330	122	80		
	0.347	176	80		
	0.273	32	70		
	0.289	68	70		
	0.310	122	70		
	0.325	176	70		
	0.256	32	60		
	0.272	68	60		
	0.290	122	60		
	0.303	176	60		
	0.239	32	50		
	0.252	68	50		
	0.270	122	93 to 80		
	0.283	176	93 to 80		
	0.221	32	40		
	0.233	68	40		
	0.251	122	40		
	0.262	176	40		
Glucose solution	0.311	35.6	89	Riedel (1949)	
	0.327	68	89		
	0.347	122	89		
	0.369	176	89		
	0.294	35.6	80		
	0.309	68	80		
	0.330	122	80		

Table 5 Thermal Conductivity of Foods (*Continued*)

Food [a]	Thermal Conductivity Btu/h·ft·°F	Temper-ature, °F	Water Content, % by mass	Reference [b]	Remarks
Glucose solution (*continued*)					
	0.346	176	80		
	0.276	35.6	70		
	0.291	68	70		
	0.311	122	70		
	0.326	176	70		
	0.258	35.6	60		
	0.272	68	60		
	0.289	122	60		
	0.306	176	60		
Corn syrup	0.325	77	—	Metzner and Friend (1959)	Density = 72 lb/ft^3
	0.280	77	—		Density = 82 lb/ft^3
	0.270	77	—		Density = 84 lb/ft^3
Honey	0.290	35.6	80	Reidy (1968)	
	0.240	156.2	80		
Molasses syrup	0.200	86	23	Popov and Terentiev (1966)	
Cake, angel food	0.057	73.4	36.1	Sweat (1985)	Density = 9.4 lb/ft^3, porosity: 88%
applesauce	0.046	73.4	23.7	Sweat (1985)	Density = 19 lb/ft^3, porosity: 78%
carrot	0.049	73.4	21.6	Sweat (1985)	Density = 20 lb/ft^3, porosity: 75%
chocolate	0.061	73.4	31.9	Sweat (1985)	Density = 21 lb/ft^3, porosity: 74%
pound	0.076	73.4	22.7	Sweat (1985)	Density = 30 lb/ft^3, porosity: 58%
yellow	0.064	73.4	25.1	Sweat (1985)	Density = 19 lb/ft^3, porosity: 78%
white	0.047	73.4	32.3	Sweat (1985)	Density = 28 lb/ft^3, porosity: 62%
Grains, Cereals, and Seeds					
Corn, yellow	0.081	89.6	0.9	Kazarian (1962)	Density = 47 lb/ft^3
	0.092	89.6	14.7		Density = 47 lb/ft^3
	0.099	89.6	30.2		Density = 42 lb/ft^3
Flaxseed	0.066	89.6	—	Griffiths and Hickman (1951)	Density = 41 lb/ft^3
Oats, white English	0.075	80.6	12.7	Oxley (1944)	
Sorghum	0.076	41	13	Miller (1963)	Hybrid Rs610 grain
	0.087		22		
Wheat, No. 1, northern hard spring	0.078	93.2	2	Moote (1953)	Values taken from plot of series of values given by authors
	0.086	—	7	Babbitt (1945)	
	0.090	—	10		
	0.097	—	14		
	0.000	32			
Wheat, soft white winter	0.070	87.8	5	Kazarian (1962)	Values taken from plot of series of values given by author; Density = 49 lb/ft^3
	0.075	87.8	10		
	0.079	87.8	15		
Fats, Oils, Gums, and Extracts					
Gelatin gel	0.302	41	94–80	Lentz (1961)	Conductivity did not vary with concentration in range tested (6, 12, 20%)
	1.236	5	94		6% gelatin concentration
	1.121	5	88		12% gelatin concentration
	0.815	5	80		20% gelatin concentration
Margarine	0.135	41	—	Hooper and Chang (1952)	Density = 62 lb/ft^3
Oil, almond	0.102	39.2	—	Wachsmuth (1892)	Density = 57 lb/ft^3
cod liver	0.098	95	—	Spells (1958, 1960-1961)	
lemon	0.090	42.8	—	Weber (1880)	Density = 51 lb/ft^3
mustard	0.098	77	—	Weber (1886)	Density = 64 lb/ft^3
nutmeg	0.090	39.2	—	Wachsmuth (1892)	Density = 59 lb/ft^3
olive	0.101	44.6	—	Weber (1880)	Density = 57 lb/ft^3
	0.097	89.6	—	Kaye and Higgins (1928)	Density = 57 lb/ft^3
	0.096	149	—		
	0.092	304	—		
	0.090	365	—		
peanut	0.097	39.2	—	Wachsmuth (1892)	Density = 57 lb/ft^3
	0.098	77	—	Woodams (1965)	
rapeseed	0.092	68	—	Kondrat'ev (1950)	Density = 57 lb/ft^3
sesame	0.102	39.2	—	Wachsmuth (1892)	Density = 57 lb/ft^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, Btu/h·ft·°F	Temperature, °F	Pressure, psia	Reference[b]	Remarks
Apple	0.0090	95	0.000386	Harper (1960, 1962)	Delicious; 88% porosity; 5.1 tortuosity factor; measured in air
	0.0107	95	0.00305		
	0.0163	95	0.0271		
	0.0234	95	0.418		
Peach	0.0095	95	0.000870	Harper (1960, 1962)	Clingstone; 91% porosity; 4.1 tortuosity factor; measured in air
	0.0107	95	0.00312		
	0.0161	95	0.0271		
	0.0237	95	0.387		
	0.0249	95	7.40		
Pears	0.0107	95	0.000309	Harper (1960, 1962)	97% porosity; measured in nitrogen
	0.0120	95	0.00283		
	0.0177	95	0.0271		
	0.0242	95	0.312		
	0.0261	95	10.0		
Beef =[a]	0.0221	95	0.000212	Harper (1960, 1962)	Lean; 64% porosity; 4.4 tortuosity factor; measured in air
	0.0238	95	0.00329		
	0.0307	95	0.0345		
	0.0358	95	0.392		
	0.0377	95	14.7		
Egg albumin gel	0.0227	106	14.7	Saravacos and Pilsworth (1965)	2% water content; measured in air
	0.0075	106	0.00064	Saravacos and Pilsworth (1965)	Measured in air
Turkey =[a]	0.0166	—	0.000773	Triebes and King (1966)	Cooked white meat; 68 to 72% porosity; measured in air
	0.0256	—	0.00218		
	0.0408	—	0.0677		
	0.0497	—	0.309		
	0.0536	—	14.3		
⊥[a]	0.0098	—	0.000812	Triebes and King (1966)	Cooked white meat; 68 to 72% porosity; measured in air
	0.0101	—	0.00274		
	0.0128	—	0.0193		
	0.0241	—	0.181		
	0.0339	—	12.7		
Potato starch gel	0.0053	—	0.000624	Saravacos and Pilsworth (1965)	Measured in air
	0.0083	—	0.0262		
	0.0168	—	0.320		
	0.0227	—	14.9		

