THERMAL CONDUCTIVITY OF PEACH, RASPBERRY, CHERRY AND PLUM JUICES AS A FUNCTION OF TEMPERATURE AND CONCENTRATION

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ABSTRACT

The thermal conductivity (k) of four fruit juices (peach, raspberry, cherry and plum) was measured using a coaxial-cylinder (steady-state) technique. Measurements were made in the temperature range from 20 to 120C and a range of concentration between 9.8 and 60.0°Brix. The total uncertainties of the k and temperature measurements were less than 2% and 0.03C, respectively. The reliability and accuracy of the experimental methodology for fruit juices was confirmed with measurements on pure water. The experimental and calculated values of k of pure water showed excellent agreement within their experimental uncertainty. The effect of temperature and concentration on the k of peach, raspberry, cherry and plum juices was evaluated. The predictive capability of various polynomial models was established.

INTRODUCTION

Accurate thermal conductivity (*k*) data for fruit juices and their variation with operating conditions (over wide temperature and concentration regions)

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are needed for a variety of research and engineering applications (developing food processes and processing equipment, the control of products, filters and mixers, quality evaluation and an understanding of the structure of food and raw agricultural materials) in many branches of the food industry. Modeling, optimization and automation of food processes is difficult because of the complexity of the raw materials and product involved, which affect thermophysical properties such as density, viscosity, C_p and k.

The k of fruit juices exhibits substantial changes with concentration and temperature during processing (storage, transport, marketing and consumption, chilled, change temperature, tank farm change concentration and evaporator change concentration; see Moressi and Spinosi [1980] and Crandall et al. [1982]). For this reason, the k and other thermophysical properties (density, heat capacity [C_p], viscosity and thermal diffusivity [a]) should be studied as a function of temperature and concentration. Little is known about the effect of temperature and concentration on the k of liquid foods. Thus, there is great practical interest in the study of the effect of temperature and concentration on k of fruit juices at equipment-operating conditions. Other thermophysical properties such as a and C_p can be estimated from k measurements. Unfortunately, the k of food products cannot be accurately predicted theoretically, because of their complicated physical and chemical structures. Therefore, the accurate measurement of k of juices is needed. The available theoretical models for liquids cannot describe complex real systems as they meet in practice. Better prediction models can be developed based on reliable experimental information on k.

The k of liquid foods was reviewed by Qashou et al. (1972), Cuevas and Cheryan (1978) and Choi and Okos (1983a, 1986a). A survey of the literature reveals the scarcity of reliable experimental k data for liquid foods. Previously, the k data of fruit and vegetable juices have been reported by several authors (Riedel 1949; Khelemshi and Zhadan 1963; Woodams 1965; Voitko et al. 1967; Dickerson 1968; Reidy 1968; Choi and Okos 1983b; Ziegler and Rizvi 1985; Constenla et al. 1989; Lau et al. 1992; Gratão et al. 2005). Different techniques (for steady-state: guarded parallel-plate, concentric-cylinder and concentric-sphere; for transient: heating and cooling curve, probe and fitch) have been used to measure the k of various juices. Reviews of the methods for k measurements of foods include Mohsenin (1980), Choi and Okos (1983a) and Jowitt et al. (1983). However, most existing k measurements for fruit juices are at room temperature and very limited concentration range.

A literature survey revealed that there are no experimental k data available for peach, cherry, plum and raspberry juices, except for a few data points reported by Riedel (1949) for cherry and raspberry juices at temperatures of 20 and 80C and at 89% mass concentration. Measurements were made by using the concentric-cylinder method. Sweat and Haugh (1974) used a probe method

to measure the *k* of cherry tomato at room temperature. Constenla *et al.* (1989) reported the *k* data for apple juice as a function of concentration and temperature in the range from 20 to 90C and at concentrations between 12 and 70°Brix. Choi and Okos (1983b) reported the *k* data for tomato juice over a wide temperature range of 30 to 150C and at concentrations between 40.0 and 95.2% of the mass. More recently, Gratão *et al.* (2005) reported the *k* of passion juice. These measurements were made using the concentric-cylinder technique in the concentration range from 0.506 to 0.902 mass fractions of water content and at temperatures from 0.4 to 68.8C. The results were correlated using a simple linear polynomial function.

