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THERMAL PROPERTIES MODELLING FOR FREEZING FRUIT AND VEGETABLE JUICES: CORRELATION OF HEAT CONTENT, SPECIFIC HEAT AND ICE CONTENT

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Abstract. **In the freezing process, water is first partly segregated from the aqueous solution by crystallization. The process is governed by the principle of freezing point depression. On the basis of an empirical freezing point depression equation, ice content was calculated by a method of mass balance. Initial freezing temperatures for 26 different fruits, vegetables, and juices are presented. The variations of heat content, apparent specific heat, and ice content in the temperatures between 80 and −40°F for apple juice, grape juice, orange juice, and orange juice concentrate are presented.**

The fruit juice processor, for the purpose of his freezing operation, needs to know the quantity of heat to be removed and the rate at which heat can be removed from juices or concentrates. A heat content chart derived from the experimental data of Riedel (5) has been applied for calculating refrigeration loads for citrus products (2, 3). However, the properties such as thermal conductivity, specific heat, and density, which are needed for calculating freezing rates are drastically changed in the freezing zone due to ice formation. A knowledge of ice content as a function of freezing temperatures will provide a basis for estimating the values of thermal properties.

The objective of this work was to apply a mathematical method to derive numerical data of heat content, apparent specific heat, and ice content based on experimental correlations established by Riedel (5).

Materials and Methods

In the freezing process, water is first partly segregated from the aqueous solution by crystallization. The process is governed by the principle of freezing point depression.

Consider a juice containing $X_w\%$ of total water, $X_o\%$ of water soluble substances (e.g. acids, sugars, etc.) and negligible amount of insoluble substances, being cooled below its initial (the highest) freezing temperature. The system now contains $P_1\%$ of ice, while $P_2\%$ of water remains unfrozen. The unfrozen solution becomes more concentrated as a result of ice formation.

An empirical freezing point depression equation for determining the initial freezing temperature as a function of soluble solids content is given as (5):

$$t\ (°F) = 32 - 0.18X - 0.00009X^3 \qquad [1]$$

where t = freezing temperature (°F); X = percent of soluble solids by weight (°Brix).

An ice content equation was derived on the basis of mass balance:

$$I = \frac{100}{X_w}\left(100 - \frac{100X_o}{X}\right) \qquad [2]$$

where I = ice content as a percent of total water (%); X_o = initial soluble solids content (%); X_w = total water content (%).

The ice content as a function of freezing temperatures was calculated by solving Eqs. [1] and [2] simultaneously.

The heat content at constant pressure is defined as the energy of a system plus the product of its pressure times its volume. We do not know the absolute value of the energy, and therefore not that of the heat content. We deal with differences of energy and differences of heat content. The symbol Δ (delta) is generally used for differences, when they are not infinitesimally small. The difference of heat content can be measured by heat changes at two temperatures.

For a juice at a room temperature (75°F) undergoing freezing to a temperature t, the difference of heat content was modeled by the sum of the latent heat change and sensible heat change as follows (5):

$$\Delta H = L{\cdot}X_i + (1 - 0.0057X_o)\ (t - 75) \qquad [3]$$

where ΔH = heat content (Btu/lb); L = latent heat of fusion of water (Btu/lb); X_i = ice fraction.

The ice fraction at freezing temperatures was calculated by solving Eq. [1] and the following equation:

$$X_i = 1 - \frac{X_o}{X} \qquad [4]$$

The latent heat was calculated by the following equation (4):

$$L = 143.8 - 0.92t - 0.00337t^2 \qquad [5].$$

The rate of change of heat content per unit temperature change is called the heat capacity at constant pressure. Since the change of heat content includes latent heat, the corresponding definition for the specific heat capacity is called apparent specific heat as a distinction with the usual definition of specific heat without phase change.

The values of apparent specific heat were calculated from Eq. [3] by the following expression (2):

$$C_p = \frac{\Delta H}{\Delta t} \qquad [6]$$

The calculated results of heat content were then converted to a reference temperature, i.e., −40°F at which the heat content equal to zero was chosen for all data presented in this paper.

Results and Discussion

On the basis of Eq. [1] the calculated initial freezing temperature for various fruits, vegetables and juices are shown in Table 1. A comparison of calculated vs. handbook values (1) for initial freezing temperature of citrus fruits is shown in Table 2. Calculations for Table 1 are in good agreement except the values for oranges.

The calculated variations of heat content, apparent specific heat, and ice content for a variety of fruit juices in the temperatures between 80 and −40°F are shown in Tables 3-6. Four different products are included: 1) 12.8° Brix apple juice (Table 3); 2) 15.3°Brix grape juice (Table 4); 3) 11°Brix orange juice (Table 5); 4) 42°Brix orange juice concentrate (Table 6).

The calculated results are in good agreement with data

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Table 1. Initial freezing temperature of fruits, vegetables and juices[z].

