Part IV

Appendices

Confectionery and Chocolate Engineering: Principles and Applications Ferenc Á. Mohos
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Appendix 1
Data on engineering properties of materials used and made by the confectionery industry

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A1.1 Carbohydrates

Table A1.1 Thermophysical data for sugar (Antokolskaia 1964).

Type	T (°C)	ρ (kg/m^3)	λ (W/m degree)	c (W s/kg degree)	$a \times 10^6$ (m^2/s)
Cube	–5	–	0.157	1340	0.1347
	15	1600	0.153	1361	0.1280
	35	–	0.145	1390	0.1194
Castor[1]	–	900	0.139	712	0.2390
Icing[2]	–	660	0.139	879	0.2360
Invert	15	1198	0.336	3207	0.0875
	35	1188	0.334	3199	0.0833
	60	1160	0.353	3408	0.0894
Dextrose[3]		1538.4 (Sokolovsky 1959)			
Dextrose hydrate		1571.4 (Sokolovsky 1959)			
Maltose		1500 (Sokolovsky (1959)			

[1]0.1% water content.
[2]0.3% water content.
[3]Water-free.

For further details, see Desent and Bouscher (1961).

Table A1.2 Thermal conductivity of crystalline sugars (Antokolskaia 1964).

Type	λ (W/m degree)
Powder	0.069
Raffinated	0.081
Light pressed	0.093
Castor	0.58
Raw	0.17

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Table A1.3 Specific and molar heat capacity of crystalline sugars (Antokolskaia 1964).

T (°C)	*c* (W s/kg degree)	*C* (W s/mole degree)
0	1088.57	385 604
20	1214.17	415 749
30	1256.04	435 427
40	1323.03	452 174
50	1356.52	464 734
60	1419.32	485 668
70	1469.57	502 416
80	1532.37	523 350
90	1578.42	540 097

Table A1.4 Melting point of sugars (Antokolskaia 1964).

Sugar	Melting point (°C)
Dextrose	146
Maltose	108
Sucrose	170–188
Raw sugar	170–188
Powdered sugar	170–188
Fructose	104

Table A1.5 Density of saturated sugar solutions as a function of temperature (Antokolskaia 1964).

T (°C)	Sugar content (g/100 cm^3 water)	Density (kg/m^3)
0	179.2	1314.0
5	184.7	1319.2
10	190.5	1323.5
15	197.0	1328.0
20	203.9	1331.9
25	211.4	1342.7
30	219.9	1342.7
35	228.4	1348.0
40	238.1	1353.5
45	248.7	1359.2
50	260.4	1365.1
55	273.1	1371.2
60	287.3	1377.5
65	302.9	1384.0
70	320.5	1390.8
75	339.9	1397.7
80	362.1	1404.9
85	386.8	1412.2
90	415.7	1419.9
95	448.6	1427.7
100	487.2	1435.9

Table A1.6 Concentration of saturated sugar/water solutions as a function of temperature (Sokolovsky 1958).

t (°C)	%	*t* (°C)	%	*t* (°C)	%
0	64.18	34	69.38	68	75.8
1	64.31	35	69.55	69	76.01
2	64.45	36	69.72	70	76.22
3	64.59	37	69.89	71	76.43
4	64.73	38	70.06	72	76.54
5	64.87	39	70.24	73	76.85
6	65.01	40	70.42	74	77.06
7	65.15	41	70.6	75	77.27
8	65.29	42	70.78	76	77.48
9	65.48	43	70.96	77	77.7
10	65.58	44	71.14	78	77.92
11	65.73	45	71.32	79	78.14
12	65.88	46	71.5	80	78.36
13	66.03	47	71.68	81	78.58
14	66.18	48	71.87	82	78.8
15	66.33	49	72.06	83	79.02
16	66.48	50	72.25	84	79.24
17	66.63	51	72.44	85	79.46
18	66.78	52	72.63	86	79.69
19	66.93	53	72.82	87	79.92
20	67.09	54	73.01	88	80.15
21	67.25	55	73.2	89	80.38
22	67.41	56	73.39	90	80.61
23	67.57	57	73.58	91	80.84
24	67.73	58	73.78	92	81
25	67.89	59	73.98	93	81.3
26	68.05	60	74.18	94	81.53
27	68.21	61	74.38	95	81.77
28	68.37	62	74.58	96	82.01
29	68.53	63	74.78	97	82.25
30	68.7	64	74.98	98	82.49
31	68.87	65	75.18	99	82.73
32	69.04	66	75.38	100	82.97
33	69.21	67	75.59		

Table A1.7 Thermophysical data for sucrose solutions with various boiling points (Antokolskaia 1964).

Concentration (m/m%)	*T* (°C)	λ (W/m degree)	*c* (W s/kg degree)	η (N s/m^2) $\times 10^6$
0	100.0	0.682	4187	282.4
10	100.2	0.645	4120	366.7
20	100.4	0.642	3864	452.1
30	100.7	0.570	3626	619.7
40	101.2	0.531	3358	960.1
50	102.0	0.493	3256	1765.2
60	103.5	0.456	2939	3341.1

Table A1.8 Thermophysical characteristics of sucrose–water solutions (Sokolovsky 1959).