The *k* is one of the more difficult properties to measure because of convection (Wakeham *et al.* 1991). This article presents the first study of the measurement of *k* for selected juices over a wide range of temperatures and concentrations. The main objective was to provide a new and accurate experimental *k* data for four fruit juices at temperatures between 20 and 120C and at concentrations up to 60°Brix using a coaxial-cylinder (steady-state) technique, previously shown to produce accurate measurements on other liquids (water and aqueous solutions) at high temperatures and high pressures (Abdulagatov *et al.* 2004a,b; Abdulagatov and Azizov 2005). Another objective was to develop prediction models for the *k* of fruit juices as a function of temperature and concentration.

MATERIALS AND METHODS

The four experimental samples of cherry, peach, plum and raspberry juices were obtained from fresh full-ripe fruits from a processing plant in Baku, Azerbaijan. The natural juices were obtained by squeezing the fruits with a laboratory screw press, eliminating the suspended solids by filtering and clarifying. Concentrated juices with various soluble solids contents were obtained from the original concentrate using a rotary glass vacuum evaporator (SPT-200, Zeamil-Horyzont, Krakow, Poland) at temperature below 60C. The evaporation chamber was rotated at a constant rotational speed in a water bath at 40C. The soluble solids content was measured in °Brix using a universal laboratory refractometer (RLU-1, Ekaterinburg, Russia) at room temperature (20C). In order to adjust the concentration of the juice, the concentrated juice was diluted with distilled water. The samples were stored in a glass vessel at 2–4C until use (8 h) for the *k* measurements.

The physical and chemical characteristics of juices were measured in the chemical laboratory of the State Research Institute of Horticultural and Subtropical Crops, Baku, Azerbaijan. The microelements, potassium, calcium, magnesium and phosphates were determined using an atomic absorption

TABLE 1.
JUICE COMPOSITION

	Peach	Plum	Cherry	Raspberry
Total sugar (%)	9.30	10.5	9.43	5.50
Sucrose (%)	2.10	3.00	0.24	1.20
Glucose (%)	4.10	5.20	5.48	1.77
Fructose (%)	3.00	2.20	3.71	2.50
Pectin (%)	0.30	–	0.08	0.58
Acidity (%)	0.60	0.98	1.30	1.10
Potassium* (mg)	35.00	39.00	70.00	88.00
Calcium* (mg)	8.50	4.10	8.20	8.00
Magnesium* (mg)	9.50	3.50	7.50	24.00
Phosphates* (mg)	24.00	17.00	23.00	38.00
pH	3.90	3.50	3.10	3.70

* mg in 100 g juice.

spectrophotometer (C-115-M1, Smolensk, Russia). The glucose and fructose contents were determined by the method of Bertrand (Ermakov 1972; Kretovich 1980). The total sugar was calculated by summation of individual sugars. The pH was measured using a digital pH meter (Kent EIL 7020, Marlow, U.K.) at 20C. The total acidity was determined by potentiometric titration with 0.1 N of NaOH until pH 8, monitored with the pH meter. The measured physical and chemical characteristics of peach, plum, cherry and raspberry juices are given in Table 1.

EXPERIMENTAL APPARATUS AND PROCEDURES

Apparatus and Construction of the k Cell

The k of the juices was measured by a coaxial-cylinders (steady-state) technique (Abdulagatov $et\ al.$ 2004a,b; Abdulagatov and Azizov 2005). Figure 1a,b shows a schematic of the apparatus and k cell. The main part of the apparatus consists of a high-pressure autoclave, thermostat and k cell (Fig. 1a). The k cell consists of two coaxial cylinders: one inner (emitting) cylinder and one outer (receiving) cylinder (Fig. 1b). The cylinders were made of stainless steel (1X18H9T, 1chrome–18nickel–9titanium) and located in a high-pressure autoclave. The support of the cylinders was provided by the porcelain rings with three centering ceramic microscrews (1-mm diameter and length). The centering of the outer and inner cylinders was achieved by a microscrew (1-mm diameter and length). The deviation from concentricity was 0.002 cm or 2% of the sample layer. The quality of the centering was