Product	Moisture content (% by wt.)	Soluble solids content (% by wt.)	Insoluble solids content (% by wt.)	Initial freezing temperature (°C)	(°F)
Apple juice	87.2	12.8	—	− 1.4	29.5
Apple juice concentrate	71.9	28.1	—	− 3.9	25.0
Apple juice concentrate	49.8	50.2	—	−11.3	11.7
Applesauce	82.8	14.8	2.4	− 1.6	29.1
Asparagus (peeled)	92.6	6.0	1.4	− 0.6	30.9
Asparagus juice	94.0	6.0	—	− 0.6	30.9
Bilberries	85.1	10.5	4.4	− 1.1	30.0
Bilbery juice	89.5	10.5	—	− 1.1	30.0
Carrots	87.5	10.2	2.3	− 1.1	30.0
Cherry juice	86.7	13.3	—	− 1.4	29.5
Cucumber (peeled)	95.4	4.0	0.6	− 0.4	31.3
Grape juice	84.7	15.3	—	− 1.7	28.9
Onions	85.5	13.0	1.5	− 1.4	29.5
Orange juice	89.0	11.0	—	− 1.2	29.9
Peaches (without stone)	85.1	13.7	1.2	− 1.5	29.3
Pears (Bartlett)	83.8	14.2	2.0	− 1.6	29.1
Plums (without stone)	80.3	19.2	0.5	− 2.3	27.9
Raspberries	82.7	11.5	5.8	− 1.2	29.8
Raspberry juice	88.5	11.5	—	− 1.2	29.8
Raspberry juice concentrate	50.6	49.4	—	−11.0	12.2
Spinach	90.2	5.5	4.3	− 0.6	30.9
Strawberries	89.3	8.3	2.4	− 0.9	30.5
Strawberry juice	91.7	8.3	—	− 0.9	30.5
Sweet cherries	77.0	21.0	2.0	− 2.6	27.3
Sweet cherry juice	79.0	21.0	—	− 2.6	27.3
Tomato pulp	92.9	6.8	0.3	− 0.7	30.7

[z]Riedel (5).

Table 2. A comparison of calculated vs. handbook values for initial freezing temperature of citrus fruits.

Product	Solids content	Initial freezing temperature: Handbook value[z]	Calculated values	
	°Brix	°C	°C	°F
Grapefruit	11	−1.1	−1.2	29.8
Lemons	11	−1.4	−1.2	29.8
Limes	14	−1.6	−1.5	29.2
Oranges	13	−0.8	−1.4	29.5
Tangerines	13	−1.1	−1.4	29.5

[z]ASHRAE (1).

shown in Mollier Diagram established by Riedel (5). The calculation methods can be applied for other fruit and vegetable juices listed in Table 1.

Conclusion

The proposed mathematical models enable us to calculate the numerical data of heat content, apparent specific heat, and ice content for a wide range of temperatures. The calculated results are in good agreement with data shown in Mollier diagram. Therefore, the mathematical methods should provide a rational basis for engineering calculations.

Table 3. Heat content, apparent specific heat, and ice content of 12.8°Brix apple juice. Moisture content = 87.2%. Initial freezing temperature = 29.5°F.

Temperature (°F)	Heat content (BTU/lb.)	Apparent specific heat (BTU/lb. °F)	Ice content[z] (%)
−40.0	0.0	0.48	98
−30.0	4.8	0.53	97
−20.0	10.1	0.59	95
−15.0	13.0	0.64	94
−10.0	16.2	0.70	93
− 5.0	19.7	0.78	92
0.0	23.6	0.86	91
2.5	25.8	0.93	90
5.0	28.1	1.02	89
7.5	30.6	1.13	88
10.0	33.5	1.26	86
12.0	36.0	1.42	85
14.0	38.8	1.63	84
16.0	42.1	1.92	82
18.0	45.9	2.35	79
20.0	50.6	3.04	76
22.0	56.7	4.23	72
24.0	65.2	6.64	66
26.0	78.4	10.32	57
27.0	88.8	15.37	49
28.0	104.1	25.74	37
29.0	129.9	22.12	17
30.0	152.0	0.93	0
31.0	152.9	0.93	0
32.0	153.8	0.93	0
40.0	161.2	0.93	0
50.0	170.3	0.93	0
60.0	179.4	0.93	0
70.0	188.6	0.93	0
80.0	197.7	0.93	0

[z]Percent of total water.

Table 4. Heat content, apparent specific heat, and ice content of 15°Brix grape juice. Moisture content = 84.7%. Initial freezing temperature = 28.9°F.