Concentration (m/m%)	T (°C)	λ (W/m degree)	c (W s/kg degree)	$\nu \times 10^6$ (m²/s)	a (Prandtl)
20	50	0.5700	3760	0.9065	6.38
	60	0.5809	3775	0.7605	5.26
	70	0.5893	3790	0.6420	4.37
	80	0.5965	3805	0.5610	3.76
30	50	0.5368	3546	1.282	9.71
	60	0.5956	3568	1.082	7.84
	70	0.5536	3591	0.9063	6.49
	80	0.5604	3614	0.7750	5.48
40	50	0.502	3333	2.140	16.52
	60	0.510	3363	1.701	12.97
	70	0.518	3393	1.389	10.48
	80	0.524	3423	1.153	8.62
50	50	0.468	3119	4.173	33.82
	60	0.475	3157	3.148	25.30
	70	0.482	3195	2.442	19.47
	80	0.488	3232	1.956	15.50
60	50	0.433	2906	11.02	93.90
	60	0.440	2951	7.63	64.75
	70	0.447	2996	5.54	46.82
	80	0.452	3041	4.15	34.98
80[1]	15	0.326	1361	0.1280	

[1]Tonn (1961).

Comment: Since the Prandtl number Pr is equal to ν/a, $a = \nu/Pr$. For example (in the first row), $a = (0.9065 \times 10^{-6}/6.38)$ (m²/s) $= 0.1421 \times 10^{-6}$ m²/s.

For further details, see Tonn (1961).

Table A1.9 Thermal conductivity (W/m K) of sucrose–water solutions (Antokolskaia 1964).

Concentration (m/m%)	Temperature (°C) 0	20	30	40
0	0.583	0.599	0.614	0.628
10	0.551	0.566	0.581	0.594
20	0.520	0.535	0.548	0.560
30	0.488	0.501	0.514	0.526
40	0.457	0.470	0.480	0.492
50	0.391	0.437	0.449	0.458
60	0.384	0.405	0.415	0.419
	Temperature (°C) 50	**60**	**70**	**80**
0	0.641	0.652	0.663	0.672
10	0.607	0.617	0.628	0.636
20	0.572	0.538	0.592	0.600
30	0.536	0.547	0.555	0.563
40	0.502	0.512	0.519	0.526
50	0.481	0.477	0.484	0.491
60	0.434	0.441	0.449	0.455

Specific heat capacity of aqueous sugar solutions (Sokolovsky 1958, p. 32):

$$c_P = 1 - (0.6 - 0.0018t)S$$

where c_P is the specific heat capacity of the aqueous sugar solution (kcal/kg = 4.1868 kJ/kg), t is the temperature (°C) and S is the sugar concentration (m/m).

Thermal conductivity of aqueous sugar solutions (Sokolovsky 1958, p. 32):

$$\lambda = \lambda_W\left(1 - 10^{-5} \times KS\right)$$

where λ is the thermal conductivity of the aqueous sugar solution at 20°C (kcal/m h K = 1.163 W/m K); λ_W is the thermal conductivity of water at 20°C; K is a constant, with a value of 556 at 20°C; and S is the sugar concentration (m/m).

The thermal conductivity of an aqueous sugar solution of concentration 80 m/m% (at 20°C) is 0.28 kcal/m h K = 0.32564 W/m K.

Thermal diffusivity of crystalline sugar (Sokolovsky 1958, p. 32):

$$a = 4.93 \times 10^{-4}\ \mathrm{m^2/h} = 4.93 \times 10^{-4} \times 2.778 \times 10^{-4}\ \mathrm{m^2/s} = 1.3696 \times 10^{-7}\ \mathrm{m^2/s}$$

Table A1.10 Boiling point of sucrose–water solutions (Antokolskaia 1964).

Concentration (m/m%)	Boiling point (°C)
10	100.1
20	100.3
30	100.6
40	101.0
50	101.8
60	103.0
70	105.5
80	109.4
90	119.6

An approximate formula for the boiling point of sugar–water solutions is (Sokolovsky 1958, p. 19)

$$T\ (°\mathrm{C}) = 100°\mathrm{C} + 2.33(S/W)$$

where T is the boiling point, S is the concentration of sugar (m/m%) in the solution and W is the concentration of water (m/m%) in the solution. For example, if S = 20% and W = 80%, then T (°C) = 100 + 2.33(20/80) = 100.5825°C (in Table A1.10, 100.3°C). If S = 90% and W = 10%, then T (°C) = 100 + 2.33(90/10) = 120.97°C (in Table A1.10, 119.6°C).

For example, if the pressure is 92.51 mmHg (= 92.51 mmHg × 133.2 Pa/mmHg = 12322.332 Pa), then the boiling point of water is 50°C, and an aqueous sugar solution of 70 m/m% concentration has a boiling point t = (50 + 3.65)°C.

Table A1.11 Elevation of boiling point (°C) of sugar solutions as a function of concentration at various pressures (according to Bukharov; cited by Sokolovsky 1958, p. 20).

	Pressure (mmHg = 133.2 Pa)					
	92.51	149.38	233.7	355.1	525.76	760
Sugar (%)	50°C	60°C	70°C	80°C	90°C	100°C
5	0.05	0.05	0.05	0.06	0.06	0.06
10	0.10	0.10	0.11	0.11	0.12	0.12
15	0.17	0.18	0.18	0.19	0.19	0.20
20	0.26	0.27	0.28	0.28	0.29	0.30
25	0.39	0.40	0.42	0.43	0.41	0.45
30	0.52	0.54	0.55	0.57	0.58	0.60
35	0.69	0.71	0.73	0.76	0.78	0.80
40	0.80	0.85	0.90	0.95	1.00	1.05
45	1.02	1.10	1.18	1.25	1.32	1.40
50	1.32	1.40	1.52	1.61	1.72	1.80
55	1.70	1.82	1.94	2.06	2.18	2.30
60	2.30	2.15	2.60	2.75	2.90	3.05
65	2.80	3.00	3.20	3.40	3.60	3.80
70	3.65	3.90	4.18	4.46	4.75	5.05
75	5.05	5.40	5.80	6.20	6.60	7.00
80	(6.80)	7.30	7.85	8.35	8.90	9.40
85		(10.00)	10.75	11.50	12.25	13.00
90			(16.00)	17.20	18.40	19.60

Table A1.12 Solubility of sugar in water in the presence of glucose syrup (Sokolovsky 1958, p. 16).