[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°F. Use the isotropic model developed by Kopelman (1966).

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 is 28°F. 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

$$x_{ice} = 0.6121$$

The mass fraction of unfrozen water is then

$$x_w = x_{wo} - x_{ice} = 0.7263 - 0.6121 = 0.1142$$

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

$$\rho_w = 61.868 \text{ lb/ft}^3 \qquad k_w = 0.2830 \text{ Btu/h·ft·°F}$$
$$\rho_{ice} = 57.566 \text{ lb/ft}^3 \qquad k_{ice} = 1.521 \text{ Btu/h·ft·°F}$$
$$\rho_p = 84.318 \text{ lb/ft}^3 \qquad k_p = 0.07317 \text{ Btu/h·ft·°F}$$
$$\rho_f = 58.825 \text{ lb/ft}^3 \qquad k_f = 0.1680 \text{ Btu/h·ft·°F}$$
$$\rho_a = 152.01 \text{ lb/ft}^3 \qquad k_a = 0.1554 \text{ Btu/h·ft·°F}$$

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

$$x_w^v = \frac{x_w/\rho_w}{\sum \frac{x_i}{\rho_i}} = \frac{0.1142/61.868}{\frac{0.1142}{61.868} + \frac{0.6121}{57.566}} = 0.1479$$

$$x_{ice}^v = \frac{x_{ice}/\rho_{ice}}{\sum \frac{x_i}{\rho_i}} = \frac{0.6121/57.566}{\frac{0.1142}{61.868} + \frac{0.6121}{57.566}} = 0.8521$$

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

$$L^3 = x_w^v = 0.1479$$
$$L^2 = 0.2797$$
$$L = 0.5288$$

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):

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

$$= 1.521\left[\frac{1-0.2797}{1-0.2797(1-0.5288)}\right] = 1.2619 \text{ Btu/h·ft·°F}$$

The density of the ice/water mixture then becomes

$$\rho_{ice/water} = x_w^v \rho_w + x_{ice}^v \rho_{ice}$$
$$= (0.1479)(61.868) + (0.8521)(57.566)$$
$$= 58.202 \text{ lb/ft}^3$$

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

$$x_p^v = \frac{x_p/\rho_p}{\sum \frac{x_i}{\rho_i}} = \frac{0.1955/84.318}{\frac{0.1955}{84.318} + \frac{0.7263}{58.202}} = 0.1567$$

$$x_{ice/water}^v = \frac{x_{ice/water}/\rho_{ice/water}}{\sum \frac{x_i}{\rho_i}} = \frac{0.7263/58.202}{\frac{0.1955}{84.318} + \frac{0.7263}{58.202}} = 0.8433$$

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

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

$$= 1.2619\left[\frac{1-0.2907}{1-0.2907(1-0.5391)}\right]$$

$$= 1.0335 \text{ Btu/h·ft·°F}$$

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

$$\rho_{ice/water/protein} = x_{ice/water}^v \rho_{ice/water} + x_p^v \rho_p$$
$$= (0.8433)(58.202) + (0.1567)(84.318)$$
$$= 62.294 \text{ lb/ft}^3$$

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:

$$x_f^v = \frac{x_f/\rho_f}{\sum \frac{x_i}{\rho_i}} = \frac{0.0714/58.825}{\frac{0.0714}{58.825} + \frac{0.9218}{62.294}} = 0.0758$$

$$x_{i/w/p}^v = \frac{x_{i/w/p}/\rho_{i/w/p}}{\sum \frac{x_i}{\rho_i}} = \frac{0.9218/62.294}{\frac{0.0714}{58.825} + \frac{0.9218}{62.294}} = 0.9242$$

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

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

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

$$= 1.0335\left[\frac{1-0.1791}{1-0.1791(1-0.4232)}\right]$$

$$= 0.9461 \text{ Btu/h·ft·°F}$$

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

$$\rho_{i/w/p/f} = x_{i/w/p}^v \rho_{i/w/p} + x_f^v \rho_f$$
$$= (0.9242)(62.294) + (0.0758)(58.825)$$
$$= 62.031 \text{ lb/ft}^3$$

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:

$$x_a^v = \frac{x_a/\rho_a}{\sum \frac{x_i}{\rho_i}} = \frac{0.0102/152.01}{\frac{0.0102}{152.01} + \frac{0.9932}{62.031}} = 0.0042$$

$$x_{i/w/p/f}^v = \frac{\frac{x_{i/w/p/f}}{\rho_{i/w/p/f}}}{\sum \frac{x_i}{\rho_i}} = \frac{\frac{0.9932}{62.031}}{\frac{0.0102}{152.01} + \frac{0.9932}{62.031}} = 0.9958$$

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

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

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

$$= 0.9461\left[\frac{1-0.0260}{1-0.0260(1-0.1613)}\right]$$

$$= 0.942 \text{ Btu/h·ft·°F}$$

The density of the lean pork shoulder meat then becomes

$$\rho_{pork} = x_{i/w/p/f}^v \rho_{i/w/p/f} + x_a^v \rho_a$$
$$= (0.9958)(62.031) + (0.0042)(152.01)$$
$$= 62.4 \text{ lb/ft}^3$$