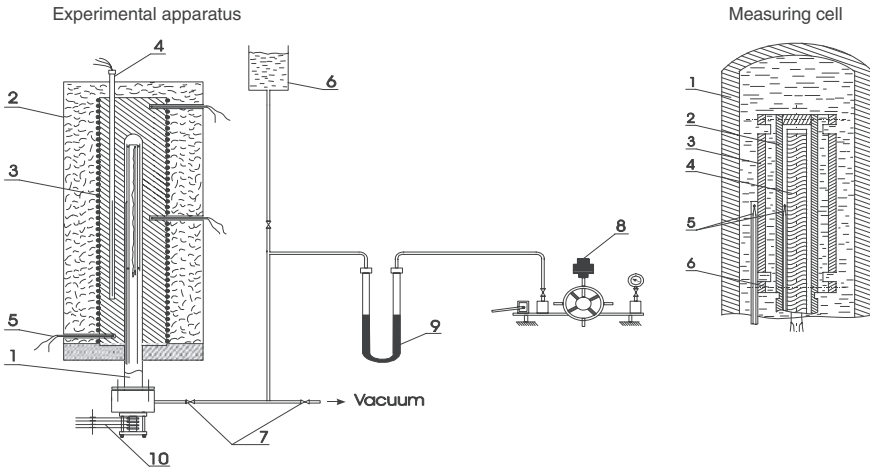Experimental apparatus

Measuring cell

FIG. 1. SCHEMATIC DIAGRAM OF THE EXPERIMENTAL APPARATUS (LEFT) AND
MEASURING CELL (RIGHT) FOR THE MEASUREMENT OF THERMAL CONDUCTIVITY
OF JUICES BY THE COAXIAL CYLINDERS METHOD

Experimental apparatus (left): 1, high-pressure autoclave; 2, thermostat; 3, heater; 4, platinum
resistance thermometer (PRT); 5, thermocouple; 6, filling tank; 7, set of valves; 8, deadweight
pressure gauge (MP-600); 9, separating U-shaped capillary tube; 10, electrical feedthrough;
measuring cell (right): 1, autoclave; 2, inner cylinder; 3, outer cylinder; 4, microheater;
5, thermocouples; 6, axial alignment screws.

checked with a cathetometer (KM-8, IPZ, Izuminsk, Russia). To minimize
conicity, the surfaces of the inner and outer cylinders were perfectly polished
with powders of succeeding smaller grain sizes (320 nm). The cylindricality
of the outer cylinder was checked with a microscope (YIM-21, LPZ, Lenin-
grad, Russia). In the lower part, the inner cylinder extension was soldered to
the flange to seal the autoclave. A shell-capillary was also soldered to this
flange, tightly fitted to the outer cylinder.

The autoclave was made from stainless steel 1X18H10T and located in
the thermostat. The thermostat is a solid (massive) copper block. The tem-
perature in the thermostat was controlled with a heater. The thermostat is
supplied with three sectioned heating elements, platinum resistance
thermometer-10 Ω (PRT-10) and three chrome–alumel thermocouples that
were located on three different levels of the copper block. The temperature
differences between various sections (levels) of the copper block were within
0.02C. The temperature was measured with a PRT and with three chrome–
alumel thermocouples. The thermocouples were located on different levels of
the thermostat to minimize the inhomogeneities in temperature. One of the
junctions of the differential chrome–copel thermocouple located in the inner
cylinder was tightly applied to the cylinder wall. The second junction of the

thermocouple was located in the shell-capillary. The thermocouples were twice calibrated with a standard resistance thermometer (manufactured in leningrad, and calibrated at the Russian Institute of Physical and Technical Measurements, Moscow, Russia). The difference between calibrations was 0.01C. The temperature-sensitive element of the thermocouple was located on the same level as the measuring cell. The reading of the single thermocouples differed by ±0.01C. Measurements started when differences of readings among all the thermocouples were minimal (0.02C).

Geometrical Characteristics of the *k* Cell

The important dimensions of the *k* cell are: (1) outside diameter (o.d.) of the inner cylinder, $d_2 = (10.98 \pm 0.01) \times 10^{-3}$ m; (2) inside diameter (i.d.) of the outer cylinder, $d_2 = (12.92 \pm 0.02)\ 10^{-3}$ m; (3) the length of the measuring section of the inner cylinder (emitter), $l = (150.0 \pm 0.1) \times 10^{-3}$ m; and (4) the gap between cylinders (thickness of the liquid gap), $d = (0.97 \pm 0.03) \times 10^{-3}$ m. The choice of this gap was a compromise between decreasing convection and accommodation effect. The acceptable value for the thickness of the liquid layer *d* is between 0.5 and 1.0 mm. If $d > 1$ mm, a natural convection of heat transfer will develop. The optimal ratio of l/d_2 should be 10 to 15 (Kondrat'ev 1957). It is very difficult to keep the homogeneity of the temperature distribution along the length of the inner cylinder when this ratio *is* greater than 15. If $l/d_2 < 10$ the influence of the end effect is significant.