	A	*B*	*C*	*D*	*E*
20°C	67.09	0	203	0	203
	57.51	10.56	180.2	33.1	213.3
	51.23	17.74	165.09	57.17	222.26
	4.51	21.76	163.16	73.19	236.35
	43.26	28.8	154.82	103.07	257.89
50°C	72.25	0	260.36	0	260.36
	62.97	10.05	233.39	37.25	270.64
	55.05	18.26	208.16	69.01	277.17
	51.03	24	204.37	96.12	300.49
	46.81	28.86	193.19	119.52	312.71
	44.47	32.02	189.15	136.2	325.35
	37.96	40.54	176.56	188.56	365.12
70°C	76.22	0	322.83	0	322.83
	67.43	9.92	207.7	43.7	341.49
	60.6	17.55	277.35	80.32	357.67
	55.14	24.95	276.95	125.31	402.26
	52.7	28.1	274.48	146.35	420.83
	49.69	32.16	273.77	177.19	450.96

A = concentration of sugar (m/m%) in 100 g of solution.
B = concentration of glucose syrup (m/m%) in 100 g of solution.
C = sugar (g) per 100 g of water.
D = glucose syrup dry content (g) per 100 g of water.
$E = C + D$.

Table A1.13 Solubility of sugar in water in the presence of invert sugar (Sokolovsky 1958, p. 17).

	A	*B*	*C*	*D*	*E*
23.1°C	67.59	0	208.55	0	208.55
	57.84	11.9	191.14	39.32	230.46
	47.31	25.39	173.3	93	266.3
	28.66	36.9	158.18	150.98	309.16
30°C	68.11	–	213.58	–	213.58
	56.32	14.94	195.96	51.98	247.94
	50.97	21.86	187.6	80.46	268.06
	49.91	23.21	185.68	86.34	272.02
	48.95	24.46	184.09	91.99	276.08
	46.36	28.01	180.88	109.29	290.17
	39.23	37.48	168.43	160.93	329.36
	32.06	47.02	153.25	224.76	378.01
	31.85	47.62	155.13	231.95	387.08
	26.03	56.37	147.9	320.28	468.18
	21.18	63.68	139.89	420.61	560.5
	20.59	64.47	137.82	431.52	569.34
50°C	72.22	–	260.36	–	260.36
	62.81	11.42	243.73	44.31	288.04
	53.8	22.65	228.45	96.17	324.62
	46.2	32.32	215.08	150.46	365.54
	35.75	46.05	196.43	253.2	449.45

A = concentration of sugar (m/m%) in 100 g of solution.
B = concentration of glucose syrup (m/m%) in 100 g of solution.
C = sugar (g) per 100 g of water.
D = glucose syrup dry content (g) per 100 g of water.
$E = C + D$.

Table A1.14 Boiling point of aqueous glucose syrup solutions at atmospheric pressure (Sokolovsky 1958, p. 40).

G (%)	Boiling point (°C)
20	100.55
25	100.7
30	100.85
35	101.05
40	101.45
45	102
50	102.75
55	103.75
60	105.05
65	106.6
70	108.4
75	110.45
80	113
85	117.75
90	127

G (%) = glucose syrup dry content (m/m%).

Table A1.15 Elevation of boiling point of glucose solutions as a function of concentration at various pressures (according to Bukharov; cited by Sokolovsky 1958).

	Pressure (mmHg)					
	92.51	149.8	233.7	355.1	525.76	760
Glucose (%)	50°C	60°C	70°C	80°C	90°C	100°C
5	0.08	0.03	0.09	0.1	0.11	0.11
10	0.16	0.17	0.18	0.19	0.21	0.22
15	0.25	0.26	0.28	0.30	0.32	0.35
20	0.39	0.41	0.41	0.48	0.51	0.55
25	0.51	0.55	0.59	0.63	0.67	0.7
30	0.62	0.66	0.70	0.75	0.80	0.85
35	0.78	0.84	0.9	0.96	1.02	1.05
40	1.04	1.11	1.2	1.28	1.36	1.45
45	1.15	1.55	1.66	1.78	1.9	2
50	1.98	2.12	2.28	2.42	2.59	2.75
55	2.7	2.9	3.1	3.3	3.59	3.75
60	3.63	3.9	1.17	4.45	4.75	5.05
65	4.73	5.07	5.43	5.89	6.19	6.6
70	6.04	6.47	6.93	7.4	7.9	8.10
75	7.47	8.02	8.58	9.17	9.79	10.45
80	9.29	9.98	10.69	11.42	12.17	13
85	12.01	13.6	14.69	15.59	16.65	17.75
90	19.14	20.5	21.08	23.62	25.27	27

1 mmHg = 133.2 Pa.

Table A1.16 Dynamic viscosity (N s/m^2 = Pa s) of sucrose–water solutions (Antokolskaia 1964).