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, Centistokes	Water Content, % by mass	Fat Content, % by mass	Apparent Density, lb/ft^3	Temperature, °F	Reference
Fruits and Vegetables						
Apple, Red Delicious, whole[a]	0.14	85	—	52.4	32 to 86	Bennett et al. (1969)
dried	0.096	42	—	53.4	73	Sweat (1985)
Applesauce	0.11	37	—	—	41	Riedel (1969)
	0.11	37	—	—	149	Riedel (1969)
	0.12	80	—	—	41	Riedel (1969)
	0.14	80	—	—	149	Riedel (1969)
Apricots, dried	0.11	44	—	82.6	73	Sweat (1985)
Bananas, flesh	0.12	76	—	—	41	Riedel (1969)
	0.14	76	—	—	149	Riedel (1969)
Cherries, flesh[b]	0.13	—	—	65.5	32 to 86	Parker and Stout (1967)
Dates	0.10	35	—	82.3	73	Sweat (1985)
Figs	0.096	40	—	77.4	73	Sweat (1985)
Jam, strawberry	0.12	41	—	81.7	68	Sweat (1985)
Jelly, grape	0.12	42	—	82.4	68	Sweat (1985)
Peaches[b]	0.14	—	—	59.9	36 to 90	Bennett (1963)
dried	0.12	43	—	78.6	73	Sweat (1985)
Potatoes, whole	0.13	—	—	65 to 67	32 to 158	Mathews and Hall (1968), Minh et al. (1969)
mashed, cooked	0.12	78	—	—	41	Riedel (1969)
	0.15	78	—	—	149	Riedel (1969)
Prunes	0.12	43	—	76.1	73	Sweat (1985)
Raisins	0.11	32	—	86.1	73	Sweat (1985)
Strawberries, flesh	0.13	92	—	—	41	Riedel (1969)
Sugar beets	0.13	—	—	—	32 to 140	Slavicek et al. (1962)
Meats						
Codfish	0.12	81	—	—	41	Riedel (1969)
	0.14	81	—	—	149	Riedel (1969)
Halibut[c]	0.15	76	1	66.8	104 to 149	Dickerson and Read (1975)
Beef, chuck[d]	0.12	66	16	66.2	104 to 149	Dickerson and Read (1975)
round[d]	0.13	71	4	68.0	104 to 149	Dickerson and Read (1975)
tongue[d]	0.13	68	13	66.2	104 to 149	Dickerson and Read (1975)
Beefstick	0.11	37	—	65.5	68	Sweat (1985)
Bologna	0.13	65	—	62.4	68	Sweat (1985)
Corned beef	0.11	65	—	—	41	Riedel (1969)
	0.13	65	—	—	149	Riedel (1969)
Ham, country	0.14	72	—	64.3	68	Sweat (1985)
smoked[d]	0.12	64	—	—	41	Riedel (1969)
	0.13	64	14	68.0	104 to 149	Dickerson and Read (1975)
Pepperoni	0.093	32	—	66.1	68	Sweat (1985)
Salami	0.13	36	—	59.9	68	Sweat (1985)
Cakes						
Angel food	0.26	36	—	9.2	73	Sweat (1985)
Applesauce	0.12	24	—	18.7	73	Sweat (1985)
Carrot	0.12	22	—	20.0	73	Sweat (1985)
Chocolate	0.12	32	—	21.2	73	Sweat (1985)
Pound	0.12	23	—	30.0	73	Sweat (1985)
Yellow	0.12	25	—	18.7	73	Sweat (1985)
White	0.10	32	—	27.8	73	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:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2528 \text{ Btu} \tag{40}$$

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 Btu/h·lb as a function of temperature t in °F:

$$W = 0.00460 f(t)^g \tag{41}$$

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

Table 8 Commodity Respiration Coefficients

Commodity	Respiration Coefficients *f*	Respiration Coefficients *g*	Commodity	Respiration Coefficients *f*	Respiration Coefficients *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 32°F, the rate of respiration rarely increases because no ripening takes place. However, if fruits are stored at higher temperatures (50 to 60°F), the respiration rate increases because of ripening and then decreases. Soft fruits, such as blueberries, figs, and strawberries, decrease in respiration with time at 32°F. 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 32 and 40°F, 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 50°F 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 of Fresh Fruits and Vegetables Held at Various Temperatures