Temperature (°F)	Heat content (BTU/lb.)	Apparent specific heat (BTU/lb. °F)	Ice content[z] (%)
−40.0	0.0	0.50	97
−30.0	5.0	0.56	96
−20.0	10.6	0.63	94
−15.0	13.8	0.68	93
−10.0	17.2	0.75	92
− 5.0	21.0	0.85	90
0.0	25.2	0.94	89
2.5	27.6	1.03	88
5.0	30.1	1.13	86
7.5	33.0	1.26	85
10.0	36.1	1.42	83
12.0	39.0	1.61	82
14.0	42.2	1.86	80
16.0	45.9	2.21	78
18.0	50.3	2.72	75
20.0	55.8	3.54	71
22.0	62.8	4.96	66
24.0	72.8	7.84	59
26.0	88.4	12.25	47
27.0	100.7	18.28	37
28.0	119.0	28.47	22
29.0	147.4	0.91	0
30.0	148.3	0.91	0
31.0	149.2	0.91	0
32.0	150.1	0.91	0
40.0	157.3	0.91	0
50.0	166.2	0.91	0
60.0	175.1	0.91	0
70.0	184.0	0.91	0
80.0	193.0	0.91	0

[z]Percent of total water.

Table 5. Heat content, apparent specific heat, and ice content of 11°Brix orange juice. Moisture content = 89%. Initial freezing temperature = 29.9°F.

Temperature (°F)	Heat content (BTU/lb.)	Apparent specific heat (BTU/lb. °F)	Ice content[z] (%)
−40.0	0.0	0.46	98
−30.0	4.6	0.51	97
−20.0	9.7	0.56	96
−15.0	12.5	0.60	95
−10.0	15.5	0.66	94
− 5.00	18.8	0.73	93
0.0	22.5	0.80	92
2.5	24.5	0.86	92
5.0	26.6	0.94	91
7.5	29.0	1.03	90
10.0	31.5	1.15	89
12.0	33.8	1.28	87
14.0	36.4	1.46	86
16.0	39.3	1.72	85
18.0	42.8	2.09	83
20.0	47.0	2.68	80
22.0	52.3	3.70	77
24.0	59.7	5.77	72
26.0	71.2	8.94	63
27.0	80.2	13.28	57
28.0	93.5	22.19	47
29.0	115.7	39.60	30
30.0	155.3	0.94	0
31.0	156.2	0.94	0
32.0	157.1	0.94	0
40.0	164.4	0.94	0
50.0	173.5	0.94	0
60.0	182.7	0.94	0
70.0	191.8	0.94	0
80.0	201.0	0.94	0

[z]Percent of total water.

Table 6. Heat content, apparent specific heat, and ice content of 42°Brix orange juice concentrate. Moisture content = 58%. Initial freezing temperature = 17.8°F.

Temperature (°F)	Heat content (BTU/lb.)	Apparent specific heat (BTU/lb. °F)	Ice content[z] (%)
−40.0	0.0	0.75	88
−30.0	7.5	0.89	83
−20.0	16.5	1.04	76
−15.0	21.7	1.17	72
−10.0	27.5	1.35	67
− 5.0	34.3	1.59	62
0.0	42.3	1.84	55
2.5	46.9	2.06	50
5.0	52.0	2.34	46
7.5	57.9	2.69	40
10.0	64.6	3.12	33
12.0	70.8	3.62	27
14.0	78.1	4.30	19
16.0	86.7	5.05	10
18.0	96.8	0.76	0
20.0	98.3	0.76	0
22.0	99.8	0.76	0
24.0	101.2	0.76	0
26.0	102.7	0.76	0
27.0	103.5	0.76	0
28.0	104.2	0.76	0
29.0	105.0	0.76	0
30.0	105.7	0.76	0
31.0	106.5	0.76	0
32.0	107.2	0.76	0
40.0	113.2	0.76	0
50.0	120.6	0.76	0
60.0	128.1	0.76	0
70.0	135.6	0.76	0
80.0	143.0	0.76	0

[z]Percent of total water.

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THE SUITABILITY OF CITRUS TASTE EVAPORATORS FOR MUSCADINE GRAPE JUICE CONCENTRATE PRODUCTION

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Abstract. **Grape juice concentrates were prepared from 'Carlos,' 'Dixie,' and 'Noble' varieties using juice extraction and adjustment procedures specific for muscadines. Juices were concentrated from about 13 to 68° Brix in 227 kg/hr TASTE evaporators with and without essence recovery capabilities. Concentration produced little change in juice composition or quality. Addition of Muscadine or Concord grape essence to reconstituted juices did not enhance acceptability which was comparable to commercial canned juice and frozen concentrates. The process appears promising for muscadine concentrate production employing off-season citrus industry thermally accelerated, short time evaporation (TASTE) evaporators.**

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The current rapid development of a grape industry in Florida has been accelerated by the establishment of 5 wineries in the last 3 yr and a dramatic expansion of grape plantings in state (6). Over the last decade grape plantings have increased from under 100 to over 600 bearing acres. While most of this production supports fresh market U-pick operations or the local wineries, the vineyards in the last several years have produced a modest grape surplus. It is estimated that between 15 and 25% of all grapes grown