Concentration (m/m%)	Temperature (°C) 20	30	40	50	60	70	80	90
60	0.0572	0.0331	0.0206	0.0137	0.0095	0.0069	0.0053	
61	0.0678	0.0386	0.0238	0.0156	0.0107	0.0077	0.0058	
62	0.0809	0.0454	0.0275	0.0178	0.0121	0.0086	0.0064	
63	0.0970	0.0634	0.0320	0.0204	0.0137	0.0098	0.0071	
64	0.1171	0.0636	0.0374	0.0235	0.0156	0.0108	0.0079	
65	0.1428	0.0760	0.0441	0.0272	0.0172	0.0122	0.0088	
66	0.1759	0.0916	0.0522	0.0317	0.0206	0.0139	0.0099	
67	0.2190	0.1113	0.0622	0.0372	0.0239	0.0159	0.0112	
68	0.2780	0.1388	0.0747	0.0440	0.0279	0.0183	0.0127	
69	0.3540	0.1697	0.0906	0.0524	0.0328	0.0212	0.0145	
70	0.4600	0.2141	0.1111	0.0631	0.0388	0.0248	0.0167	
71	0.6737	0.2739	0.1381	0.0768	0.0463	0.0292	0.0194	
72		0.3561	0.1737	0.0945	0.0559	0.0348	0.0227	
73		0.4695	0.2220	0.1178	0.0682	0.0418	0.0268	
74		0.6310	0.2885	0.1487	0.0841	0.0507	0.0319	
75		0.8640	0.3805	0.1900	0.1050	0.0620	0.0384	
76		1.2140	0.5130	0.2463	0.1330	0.0768	0.0466	
77			0.7010	0.3234	0.1707	0.0951	0.0572	
78			0.9800	0.4330	0.2216	0.1215	0.0711	
79			1.430	0.5930	0.2927	0.1562	0.0896	
80			2.160	0.8320	0.3939	0.2044	0.1152	0.0830
81				1.2000	0.5460	0.2722	0.1505	0.0940
82				1.8000	0.7700	0.3727	0.2000	0.1110
83					1.2500	0.5190	0.2800	0.1420
84					1.7000	0.7400	0.3760	0.1860

Table A1.17 Dynamic viscosity of saturated dextrose–water solutions (Sokolovsky 1959).

T (°C)	Concentration of dextrose (m/m%)	Dextrose dissolved in 100 g water	Viscosity (N s/m^2)
20	47.72	91.60	0.0183
30	54.64	120.46	0.0187
40	61.83	162.14	0.0224
50	70.91	243.80	0.0509
60	74.73	295.00	0.0662
70	78.23	359.94	0.0784
80	81.83	436.31	0.1040
90	84.63	552.77	

Table A1.18 Interfacial tension of sugar solutions at 20°C (Antokolskaia 1964).

Concentration (g/100 g)	σ (N/m)	Concentration (g/100 g)	σ (N/m)
0	0.0727	29.8	0.0760
6.8	0.0731	31.0	0.0762
10.0	0.07335	40.7	0.0771
13.1	0.0736	47.5	0.0780
20.5	0.0745	51.2	0.0787
22.2	0.0749	62.7	0.0796

Table A1.19 Dynamic viscosity (N s/m^2) of honey as a function of temperature (°C) and water content (m/m%) (Antokolskaia 1964).

Water content (%)	Temperature (°C)							
	10	20	30	40	50	60	70	80
14	–	59.2	14.4	4.6	1.5	1.0	0.70	0.25
16	–	22.8	5.9	2.1	0.9	0.6	0.30	0.15
19	28.0	6.5	2.7	1.0	0.5	0.3	0.20	0.10
24	4.52	1.3	0.5	0.4	0.2	0.1	0.05	0.03

Table A1.20 Thermophysical characteristics of starch syrup used for caramel production (Schriftsammlung der Arbeiten des WKNU 1950).

Dry content (m/m%)	t (°C)	ρ (kg/m^3)	λ (W/m K)	c_P (W s/kg K)	$a \times 10^6$ (m^2/s)
80	20	1420	0.326	1967.8	0.1167
	40	1395	0.314	2009.7	0.1139
	60	1370	0.314	2051.6	0.1111
	80	1340	0.302	2093.4	0.1055
85	20	1450	0.314	1884.1	0.1167
	40	1425	0.302	1925.9	0.1111
	60	1400	0.302	1967.8	0.1083
	80	1370	0.291	2008.7	0.1055
88	20	1480	0.314	1842.2	0.1167
	40	1455	0.302	1884.1	0.1111
	60	1430	0.302	1925.9	0.1083
	80	1400	0.291	1967.8	0.1055
92	20	1520	0.314	1758.5	0.1167
	40	1490	0.302	1800.3	0.1111
	60	1460	0.291	1884.1	0.1055
	80	1430	0.279	1925.9	0.1028

According to Sokolovsky (1958, p. 103), the specific heat capacity of starch (c'_P) can be calculated from

$$c'_P = [ac_P + f(100\% - a)]/100\%$$

where $c_P = 0.2697$ cal/g °C (and $f = 1$) or $c_P = 1.1284$ kJ/kg °C (and $f = 4.1839$) is the specific heat capacity of the dry content of starch, and a (%) is the water content of the starch. [This relation is based on the fact that the specific heat capacity of water is about 1 cal/(grade g) = 4.1839 kJ/(grade kg) and the values of the specific heat capacity are additive according to the ratio of ingredients.]

The values of the specific heat capacity of commercial starch products are:

Temperature (°C)	c'_P (cal/g)
0–20	0.2765
21–42	0.2978
43–62	0.3061

Table A1.21 Dynamic viscosity of aqueous solutions of invert sugar as a function of temperature (Sokolovsky 1959).

Total dry content (m/m%)	Invert sugar content (m/m%)	t (°C)	η (Pa s)	t (°C)	η (Pa s)
74.00	73.65	30.0	0.663	50.0	0.140
78.84	79.35	10.1	5.344	45.1	0.431
81.75	78.97	20.3	23.714	45.0	1.648
74.00	73.65	40.2	0.304	70.5	0.060
79.84	79.35	30.7	2.076	60.0	0.145
81.75	78.97	30.2	7.752	70.0	0.157

A1.2 Oils and fats

Table A1.22 Temperature dependence of the thermal parameters of margarine (Derneko and Schafchid 1959).