Commodity	Heat of Respiration, Btu/day per Ton of Produce 32°F	41°F	50°F	59°F	68°F	77°F	Reference
Apples							
Yellow, transparent	1513	2665	—	7889	12,392	—	Wright et al. (1954)
Delicious	757	1117	—	—	—	—	Lutz and Hardenburg (1968)
Golden Delicious	793	1189	—	—	—	—	Lutz and Hardenburg (1968)
Jonathan	865	1295	—	—	—	—	Lutz and Hardenburg (1968)
McIntosh	793	1189	—	—	—	—	Lutz and Hardenburg (1968)
Early cultivars	720-1369	1153-2342	3062-4503	3962-6844	4323-9005	—	IIR (1967)
Late cultivars	396-793	1008-1549	1513-2306	2053-4323	3242-5403	—	IIR (1967)
Average of many cultivars	505-901	1117-1585	—	2990-6808	3711-7709	—	Lutz and Hardenburg (1968)
Apricots	1153-1261	1405-1982	2449-4143	4683-7565	6484-11,527	—	Lutz and Hardenburg (1968)
Artichokes, globe	5007-9907	7025-13,220	1203-21,649	1704-31,951	3004-51,403	—	Rappaport and Watada (1958), Sastry et al. (1978)
Asparagus	6015-17,651	12,032-30,043	23,630-67,146	35,086-72,152	60,121-10,228	—	Lipton (1957), Sastry et al. (1978)
Avocados	*[b]	*[b]	—	13,616-34,581	16,246-76,439	—	Biale (1960), Lutz and Hardenburg (1968)
Bananas							
Green	*[b]	*[b]	†[b]	4431-7626	6484-11,527	—	IIR (1967)
Ripening	*[b]	*[b]	†[b]	6484-9726	7204-18,011	—	IIR (1967)
Beans							
Lima, unshelled	2306-6628	4323-7925	—	22,046-27,449	29,250-39,480	—	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
shelled	3890-7709	6412-13,436	—	—	46,577-59,509	—	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
Snap	*[b]	7529-7709	12,032-12,824	18,731-20,533	26,044-28,673	—	Ryall and Lipton (1972), Watada and Morris (1966)
Beets, red, roots	1189-1585	2017-2089	2594-2990	3711-5115	—	—	Ryall and Lipton (1972), Smith (1957)
Berries							
Blackberries	3458-5043	6304-10,086	11,527-20,893	15,489-32,060	28,818-43,227	—	IIR (1967)
Blueberries	505-2306	2017-2702	—	7529-13,616	11,419-19,236	—	Lutz and Hardenburg (1968)
Cranberries	*[b]	901-1008	—	—	2413-3999	—	Anderson et al. (1963), Lutz and Hardenburg (1968)
Gooseberries	1513-1909	2702-2990	—	4791-7096	—	—	Lutz and Hardenburg (1968), Smith (1966)
Raspberries	3890-5512	6808-8501	6124-12,248	18,119-22,334	25,215-54,033	—	Haller et al. (1941), IIR (1967), Lutz and Hardenburg (1968)
Strawberries	2702-3890	3602-7313	10,807-20,893	15,634-20,317	22,514-43,154	37,247-46,468	IIR (1967), Lutz and Hardenburg (1968), Maxie et al. (1959)
Broccoli, sprouting	4107-4719	7601-35,226	—	38,256-74,890	61,274-75,106	85,805-23,376	Morris (1947), Lutz and Hardenburg (1968), Scholz et al. (1963)
Brussels sprouts	3386-5295	7096-10,698	13,904-18,623	21,037-23,523	19,848-41,894	—	Sastry et al. (1978), Smith (1957)
Cabbage							
Penn State[c]	865	2089-2234	—	4935-6988	—	—	Van den Berg and Lentz (1972)
White, winter	1081-1801	1621-3062	2702-3962	4323-5944	7925-9006	—	IIR (1967)
spring	2089-2990	3890-4719	6412-7313	11,815-12,609	—	—	Sastry et al. (1978), Smith (1957)
Red, early	1693-2161	3423-3783	5224-61,238	8105-9366	12,248-12,608	—	IIR (1967)
Savoy	3422-4683	5584-6484	11,527-13,509	19,272-21,794	28,818-32,420	—	IIR (1967)
Carrots, roots							
Imperator, Texas	3386	4323	6916	8718	15,526	—	Scholz et al. (1963)
Main crop, United Kingdom	757-1513	1296-2666	2161-3423	6448-14,589 at 65°F	—	—	Smith(1957)
Nantes, Canada[d]	684	1477	—	4755-6232	—	—	Van den Berg and Lentz (1972)
Cauliflower							
Texas	3926	4503	7456	10,158	17,687	—	Scholz et al. (1963)
United Kingdom	1693-5295	4323-6015	9006-10,734	14,841-18,047	—	—	Smith (1957)
Celery							
New York, white	1585	2413	—	8215	14,229	—	Lutz and Hardenburg (1968)
United Kingdom	1117-1585	2017-2810	4323-6015	8609-9221 at 65°F	—	—	Smith(1957)
Utah, Canada[e]	1117	1982	—	6556	—	—	Van den Berg and Lentz (1972)
Cherries							
Sour	296-2918	2810-2918	—	6015-11,022	8609-11,022	11,708-15,634	Hawkins (1929), Lutz and Hardenburg (1968)

Table 9 Heat of Respiration of Fresh Fruits and Vegetables Held at Various Temperatures (*Continued*)