The fruit juices under investigation were confined in the vertical gap of the cell. The *k* cell was filled with sample using the set of valves (Fig. 1a). Before filling, the cell was heated and evacuated. To fill the measuring cell (gap between cylinders) with test juice sample, slots of 2-mm width and 25-mm length were made on the outer cylinder (3 mm from the end). All connecting tubes, including the filling unit and high-pressure U-shaped vessel, were made of stainless steel.

In the cell, heat was generated in the microheater (Fig. 1b), which consists of an isolated high-temperature lacquer-covered constantan wire of 0.1-mm diameter. The microheater was mounted inside the inner cylinder (emitter), which was closely wound around the surface of a 2-mm diameter ceramic tube and isolated with high-temperature lacquer. The tube was tightly fitted inside a heater pocket of 6-mm diameter on the inner cylinder. All heaters were made with 0.1-mm diameter constantan wire and isolated with high-temperature lacquer.

The electrical schema of the measurements consists of circuits of PRT, calorimetric heater, differential and single thermocouples. All electrical measurements were performed with compensation method using direct current semiautomatic potentiometers (P323/2).

Principle of Operation, Working Equation and Corrections

With this method, the heat generated in an inner emitting cylinder is conducted radially through the narrow juice-filled annulus to a coaxial receiving cylinder. The k of the fluid was deduced from measurements of heat Q transmitted across the solution layer, the temperature difference ΔT between the inner and outer cylinders, the thickness of the solution layer d and effective length l of measuring part of the cylinder (effective length of the cylinders) (Wakeham *et al.* 1991; Abdulagatov *et al.* 2004a,b). The k of the sample at a given temperature was calculated from the relation:

$$k = \frac{Q \ln(d_2 / d_1)}{2\pi l \Delta T}$$
(1)

where $Q = Q_{meas} - Q_{los}$ is the amount of heat transferred by conduction alone across the juice layer between the cylinders, Q_{meas} is the amount of heat released by the calorimetric microheater, Q_{los} is the amount of heat losses through the ends of the measuring cell (end effect) and ΔT is the temperature difference between the inner and outer cylinders (across the sample layer). The values of Q and ΔT are measured indirectly and some corrections are necessary. The temperature difference in the sample layer can be determined as:

$$\Delta T = \Delta T_{meas} - \Delta T_{corr}$$
(2)

where $\Delta T_{corr} = \Delta T_{cl} + \Delta T_{lac}$; ΔT_{cl} and ΔT_{lac} are the temperature differences in the cylinder walls and lacquer coat, respectively, and ΔT_{meas} is the temperature difference measured with differential thermocouples. It is difficult to estimate the values of the Q_{los} and ΔT_{corr} by calculation. In this study, the values of Q_{los} and ΔT_{corr} were estimated by using measurements from a standard liquid with well-known k (International Association of Properties of Water and Steam [IAPWS] standard, Kestin *et al.* 1984). The calibration was made with pure water at a few selected temperatures between 20 and 127C. The amount of heat flow Q and the temperature difference ΔT were 13.06 W and 3.5C, respectively. The estimated value of Q_{los} was about 0.05 W. This value is negligible (0.38%) by comparison with the heat transfer by conduction, $Q = 13.06$ W. After taking into account all corrections, the final working equation for the k can be written as (Abdulagatov *et al.* 2004a,b; Abdulagatov and Azizov 2005):

$$k = A \frac{Q_{meas} - Q_{los}}{\Delta T_{meas} - \Delta T_{corr}}$$
(3)

where $A = \ln\left(\dfrac{d_2}{d_1}\right)\Big/2\pi l$ is the geometric constant, which can be determined with the geometrical characteristics of the experimental cell. The values of A can also be determined by means of a calibration technique using k data for the reference fluid (pure water, IAPWS standard, Kestin *et al.* 1984). The values of the cell constant determined both with geometrical characteristics of the experimental cell and by calibration techniques (pure water at temperature 20C) are 0.1727 m^{-1} and 0.1752 m^{-1}, respectively. In this study, we used the value of A as a function of temperature derived using the calibration procedure with pure water. The geometrical constant A changed by 12% over the temperature range from 20 to 477C. Because of the large emitter size and the small fluid volume surrounding the emitter, no accommodation effect was to be expected.