T	For household use, λ (W/m degree)	Cream margarine, $a \times 10^6$ (m^2/s)
20	–	0.0736
22	0.165	0.0717
24	–	0.0714
26	0.172	–
27	–	0.0711
29	0.173	0.0678
32	0.179	0.0667

An approximation for cream margarine in the temperature range 20–32°C is

$$a \times 10^8 = 2.7778[2.65 - 0.02(T - 20)]\left(m^2/s\right)$$

where T is in degrees Celsius.

Table A1.23 Thermal properties of vegetable oils and fats at 20°C (Kiss 1988).

Thermal conductivity λ ($10^6 \times$ W/m K)	
Sunflower oil	0.1675
Soy oil	0.1763
Sunflower oil (hydrogenated)	0.1675
Thermal diffusivity a ($10 \times$ m^2/s)	
Sunflower oil	0.944
Soy oil	1.056
Specific heat capacity c_P (kJ/(kg °C)	
Sunflower oil (raffinated)	1.7752
Soy oil	1.8149
Sunflower oil (hydrogenated)	2.1311
Specific heat capacity c_P(kJ/(kg °C) of hydrogenated vegetable oils	
$c_P = c_{P.20}[1 + \alpha(t - 20)]$	
where $c_{P.20} = 2.147$ kJ/kg °C and $\alpha \times 10^3 = 1.380\,K^{-1}$	
Density ρ (kg/m^3)	
Arachis oil	913.7
Sunflower oil	918.9
Soy oil	919.4
Dielectric constant (permittivity) ε_t (F/m) as a function of temperature (t = 0–100°C)	
Arachis oil	$\varepsilon_t = 3.051 - 0.00313(t - 20)$
Sunflower oil	$\varepsilon_t = 3.11 - 0.0034(t - 20)$

A1.3 Raw materials, semi-finished products and finished products

Table A1.24 Thermophysical properties of cocoa butter, cocoa mass and chocolate (Antokolskaia 1964).

t (°C)	ρ (kg/m^3)	λ (W/m K)	c_p (W s/kg K)	a (10^6 m^2/s)
Cocoa butter				
10	927	0.291	2512	0.1250
30	910	0.325	2512	0.1444
50	895	0.372	2512	0.1867
70	880	0.430	2512	0.1944
Chocolate				
0	1235	0.214	1482.1	0.1172
10	–	0.223	1854.7	0.0975
20	–	0.233	2122.7	0.0889
35	–	0.246	1603.5	0.1244
Cocoa mass				
10	1110	0.372	2837.7	0.1279
30	1100	0.360	2637.7	0.1250
50	1090	0.349	2637.7	0.1194
70	1080	0.337	2837.7	0.1197

For cocoa mass,

$$\lambda = 1.163(0.325 - 0.005t)\ \mathrm{W/m\ K}$$

$$a \times 10^8 = 2.7778(4.65 - 0.005t)\ \mathrm{m^2/s}$$

For chocolate mass (Rapoport and Tarchova 1939), for the temperature range 30–70°C,

$\rho = (1320 - 0.5t)\ \mathrm{kg/m^3}$
$\lambda = 1.163(0.2 + 0.0007t)\ \mathrm{W/m\,K}$
$c_p = 1674.7\ \mathrm{W\,s/kg\,K}$
$a \times 10^8 = 2.7778(4 + 0.017t)\ \mathrm{m^2/s}$

Table A1.25 Chemical properties of cocoa butter.

Property	Value
Acid degree	1.6–6.0 (exceptionally up to 8)
Acid value	0.9–3.4 (exceptionally up to 4.5)
Saponification value	192–197
Iodine value	32–42 (exceptionally up to 45)
Peroxide value (mEqO_2/kg)	< 2

For further details, see Fincke (1965).

Table A1.26 Physical properties of cocoa butter.

Property	Value
Melting point (complete fusion) of modifications	
γ form	16–18°C
α form	21–24°C
β (IV) form	27–29°C
β (V) form	33–35°C
β (VI) form	36–37°C
Heat of melting, mean value [β (IV) form]	150.68 kJ/kg
Specific heat capacity, solid and liquid	2.093 kJ/kg
Density in liquid state at 30°C	901 kg/m^3

For further details, see Fincke (1965).

Table A1.27 Dynamic viscosity (Pa s) of cocoa butter as a function of temperature (°C) (Sokolovsky 1959).

t (°C)	η (Pa s)	t (°C)	η (Pa s)	t (°C)	η (Pa s)
35	0.0520	50	0.0278	65	0.0192
40	0.0383	55	0.0249	70	0.0158
45	0.0349	60	0.0206	75	0.0154

Table A1.28 Variation of the dynamic viscosity (Pa s) of chocolate as a function of the conching time (Antokolskaia 1964).

	Conching time (h)										
	0	0.5	1	2	3	4	5	24	48	72	96
Chocolate, t = 50–60°C	80	–	45	37.5	35	33.5	23	–	–	–	
‘Sport’, t = 32°C	35	–	15	12	12	12	–	–	11	11	–
‘Prima’, t = 32°C	25.5	–	15.5	14.5	–	14	–	12	11	–	–
‘Extra’, t = 32°C	30.5	27	25	21	–	18.5	15	11.4	11	–	11
Chocolate, t = 32°C	7.6	–	–	–	–	–	–	5.00	4.65	5.3	–
(Water content %)	1.19	–	–	–	–	–	–	0.96	–	0.91	–

Table A1.29 Thermophysical characteristics of some raw materials used in the confectionery industry (Danilova 1961).