Commodity	Heat of Respiration, Btu/day per Ton of Produce						Reference
	32°F	41°F	50°F	59°F	68°F	77°F	
Sweet	901-1189	2089-3098	—	5512-9907	6196-7025	—	Gerhardt et al. (1942), Lutz and Hardenburg (1968), Micke et al. (1965)
Corn, sweet with husk, Texas	9366	17,111	24,676	35,878	63,543	89,695	Scholz et al. (1963)
Cucumbers, California	*[b]	*[b]	5079-6376	5295-7313	6844-10,591	—	Eaks and Morris (1956)
Figs, mission	—	2413-2918	4863-5079	10,807-13,940	12,536-20,929	18,731-20,929	Claypool and Ozbek (1952), Lutz and Hardenburg (1968)
Garlic	648-2413	1296-2125	2017-2125	2413-6015	2197-3999	—	Mann and Lewis (1956), Sastry et al. (1978)
Grapes							
Labrusca, Concord	612	1189	—	3494	7204	8501	Lutz (1938), Lutz and Hardenburg (1968)
Vinifera, Emperor	288-505	684-1296	1801	2197-2594	—	5512-6628	Lutz and Hardenburg (1968), Pentzer et al. (1933)
Thompson seedless	432	1045	1693	—	—	—	Wright et al. (1954)
Ohanez	288	720	2	—	—	—	Wright et al. (1954)
Grapefruit							
California Marsh	*[b]	*[b]	*[b]	2594	3890	4791	Haller et al. (1945)
Florida	*[b]	*[b]	*[b]	2810	3494	4214	Haller et al. (1945)
Horseradish	1801	2377	5800	7204	9834	—	Sastry et al. (1978)
Kiwifruit	616	1455	2889	—	3858-4254	—	Saravacos and Pilsworth (1965)
Kohlrabi	2197	3602	6916	10,807	—	—	Sastry et al. (1978)
Leeks	2089-3062	4323-6412	11,815-15,021	18,227-25,756	—	—	Sastry et al. (1978), Smith (1957)
Lemons, California, Eureka	*[b]	*[b]	*[b]	3494	5007	5727	Haller et al. (1945)
Lettuce							
Head, California	2017-3711	2918-4395	6015-8826	8501-9006	13,220	—	Sastry et al. (1978)
Texas	2306	2918	4791	7925	12,536	181 at 180°F	Lutz and Hardenburg, (1968), Watt and Merrill (1963)
Leaf, Texas	5079	6448	8681	13,869	22,118	32,275	Scholz et al. (1963)
Romaine, Texas	—	4575	7817	9762	15,093	23,883	Scholz et al. (1963)
Limes, Persian	*[b]	*[b]	576-1261	1296-2306	1513-4107	3314-10,014	Lutz and Hardenburg (1968)
Mangoes	*[b]	*[b]	—	9907	16,534-33,356	26,441	Gore (1911), Karmarkar and Joshe (1941b), Lutz and Hardenburg (1968)
Melons							
Cantaloupes	*[b]	1909-2197	3423	7420-8501	9834-14,229	13,725-15,741	Lutz and Hardenburg (1968), Sastry et al. (1978), Scholz et al. (1963)
Honeydew	—	*[b]	1765	2594-3494	4395-5259	5800-7601	Lutz and Hardenburg (1968), Pratt and Morris (1958), Scholz (1963)
Watermelon	*[b]	*[b]	1657	—	3818-5512	—	Lutz and Hardenburg (1968), Scholz et al. (1963)
Mint[l]	1769-3306	6614	16,754-20,061	23,148-29,981	36,595-50,041	56,655-69,883	Hruschka and Want (1979)
Mushrooms	6196-9618	15,634	—	—	58,104-69,738	—	Lutz and Hardenburg (1968), Smith (1964)
Nuts (kind not specified)	181	360	720	720	1081	—	IIR (1967)
Okra, Clemson	*[b]	76,043	19,236	32,132	57,527	76,040 at 85°F	Scholz et al. (1963)
Olives, Manzanillo	*[b]	*[b]		4791-8609	8501-10,807	9006-13,436	Maxie et al. (1959)
Onions							
Dry, Autumn Spice[f]	505-684	793-1477	—	2089-5548	—	—	Van den Berg and Lentz (1972)
White Bermuda	648	757	1585	2449	3711	6196 at 80°F	Scholz et al. (1963)
Green, New Jersey	2306-4899	3819-15,021	7961-12,968	14,553-21,434	17,205-34,225	21,541-46,217	Lutz and Hardenburg (1968)
Oranges							
Florida	684	1405	2702	4611	6628	7817 at 80°F	Haller et al. (1945)
California, w. navel	*[b]	1405	2990	5007	6015	7997	Haller et al. (1945)
Valencia	*[b]	1008	2594	2810	3890	4611	Haller et al. (1945)
Papayas	*[b]	*[b]	2485	3314-4791	—	8609-21,613	Jones (1942), Pantastico (1974)
Parsley[l]	7277-10,140	14,549-18,738	28,879-36,155	31,746-49,163	43,208-56,216	67,902-75,174	Hruschka and Want (1979)

Table 9 Heat of Respiration of Fresh Fruits and Vegetables Held at Various Temperatures (*Continued*)

Commodity	Heat of Respiration, Btu/day per Ton of Produce						Reference
	32°F	41°F	50°F	59°F	68°F	77°F	
Parsnips							
United Kingdom	2558-3423	1946-3854	4503-5800	7096-9438	—	—	Smith (1957)
Canada, Hollow Crown[g]	793-1801	1369-3386	—	4755-10,195	—	—	Van den Berg and Lentz (1972)
Peaches							
Elberta	829	1441	3458	7565	13,509	19,812 at 80°F	Haller et al. (1932)
Several cultivars	901-1405	1405-2017	—	7313-9330	13,040-22,549	17,939-26,837	Lutz and Hardenburg (1968)
Peanuts							
Cured[h]	3 at 85°F					51 at 85°F	Thompson et al. (1951)
Not cured, Virginia Bunch[i]						3120 at 85°F	Schenk (1959, 1961)
Dixie Spanish						1823 at 85°F	Schenk (1959, 1961)
Pears							
Bartlett	684-1513	1117-2197	—	3314-13,220	6628-15,417	—	Lutz and Hardenburg (1968)
Late ripening	576-793	1296-3062	1729-4143	6124-9366	7204-16,210	—	IIR (1967)
Early ripening	576-1081	1621-3423	2161-4683	7565-11,887	8645-19,812	—	IIR (1967)
Peas							
Green-in-pod	6700-10,302	12,139-16,822	—	39,372-44,595	54,105-79,645	75,646-83,067	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
Shelled	10,410-16,642	17,435-21,444	—	—	76,871-10,893	—	Lutz and Hardenburg (1968), Tewfik and Scott (1954)
Peppers, sweet	*[b]	*[b]	3170	5043	9654	—	Scholz et al. (1963)
Persimmons		1296		2594-3098	4395-5295	6412-8826	Gore (1911), Lutz and Hardenburg (1968)
Pineapple							
Mature green	*[b]	*[b]	1225	2846	5331	7817 at 80°F	Scholz et al. (1963)
Ripening	*[b]	*[b]	1657	3999	8790	13,797	Scholz et al. (1963)
Plums, Wickson	432-648	865-1982	1981-2522	2630-2737	3962-5727	6160-15,634	Claypool and Allen (1951)
Potatoes							
California white, rose							
immature	*[b]	2594	3098-4611	3098-6808	3999-9932		Sastry et al. (1978)
mature	*[b]	1296-1513	1467-2197	1467-2594	1467-3494		Sastry et al. (1978)
very mature	*[b]	1117-1513	1513	1513-2197	2017-2630		Sastry et al. (1978)
Katahdin, Canada[j]	*[b]	865-936		1729-2234			Van den Berg and Lentz (1972)
Kennebec	*[b]	793-936		936-1982			Van den Berg and Lentz (1972)
Radishes							
With tops	3206-3818	4214-4611	6808-8105	15,417-17,146	27,341-30,043	34,869-42,470	Lutz and Hardenburg (1968)
Topped	1189-1296	1693-1801	3314-3494	6124-7204	10,519-10,807	14,841-16,751	Lutz and Hardenburg (1968)
Rhubarb, topped	1801-2918	2413-3999		6808-10,014	8826-12,536		Hruschka (1966)
Rutabaga, Laurentian, Canada[k]	432-612	1045-1124		2342-3458			Van den Berg and Lentz (1972)
Spinach							
Texas		10,122	24,387	39,409	50,683		Scholz et al. (1963)
United Kingdom, summer	2558-4719	6015-7096	12,896-16,534		40,777-47,657 at 65°F		Smith (1957)
winter	3854-5584	6448-13,869	15,021-22,766		42,938-53,673 at 65°F		Smith (1957)
Squash							
Summer, yellow, straight-neck	†[b]	†[b]	7709-8105	16,534-20,028	18,731-21,434		Lutz and Hardenburg (1968)
Winter butternut	*[b]	*[b]				16,318-26,908	Lutz and Hardenburg (1968)
Sweet Potatoes							
Cured, Puerto Rico	*[b]	*[b]	†[b]	3530-4863			Lewis and Morris (1956)
Yellow Jersey	*[b]	*[b]	†[b]	4863-5079			Lewis and Morris (1956)
Noncured	*[b]	*[b]	*[b]	6304		11,923-16,138	Lutz and Hardenburg (1968)
Tomatoes							
Texas, mature green	*[b]	*[b]	*[b]	4503	7637	9402 at 80°F	Scholz et al. (1963)
ripening	*[b]	*[b]	*[b]	5872	8933	10,627 at 80°F	Scholz et al. (1963)
California mature green	*[b]	*[b]	*[b]		5295-7709	6592-10,591	Workman and Pratt (1957)