Convection Heat Transfer

Convection heat transfer increases with increasing values of the Rayleigh number (Ra). The k measurements between coaxial cylinders show that the convection regime is related to the Ra:

$$Ra = GrPr = \frac{g \cdot \alpha_p \cdot \Delta T \cdot d^3 \cdot C_p \cdot \rho^2}{\lambda \cdot \eta}, \tag{4}$$

where Gr and Pr are the Grashof and Prandtl numbers, respectively, g is the gravitational constant, α_p is the thermal expansion coefficient of the fluid, ρ is the density, C_p is the specific heat at constant pressure and η is the viscosity coefficient.

To reduce the values of Ra, a small gap distance between cylinders $d = (0.97 \pm 0.03) \times 10^{-3}$ m was used. This made it possible to minimize the risk of convection. Convection could develop when the Ra exceeds a certain critical value Ra_c, which for vertical coaxial cylinders is about 1000. Therefore, $Ra > 1000$ was considered as the criterion for the upset of convection. In the range of the present experiments, the values of Ra were always less than 500 and Q_{con} was estimated to be negligible. The absence of convection was verified experimentally by measuring the k at different ΔT across the measurement gap and different power Q transferred from the inner to outer cylinder. The measured k values were indeed independent of the two parameters.

Heat Transfer by Radiation

Any conductive heat transfer must be accompanied by simultaneous radiative transfer. The correction depends upon whether or not the fluid

absorbs radiation. If the juice is entirely transparent, then the conductive and radiative heat fluxes are additive and independent and usually negligible. When the juice absorbs and reemits radiation (partially transparent), the problem is more complicated because the radiative and conductive fluxes are coupled. In this case, effect heat transferred by radiation can be derived from the solution of the integro-differential equation describing coupled radiation and conduction. This problem is amenable to exact study only numerically. The approximate solution indicates that the magnitude of radiative contribution to the heat flux depends on the characteristic of the juice for radiative absorption. This characteristic optical property of juice is seldom known so that it is not possible to apply a correction for radiation routinely. There are some situations under which some contribution from radiative transport is negligible. The inner and outer cylinders were perfectly polished with powders of succeeding smaller grain sizes (320 nm), their emissivity was small ($\varepsilon = 0.32$) and heat flux arising from radiation Q_{rad} was negligible in comparison with the heat transfer by conduction in the temperature range of our experiment. To minimize the heat transfer by radiation, the solid material (stainless-steel 1X18H9T) of low emissivity ($\varepsilon = 0.32$) was used for the cylinders and thin layers of fluid were also used (0.97 mm). In this way, heat transport by radiation can be strongly minimized.

Because heat transfer by radiation is proportional to $4T^3\Delta T$, we would expect radiation losses to substantially increase with the cell temperature. In the present study, we did not study the influence of the cylinder wall emissivity on the conductive heat transfer. But this type of correction is included in the calibration procedure. The values of the Q_{rad} can be estimated as:

$$Q_{rad} = \varepsilon\sigma S4T^3\Delta T \tag{5}$$

where $\varepsilon = 0.32$ is the cylinder material emissivity coefficient, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$ is the Stefan-Boltzmann constant, and $S = 5.17 \times 10^{-3}\ \mathrm{m^2}$ is the mean surface of the fluid layer. The emissivity of walls was small and Q_{rad} (estimated by Eq. 5) was negligible (≈ 0.068 W at maximum temperature of 120C) in comparison with the heat transfer (13.06 W) by conduction in the temperature range of our experiment.

Assessment of Uncertainties

The k was obtained from the measured quantities A, Q, T, ΔT, d_1 and d_2. The accuracy of the k measurements was assessed by analyzing the sensitivity of Eq. (3) to the experimental uncertainties of the measured quantities. The maximum relative root–mean–square deviations ($\delta k/k$) of k measurements associated with A, Q, T, ΔT and x measurements can be estimated from the equation:

TABLE 2.
TEST MEASUREMENTS OF THERMAL CONDUCTIVITY ($W \cdot m^{-1} \cdot K^{-1}$) OF PURE WATER

T (C)	20	40	60	80	100	120
k (this work)	0.601	0.630	0.654	0.670	0.679	0.689
IAPWS* standard	0.599	0.631	0.654	0.670	0.679	0.683
Deviation (%)	0.334	0.159	0.000	0.000	0.000	0.879