Material	t (°C)	ρ (kg/m^3)	λ (W/(m K)	c_P (W s/kg K)	$a \times 10^6$ (m^2/s)
Cocoa beans	20	560	0.105	2260.9	0.0819
	50	0.099	2260.9	0.0777	
	70	0.093	2260.9	0.0763	
	110	0.093	2260.9	0.0750	
Citric acid	15	1542	0.179	1394.2	0.1436
	30	–	0.177	1381.6	0.1430
	50	0.174	1873.3	0.1411	
Melange	–10	952	0.209	4438	0.3249
	5	–	0.456	3810	0.1167
	15	1015	0.463	3747.2	0.1222
	25	1010	0.467	3642.5	0.1277
Honey	–5	1010	0.654	1821.3	0.1250
	15	1435	0.349	2306.9	0.1055
	20	1345	–	2428.3	0.1055
	35	1345	0.370	2993.6	0.0867

According to Danilova (1961), the data for *honey* can be calculated in the temperature interval 5–35°C as follows:

$\rho = 1442 - 0.4t$ (kg/m^3)
$\lambda = 1.163(0.29 + 0.00075t)$ (W/m K)
$c_P = 4186.8(0.54 + 0.0035t)$ (W s/kg K)
$a \times 10^8 = 2.778(4.3 - 0.033t)$ (m^2/s)

For further details, see Kältetechnik (1960).

Table A1.30 Thermophysical properties of sweets and chocolate.

Product	ρ (kg/m^3)	λ (W/m K)	c (W s/kg K)	$a \times 10^6$ (m^2/s)
Pralines with fruit juice[1]				$0.1 - 7.4 \times 10^{-4}(t - 40)$
Wafer	–	$1.163(0.046 + 0.0015t)$	$4186.8(0.35 + 0.00033t)$	$2.7778(7.7 - 0.28t)$
Zwieback	–	–	$4186.8(0.572 - 0.0007t)$	$2.7778(3.35 + 0.0047t)$
'Sport' cake	–	$1.163(0.098 + 0.0001t)$	$4186.8(0.575 - 0.0022t)$	$2.7778(2.8 + 0.121t)$
Chocolate	1315	$1.163(0.2 + 0.0007t)$	1591–1675	$2.7778(4 + 0.017t)$

t = temperature in °C.
Latent heat of melting: 124.604 kW s/kg (Danilova *et al.* 1961).
[1]Antokolskaia (1964).

For chocolate mass, the following relationships were given by Rapoport and Tarchova (1939) for the temperature range 30–70°C:

ρ (kg/m^3) = $1320 - 0.5t$
λ (W/m K) = $1.163(0.2 + 0.0007t)$
c (W s/kg K) = 1674.7 (= 0.4 kcal/kg °C)
$a \times 10^8$ (m^2/s) = $2.7778\ (4 + 0.017t)$

where t (°C) is the temperature.

For the *viscosity of chocolate*, see Section 4.9.1 and Appendix 3.

Table A1.31 Hardness of various chocolate brands (Sokolovsky 1959).

Brand	Hardness (N/m^2)
Prima	5981
Goldetikett	5680
Sport	3130
Vanille	3230
Extra	3430
Cream	1860
Soy	1270

Table A1.32 Thermophysical properties of sweets (Danilova *et al.* 1961).

Product	t (°C)	ρ (kg/m^3)	λ (W/m K)	c (W s/kg K)	$a \times 10^6$ (m^2/s)
Wafer	30	–	0.106	–	0.1900
Zwieback	15	–	0.123	2365.5	0.0944
	25	–	0.123	2302.7	0.0967
	30	–	0.124	2302.7	0.0972
Filled drops	5	1370	0.436	2080.8	0.1528
	30	–	0.436	2281.8	0.1394
	45	–	0.436	2453.5	0.1297
Romaschka (drops)	1224	0.283	1704	0.1353	
Jelly (marmalade)	25	1411	0.384	2951.9	0.0922
	50	–	0.372	2834.5	0.0944
	85	–	0.360	2784.2	0.0950
Marzipan	14	1360	0.372	1808.7	0.1514
	25	–	0.366	1800.3	0.1500
	35	–	0.359	1779.4	0.1486
Pralines	–	1204	0.250	1410.9	0.1475
Pralines with fruit	25	940	0.212	2101.8	0.1075
juice filling	50	–	0.215	2491.2	0.0919
	85	–	0.222	3328.5	0.0708
'Lakton'	–	519	0.099	1724.9	0.0867
'Cream'	25	642	0.116	2181.3	0.0830
	45	–	0.120	1997.1	–
	65	–	0.122	1687.3	–
	85	–	0.124	1624.5	–
Cake	25	705	0.128	2177.1	0.0833
'Unsere Marke'	45	–	0.128	1967.8	0.0917
'Sport'	25	–	0.116	2177.1	0.0830
	45	–	0.120	1997.1	0.0933
	65	–	0.122	1687.3	0.1128
	85	–	0.124	1624.5	0.1219
Cocoa powder	0	–	0.062	1226.7	0.1067
	10	–	0.063	1377.5	0.0967
	15	1475[1]	0.064	1557.5	0.0864
	20	–	0.064	1988.7	0.0680
	27	–	0.065	1821.3	0.0753
	35	–	0.066	1423.5	0.0983
	40	–	0.066	1285.3	0.1094
Honey cake	15	538	0.080	1791.9	0.0833
	22	–	0.081	1771.0	0.0855
	30	–	0.085	1825.4	0.0864
Honey cake 'Minze'		520	0.099	1984.5	0.0928
'Sachsen'	–	648	0.087	1930.1	0.0808
Halawa	0	950	0.196	1976.2	0.1047
	26	–	0.206	2265.1	0.0958
	40	–	0.200	2265.1	0.0930
	60	–	0.213	2499.5	0.0894
Chocolates 'Gold	10	1270	0.244	1674.7	0.1139
anchor'	30	1260	0.256	1674.7	0.1122
	50	1250	0.267	1674.7	0.1278
	70	1240	0.267	1591.0	0.1361
'Soy beans'	18	1150	0.219	2344.6	0.0980
	35	–	0.209	1992.9	0.0911
'Sport'	15	–	–	1381.6	–
'Extra' (milk)	15	–	–	1967.8	–

[1] Akhindinov and Polakova (1962).
According to Akhindinov and Polakova (1962), for cocoa powder ρ = 857–1475 (kg/m^3).