Table 9 Heat of Respiration of Fresh Fruits and Vegetables Held at Various Temperatures (*Continued*)

Commodity	Heat of Respiration, Btu/day per Ton of Produce 32°F	41°F	50°F	59°F	68°F	77°F	Reference
Turnip, roots	1909	2089-2197		4719-5295	5295-5512		Lutz and Hardenburg (1968)
Watercress[l]	3306	9920	20,061-26,674	29,981-43,208	66,576-76,719	76,720-96,561	Hruschka and Want (1979)

[a]Column headings indicate temperatures at which respiration rates were determined, within 2°F, 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 32°F, 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 59°F.
[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 h curing was almost negligible, even at 85°F.
[i]Respiration for freshly dug peanuts, not cured, with about 35 to 40% moisture. During curing, peanuts in the shell were dried to about 5 to 6% moisture, and in roasting are dried further to about 2% moisture.
[j]Rates are for 30 to 60 days and 120 to 180 days with rate declining with time at 41°F but increasing at 59°F as sprouting started.
[k]Rates are for 30 to 60 days and 120 to 180 days; rates increased with time, especially at 59°F where sprouting occurred.
[l]Rates are for 1 day after harvest.

Table 10 Change in Respiration Rates with Time

Commodity	Days in Storage	Heat of Respiration, Btu/day per Ton of Produce 32°F	41°F	Reference
Apples, Grimes	7	648	2882 at 50°F	Harding (1929)
	30	648	3854	
	80	648	2413	
Artichokes, globe	1	9907	13,220	Rappaport and Watada (1958)
	4	5512	7709	
	16	3314	5727	
Asparagus, Martha Washington	1	17,652	2316	Lipton (1957)
	3	8682	14,337	
	16	6160	6629	
Beans, lima, in pod	2	6593	7925	Tewfik and Scott (1954)
	4	4431	6376	
	6	3890	5836	
Blueberries, Blue Crop	1	1585	—	
	2	584	—	
		1261	—	
Broccoli, Waltham 29	1	—	16,102	
	4	—	9690	
	8	—	7277	
Corn, sweet, in husk	1	11,312	—	Scholz et al. (1963)
	2	8106	—	
	4	6772	—	
Figs, Mission	1	2882	—	Claypool and Ozbek (1952)
	2	2630		
	12	2630	—	

Commodity	Days in Storage	Heat of Respiration, Btu/day per Ton of Produce 32°F	41°F	Reference
Garlic	10	865	1982	Mann and Lewis (1956)
	30	1333	3314	
	180	3098	7277	
Lettuce, Great Lakes	1	3747	4395	Pratt et al. (1954)
	5	1982	33	
	10	1765	3314	
Olives, Manzanillo	1	—	8610 at 60°F	Maxie et al. (1960)
	5	—	6376	
	10	—	4864	
Onions, red	1	360	—	Karmarkar and Joshe (1941a)
	30	541	—	
	120	720	—	
Plums, Wickson	2	432	865	Claypool and Allen (1951)
	6	432	1549	
	18	648	1982	
Potatoes	2	—	1333	Morris (1959)
	6	—	1765	
	10	—	1549	
Strawberries, Shasta	1	3873	6305	Maxie et al. (1959)
	2	2918	6772	
	5	2918	7277	
Tomatoes, Pearson, mature green	5	—	706 at 70°F	Workman and Pratt (1957)
	15	—	6160	
	20	—	5295	

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:

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

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 of Certain Fruits and Vegetables

Commodity and Variety	Transpiration Coefficient, ppm/h·in. Hg	Commodity and Variety	Transpiration Coefficient, ppm/h·in. Hg	Commodity and Variety	Transpiration Coefficient, ppm/h·in. Hg
Apples		**Leeks**		**Pears**	
Jonathan	430	Musselburgh	12,600	Passe Crassane	974
Golden Delicious	710	*Average for all varieties*	**9600**	Beurre Clairgeau	986
Bramley's Seedling	510	**Lemons**		*Average for all varieties*	**840**
Average for all varieties	**510**	Eureka			
Brussels Sprouts		dark green	2760	**Plums**	
Unspecified	40,100	yellow	1700	Victoria	
Average for all varieties	**75,000**	*Average for all varieties*	**2270**	unripe	2410
Cabbage		**Lettuce**		ripe	1400
Penn State ballhead		Unrivalled	106,000	Wickson	1510
trimmed	3300	*Average for all varieties*	**90,200**	*Average for all varieties*	**1660**
untrimmed	4920	**Onions**			
Mammoth		Autumn Spice		**Potatoes**	
trimmed	2920	uncured	1170	Manona	
Average for all varieties	**2720**	cured	535	mature	304
Carrots		Sweet White Spanish		Kennebec	
Nantes	20,000	cured	1500	uncured	2080
Chantenay	21,500	*Average for all varieties*	**730**	cured	730
Average for all varieties	**14,700**	**Oranges**		Sebago	
Celery		Valencia	710	uncured	1920
Unspecified varieties	25,400	Navel	1270	cured	462
Average for all varieties	**21,500**	*Average for all varieties*	**1430**	*Average for all varieties*	**540**
Grapefruit		**Parsnips**			
Unspecified varieties	380	Hollow Crown	23,500	**Rutabagas**	
Marsh	670			Laurentian	5710
Average for all varieties	**990**	**Peaches**			
Grapes		Redhaven			
Emperor	960	hard mature	11,200	**Tomatoes**	
Cardinal	1220	soft mature	12,400	Marglobe	864
Thompson	2480	Elberta	3330	Eurocross BB	1410
Average for all varieties	**1500**	*Average for all varieties*	**6970**	*Average for all varieties*	**1710**