Table A1.33 Density of sugar confectionery products (Antokolskaia 1964).

Product	Density (kg/m^3)
'Bon-Bon' drops with chocolate–hazelnut filling (35%)	1350–1355
Drops with berry filling	1430–1435
Drops	1220–1225
Fruit jelly bonbon	1359

Table A1.34 Dynamic viscosity (Pa s) of various fondant masses as a function of temperature (°C) (Antokolskaia 1964).

Temperature (°C)	Viscosity (Pa s)
Fondant mass for 'Riviera' (water content 10.5%; invert sugar 6.3%)	
70	5.2
68	5.4
67	6.0
66	8.0
65	8.6
62	10.4
60	11.6
Fondant mass for 'Happy Childhood' (water content 10.5%; invert sugar 5.8%)	
79	16.0
77	20.0
75	23.0
74	36.0
72	44.0
Fondant mass for 'Shio-Shio-San' (water content 9.0%; invert sugar 6.0%)	
80	8.0–9.0
79	13.0
77	18.4
76	21.6
75	25.2
74	32.0
70	50.0
Toffee mass 'Kis-Kis' (water content 17%)	
60	2.48
70	1.15
80	0.67
90	0.36
100	0.26
Toffee mass 'Kis-Kis' (water content 9%)	
60	559.3
80	116.6
85	64.4
90	43.0
100	33.7
Toffee mass 'Kis-Kis' (water content 8%)	
70	487.8
85	122.8
90	43.0
Toffee mass 'Gold Key' (water content 19%)	
60	3.91
70	2.18
80	1.13
90	0.62
100	0.38

Table A1.35 Thermophysical properties of semi-products used for cakes (Antokolskaia 1964).

	t (°C)	ρ (kg/m^3)	λ (W/m K)	c (W s/kg K)	$a \times 10^6$ (m^2/s)
Toffee					
	25	1400	0.291	2239.9	0.0928
	40	–	0.291	2260.9	0.0919
	60	–	0.291	2281.8	0.0911
	85	–	0.291	2311.1	0.0900
Hard-boiled sugar mass					
Water content 2%					
	20	1600	0.314	1381.6	0.1444
	40	1570	0.291	1465.4	0.1278
	60	1540	0.267	1832.8	0.1055
	80	1500	0.256	1718.6	0.1000
Water content 3–5%					
	20	1550	0.314	1716.8	0.1187
	40	1520	0.302	1758.5	0.1111
	60	1490	0.291	1842.2	0.1055
	80	1460	0.279	1884.1	0.1000
Fondant					
	20–60	1392	0.373	1737.5	0.1542
With nuts		1005	0.173	1490.5	0.1058
	20	1397	0.352	1632.8	0.1480
With cream		1397	0.327	1511.4	0.1564

For *hard-boiled sugar mass*, in the temperature range 15–85°C,

$$\lambda = 1.163(0.265 + 0.0005t)\ (\mathrm{W/m\ K})$$
$$c_P = 4186.8(0.43 + 0.0025t)\ (\mathrm{W\ s/kg\ K})$$
$$a \times 10^8 = 2.7778(4.55 - 0.021t)\ (\mathrm{m^2/s})$$

On the basis of the figures published by Antokolskaia (1964), the following approximate formulae can be used in the temperature range 0–80°C.

For *fondant mass*,

$$\lambda = 0.43 + (t - 10)8.3 \times 10^{-4}\ (\mathrm{W/m\ K})$$
$$c_P = 1778 + 15.7(t - 10)\ (\mathrm{W\ s/kg\ K})$$

For *fondant filling*,

$$a \times 10^6 = 0.16 - 0.001(t - 20)\ (\mathrm{m^2/s})$$

For *hard-boiled sugar mass*,

$$c_P = 1100 + 6.67(t - 10)\ (\mathrm{W\ s/kg\ K})$$
$$a \times 10^6 = 0.1 - 6.67 \times 10^{-4}\ (t - 50)\ (\mathrm{m^2/s})$$

Table A1.36 Dynamic viscosity (Pa s) of hard-boiled sugar masses with different molasses contents as a function of temperature (°C) (Nachschlagewerk des Konditors 1958, Sokolovsky *et al.* 1958).

Water (%)	Temperature (°C)	Dynamic viscosity (Pa s)	Molasses (%)
1.91	135	18.4	15
	125	31.0	
	115	79.7	
	105	240	
	95	950	
	90	2020	
	85	4680	
	80	11 800	
	75	31 700	
1.84	135	–	25
	125	37.2	
	115	95.8	
	105	325	
	95	1400	
	90	3030	
	85	7320	
	80	17 400	
2.48	135	–	25
	125	–	
	115	55.0	
	105	154.7	
	95	690.0	
	90	1562.3	
	85	4470	
	80	12 100	
	75	39 900	
2.3	135	–	35
	125	–	
	115	100.3	
	105	382	
	95	2000	
	90	4820	
	85	11 500	
	80	30 060	
	75	95 600	
2.7	135	–	50
	125	–	
	115	110	
	105	390	
	95	2400	
	90	5000	
	85	11 700	
	80	35 000	

Table A1.37 Density and dynamic viscosity of biscuit dough as a function of temperature (Antokolskaia 1964).

t (°C)	ρ (kg/m^3)	η (Pa s)
Kneading under pressure (water content 38%)		
18	880	11.5
19	880	9.5
20	880	7.9
Kneading at atmospheric pressure (water content 37%)		
20	1034	7.4
21	1034	6.5
22	1032	5.9
23	1032	5.5
24	1027	4.9
25	1027	4.3
26	1024	4.0

Table A1.38 Density and thermophysical properties of wafer batter and of biscuit and cracker doughs (Antokolskaia 1964).

t (°C)	ρ (kg/m^3)	λ (W/m K)	c_P (W s/kg K)	$a \times 10^6$ (m^2/s)
Wafer batter				
15	–	0.477	3621.6	0.1205
25	–	0.477	3600.6	0.1250
40	–	0.483	3600.6	0.1267
60	1100	0.483	3558.8	0.1244
85	–	0.488	3600.6	–
Zwieback dough				
15	1165	0.331	2625.1	0.1083
22	–	0.338	2713.1	0.1069
40	–	0.348	2847.0	0.1047
Semi-sweet biscuit dough				
20	–	0.401	2909.8	0.1036
26	1222–1330	0.409	29515.9	0.1039
36	–	0.420	2997.7	0.1050
Cracker dough (laminated)				
15	1295	0.326	2352.9	0.1069
22	–	0.328	2323.7	0.1092
30	–	0.329	2260.9	0.1125
40	–	0.335	2219.0	0.1167
Sweet biscuit dough				
15	1280	0.338	2491.1	0.1061
22	–	0.340	2512.1	0.1056
30	–	0.338	2533.0	0.1044
Hard–sweet biscuit dough				
15	1330	0.385	2658.8	0.1083
24	–	0.407	2888.9	0.1055
30	–	0.430	3181.9	0.1014

For *Zwieback dough*,

$$\lambda = 1.163(0.275 + 0.005t)\ (\text{W/m K})$$

$$c_P = 4186.8(0.62 + 0.0012t)\ (\text{W s/kg K})$$

According to Danilova *et al.* (1961), for *short dough* (sheeted),

$$\lambda = 1.163(0.28 + 0.00014t)\ (\text{W/m K})$$

$$c_P = 4186.8(0.58 - 0.0013t)\ (\text{W s/kg K})$$

$$a \times 10^8 = 2.7778(3.65 + 0.0143t)\ (\text{m}^2/\text{s})$$

Table A1.39 Dynamic viscosity of sweet biscuit dough as a function of time of kneading (Antokolskaia 1964).

Time of kneading (min)	η (MPa s)
10	0.38
20	0.36
30	0.26
40	0.17
60	0.60
80	0.69
90	1.1

Table A1.40 Viscosity (MPa s) of the cracker dough for 'Krokett' and the sweet biscuit dough for 'Sachar' as a function of the amount of gluten of different qualities (Antokolskaia 1964).

		Viscosity (MPa s)	
Elasticity of gluten	Amount of gluten (%)	Cracker dough (39°C) (water content 24–25%)	Sweet biscuit dough (25–26°C) (water content 17–19%)
Weak	17	0.86	1.00
	20	0.95	2.0
	33	1.00	2.60
Medium	19	0.36	0.10
	22	0.70	0.80
	32	0.96	0.85
Strong	19	0.30	0.80
	22	0.25	0.70
	24	0.25	0.65
	34	0.25	0.60

Table A1.41 Dynamic viscosity of honey-cake dough (water content 20%) as a function of time of kneading at 30°C (Antokolskaia 1964).

Time of kneading (min)	Viscosity (MPa s)
15	0.25
30	0.26
45	0.30
60	0.29

Table A1.42 Dynamic viscosity of honey-cake dough as a function of temperature (Antokolskaia 1964).

Temperature (°C)	Viscosity (MPa s)
20	0.55–0.93
30	0.27
40	0.26

Table A1.43 Dynamic viscosity of honey-cake dough as a function of water content (Antokolskaia 1964).

Brand name	Water content (%)	Viscosity (MPa s)
Moskauer Batoni	20.0	0.40
	20.8	0.25
	21.0	0.18
	22.6	0.16
	23.0	0.14
Honey	21.0	0.30
	23.0	0.20

Table A1.44 Density and dynamic viscosity of wafer batter as a function of water content at 20°C (two types, with different elasticity values of gluten) (Antokolskaia 1964).

Water content (%)	Density (kg/m^3)	Viscosity (Pa s)
Gluten content of flour 27%		
60.0	1136–1140	4.2–4.6
62.0	1154	1.1–1.2
64.0	1142–1144	1.15–1.20
65.0	1133–1137	0.83–0.84
Gluten content of flour 32%		
60.6	–	12.4
62.0	–	9.5
64.0	–	3.3
65.0	–	2.3
66.0	–	1.1

Table A1.45 Dynamic viscosity of wafer batter (water content 62.3–62.6%) as a function of temperature (Antokolskaia 1964).

Temperature (°C)	Viscosity (Pa s)
15	1.80
20	1.51
25	1.40
30	1.08

Table A1.46 Thermal conductivity of raw materials (Nachschlagewerk des Konditors 1958).

Raw material	Water content (m/m%)	λ (cal/g °C)
Wheat flour	Dry content	0.340
	13.0	0.426
	13.5	0.429
	14.0	0.432
	14.5	0.436
	15.0	0.439
	15.5	0.442
Crystalline sugar	0.1–0.2	0.301
Sugar powder	0.5	0.308
Maize starch	13.0	0.423
Cows' milk	87.5	0.940
Condensed milk	30.0	0.630
Sodium carbonate	1.0	0.539
Salt	2.0	0.220
Ammonium carbonate	–	0.610
Butter	14.2	0.688
	13.6	0.574
	13.5	0.557
Butter, fried	0.1	0.521
Margarine	15.0	0.500
Honey	18.0	0.450
Starch syrup	20.0	0.700
Invert syrup	33.5	0.600
Egg	74.0	0.760
Crystalline vanillin	0.5–1.0	0.310
Flavourings	–	0.540