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 from Geankoplis (1978):

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

Re is the Reynolds number ($\mathrm{Re} = ud/\nu$) and Sc is the Schmidt number ($\mathrm{Sc} = \nu/\delta$), 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, lb/ft²·h·in. Hg			
Commodity	Low	Mean	High	Standard Deviation
Apples	2.77×10^{-4}	4.17×10^{-4}	5.67×10^{-4}	7.49×10^{-5}
Blueberries	2.38×10^{-3}	5.47×10^{-3}	8.46×10^{-3}	1.60×10^{-3}
Brussels sprouts	2.41×10^{-2}	3.32×10^{-2}	4.64×10^{-2}	6.09×10^{-3}
Cabbage	6.24×10^{-3}	1.68×10^{-2}	3.25×10^{-2}	7.09×10^{-3}
Carrots	7.94×10^{-2}	3.90×10^{-1}	9.01×10^{-1}	1.90×10^{-1}
Grapefruit	2.72×10^{-3}	4.19×10^{-3}	5.54×10^{-3}	8.24×10^{-4}
Grapes	—	1.00×10^{-3}	—	—
Green peppers	1.36×10^{-3}	5.39×10^{-3}	1.09×10^{-2}	1.77×10^{-3}
Lemons	2.72×10^{-3}	5.19×10^{-3}	8.74×10^{-3}	1.60×10^{-3}
Lima beans	8.16×10^{-3}	1.08×10^{-2}	1.43×10^{-2}	1.47×10^{-3}
Limes	2.60×10^{-3}	5.54×10^{-3}	8.69×10^{-3}	1.40×10^{-3}
Onions	—	2.22×10^{-3}	—	—
Oranges	3.45×10^{-3}	4.29×10^{-3}	5.34×10^{-3}	5.24×10^{-4}
Peaches	3.40×10^{-3}	3.55×10^{-2}	1.15×10^{-1}	1.30×10^{-2}
Pears	1.31×10^{-3}	1.71×10^{-3}	3.00×10^{-3}	3.72×10^{-4}
Plums	—	3.44×10^{-3}	—	—
Potatoes	—	1.59×10^{-3}	—	—
Rutabagas (swedes)	—	2.91×10^{-1}	—	—
Snap beans	8.64×10^{-3}	1.41×10^{-2}	2.50×10^{-2}	4.42×10^{-3}
Sugar beets	2.27×10^{-2}	8.39×10^{-2}	2.18×10^{-1}	5.02×10^{-2}
Strawberries	9.86×10^{-3}	3.40×10^{-2}	6.62×10^{-2}	1.20×10^{-2}
Tomatoes	5.42×10^{-4}	2.75×10^{-3}	6.07×10^{-3}	1.67×10^{-3}

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, in.**[a]	**Transfer Medium**	**Δ*t* and/or Temp. *t* of Medium, °F**	**Velocity of Medium, ft/s**	**Reynolds Number Range**[b]	***h*, Btu/ h·ft²·°F**	**Nu-Re-Pr Correlation**[c]	**Reference**	**Comments**
Apple	Spherical	Air	t = 81	0	N/A	2.0	N/A	Kopelman et al. (1966)	N/A indicates that data were not reported in original article
Jonathan	2.0			1.3		3.0			
				3.0		4.8			
				6.7		8.0			
				17.0		9.4			
	2.3			0		2.0			
				1.3		3.0			
				3.0		4.9			
				6.7		7.9			
				17.0		9.6			
	2.4			0		2.0			
				1.3		2.8			
				3.0		4.6			
				6.7		6.9			
				17.0		8.9			
Red Delicious	2.5	Air	Δt = 41	4.9	N/A	4.8	N/A	Nicholas et al. (1964)	Thermocouples at center of fruit
			t = 31	15.0		10.0			
	2.8			4.9		2.5			
				15.0		6.5			
	3.0			0		1.8			
				4.9		4.0			
				9.8		5.8			
				15.0		6.1			
	2.2	Water	Δt = 46	0.90		16.0			
	2.8		t = 32			14.0			
	3.0					9.8			
Beef	142 lb*	Air	t = –3	5.9	N/A	3.8	N/A	Fedorov et al. (1972)	*For size indication
carcass	187 lb*			1.0		1.8			
patties	Slab	Air	t = –26 to –18	9.2 to 20	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 32	6.9 to 9.8	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, in.**[a]	**Transfer Medium**	**Δt and/or Temp. t of Medium, °F**	**Velocity of Medium, ft/s**	**Reynolds Number Range**[b]	**h, Btu/ $h \cdot ft^2 \cdot °F$**	**Nu-Re-Pr Correlation**[c]	**Reference**	**Comments**
Cheese	Brick	Air	t = –29 to 36	9.8	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 1.5	Air	t = 39	3.28 4.10 4.92 5.74 6.56	N/A	3.2 305 3.8 4.1 4.7	$Nu = 0.291 Re^{0.592} Pr^{0.333}$	Dincer (1994)	Diameter = 38 mm Length = 160 mm
Eggs, Jifujitori	1.3	Air	Δt = 81	6.6 to 26	6000 to 15,000	N/A	$Nu = 0.46 Re^{0.56}$ ±1.0%	Chuma et al. (1970)	5 points in correlation
Leghorn	1.7	Air	Δt = 81	6.6 to 26	8000 to 25,000	N/A	$Nu = 0.71 Re^{0.55}$ ±1.0%	Chuma et al. (1970)	5 points in correlation
Entrees	Brick	Air	t = –36 to 32	9.2 to 16	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 1.85	Air	t = 39	3.61 4.92 5.74 8.20	N/A	4.2 4.6 4.8 5.8	$Nu = 1.560 Re^{0.426} Pr^{0.333}$	Dincer (1994)	
Fish, Pike, perch, sheatfish	N/A	Air	N/A	3.2 to 22	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 –18	8.9 to 23	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 0.43	Air	t = 39	3.28 4.10 4.92 5.74 6.56	N/A	5.4 6.0 6.7 7.2 7.4	$Nu = 0.291 Re^{0.592} Pr^{0.333}$	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 = –10 t = –55 t = –60 t = –70 t = –80	2.0	N/A	3.6 3.6 3.5 3.5 3.2	N/A	Van den Berg and Lentz (1957)	38 points total Values are averages
Meat	Slabs 0.91 thick	Air	t = 32	1.8 4.6 12.0	N/A	1.9 3.5 6.2	N/A	Radford et al. (1976)	
Oranges, grapefruit, tangelos, bulk packed	Spheroids 2.3 3.1 2.1	Air	Δt = 70 to 56 t = 16	0.36–1.1	35,000 to 135,000	11.7*	$Nu = 5.05 Re^{0.333}$	Bennett et al. (1966)	Bins 42 × 42 × 16 in. 36 points in correlation. Random packaging. Interstitial velocity. *Average for oranges
	Spheroids 3.0 4.2	Air	Δt = 91 t = 32	0.17 to 6.7	180 to 18,000	N/A	$Nu = 1.17 Re^{0.529}$	Baird and Gaffney (1976)	20 points in correlation Bed depth: 26 in.
Peas Fluidized bed	Spherical N/A	Air	t = –15 to –35	4.9 to 2.4 ±1.0	1000 to 4000	N/A	$Nu = 3.5 \times 10^{-4} Re^{1.5}$	Kelly (1965)	Bed depth: 2 in.
Bulk packed	Spherical N/A	Air	t = –15 to –35	4.9 to 2.4 ±1.0	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, in.**[a]	**Transfer Medium**	**Δt and/or Temp. t of Medium, °F**	**Velocity of Medium, ft/s**	**Reynolds Number Range**[b]	**h, Btu/ h·ft^2·°F**	**Nu-Re-Pr Correlation**[c]	**Reference**	**Comments**
Pears	Spherical 2.36	Air	t = 39	3.28 4.10 4.92 5.74 6.56	N/A	2.2 2.5 2.8 2.8 3.4	$Nu = 1.560 Re^{0.426} Pr^{0.333}$	Dincer (1994)	
Pizza	Slab	Air	t = –29 to –15	9.8 to 12	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 = 40	2.2 4.0 4.5 5.7	3000 to 9000	2.5* 3.4 3.6 4.3	$Nu = 0.364 Re^{0.558} Pr^{1/3}$ (at top of bin)	Minh et al. (1969) Use interstitial velocity to calculate Re Bin is 30 × 20 × 9 in. *Each h value is average of 3 reps with airflow from top to bottom	
Patties, fried	Slab	Air	t = –26 to –18	7.5 to 11	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	2.6 to 20.8 lb*	**	Δt = 32	***	N/A	74 to 83	N/A	Lentz (1969)	Vacuum packaged *To give indications of size. **$CaCl_2$ Brine, 26% by mass ***Moderately agitated Chickens 2.4 to 6.4 lb Turkeys 11.9 to 21 lb
Chicken breast	N/A	Air	t = –29 to 28	3.3 to 9.8	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 8.6	8.9 to 9.8	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 2.6	Air	N/A	22	1200 to 4600	N/A	$Nu = 1.07 Re^{0.64}$	Otten (1974)	8 points in correlation Bed depth: 1.3 in.
Squash	Cylinder 1.8	Water	1.64 3.28 4.92	0.16	N/A	47.9 36.1 29.2	N/A	Dincer (1993)	Diameter = 1.8 in. Length = 6.1 in.
Tomatoes	Spherical 2.75	Air	t = 39	3.28 4.10 4.92 5.74 6.56	N/A	1.9 2.3 2.4 2.6 3.0	$Nu = 1.560 Re^{0.426} Pr^{0.333}$	Dincer (1994)	
Karlsruhe substance	Slab 3.0	Air	Δt = 96 t = 100	N/A	N/A	2.9	N/A	Cleland and Earle (1976)	Packed in aluminum foil and brown paper
Milk Container	Cylinder 2.8 × 3.9 2.8 × 5.9 2.8 × 9.8	Air	Δt = 9.5	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 2.8 in. dia.
Acrylic	Ellipsoid 3.0 (minor axis) G = 0.297 to 1.0	Air	Δt = 80	6.9 to 26	12,000 to 50,000	N/A	$Nu = aRe^b$ $a = 0.32 - 0.22G$ $b = 0.44 + 0.23G$	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 3.0	Air	t = 24	2.17 4.04 4.46 5.68	3700 to 10,000	2.6* 2.5 3.9 3.8	$Nu = 2.58 Re^{0.303} Pr^{1/3}$	Minh et al. (1969) Random packed. Interstitial velocity used to calculate Re Bin dimensions: 30 × 18 × 24 in. *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 32°F = 144 Btu/lb
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 = 1.986 Btu/lb mol·°R
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, °F
t_f = initial freezing temperature of food, °F
t_r = reference temperature = –40°F
t_s = surface temperature, °F
t_∞ = ambient temperature, °F
T = food temperature, °R
T_f = initial freezing point of food, °R
T_o = freezing point of water; T_o = 491.7°R
T_r = reference temperature = 419.7°R (–40°F)
$\bar{T}$ = 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, Btu/h·lb
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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