* Internationally accepted International Association of Properties of Water and Steam (IAPWS) standard data for the thermal conductivity of pure water (Kestin *et al.* 1984).

$$\frac{\delta k}{k} = \frac{1}{k}\sqrt{\left(\frac{\partial k}{\partial A}S_A\right)^2 + \left(\frac{\partial k}{\partial Q}S_Q\right)^2 + \left(\frac{\partial k}{\partial \Delta T}S_{\Delta T}\right)^2 + \left(\frac{\partial k}{\partial T}S_T\right)^2 + \left(\frac{\partial k}{\partial x}S_x\right)^2} \quad (6)$$

where $S_A = 0.0009$ m^{-1}, $S_Q = 2.6 \cdot 10^{-3}$ W, $S_\Delta = 0.005$C, $S_T = 0.030$C and $S_x = 0.005°$Brix are the root–mean–square deviations of A, Q, ΔT, T and x measurements, respectively (Abdulagatov *et al.* 2004a,b). The value of root–mean–square deviation of heat losses through the ends of the measuring cell is about $S_{Q_{los}} = 0.001$ W. As the uncertainties of the measured values d_1, d_2 and l are 0.15, 0.09 and 0.07%, respectively, the corresponding uncertainty of A is 0.50%. Values for the partial derivatives $(\partial k/\partial T)_x$ and $(\partial k/\partial x)_T$ were calculated using the correlating equation for k reported in the next section.

The uncertainty in heat flow Q measurement is about 0.1%. To make sure that the cell was in equilibrium, the measurements were initiated 10 h after the time when the thermostat temperature reached the prescribed temperature. About 5–6 measurements were taken at one state and the average values of k calculated. Reproducibility of the measurements was about 0.5%. From the uncertainty of the measured quantities and the corrections mentioned above, the total maximum relative uncertainty $\delta k/k$ in measuring the k was 2%. All the other uncertainties were assumed negligible.

Performance Tests

To check and confirm the reliability and accuracy of the measurement method and correct operation of the apparatus, the k data were taken for pure water in the temperature range from 20 to 120C (Table 2). The agreement between test measurements for pure water and the IAPWS standard (Kestin *et al.* 1984) calculations is excellent. This k apparatus was successfully employed in our previous studies of k of pure liquids, water and aqueous solutions (Abdulagatov *et al.* 2004a,b; Abdulagatov and Azizov 2005).

TABLE 3.
EXPERIMENTAL THERMAL CONDUCTIVITY ($W \cdot m^{-1} \cdot C^{-1}$) OF FRUIT JUICES AS A
FUNCTION OF TEMPERATURE (C) AT VARIOUS CONCENTRATION (°BRIX)

°Brix	Temperature										
	20	30	40	50	60	70	80	90	100	110	120
Peach											
14.8	0.545	0.553	0.562	0.570	0.576	0.582	0.588	0.595	0.600	0.605	0.610
20.0	0.524	0.534	0.541	0.548	0.555	0.562	0.568	0.575	0.580	0.585	0.590
30.0	0.490	0.497	0.507	0.514	0.521	0.528	0.535	0.541	0.547	0.553	0.556
40.0	0.453	0.464	0.473	0.482	0.490	0.496	0.502	0.506	0.510	0.513	0.517
50.0	0.420	0.432	0.444	0.454	0.461	0.467	0.475	0.480	0.484	0.488	0.490
60.0	0.390	0.402	0.413	0.423	0.432	0.440	0.447	0.453	0.457	0.460	0.462
Plum											
15.1	0.535	0.546	0.555	0.565	0.573	0.583	0.590	0.597	0.605	0.611	0.617
20.0	0.511	0.524	0.533	0.543	0.550	0.559	0.566	0.575	0.582	0.588	0.593
30.0	0.469	0.481	0.492	0.503	0.510	0.517	0.526	0.532	0.540	0.545	0.550
40.0	0.434	0.446	0.457	0.467	0.474	0.481	0.489	0.497	0.504	0.510	0.515
50.0	0.405	0.417	0.427	0.437	0.445	0.452	0.462	0.468	0.475	0.481	0.486
60.0	0.380	0.389	0.401	0.411	0.421	0.430	0.437	0.445	0.453	0.459	0.465
Raspberry											
9.8	0.555	0.564	0.574	0.585	0.595	0.604	0.615	0.620	0.629	0.634	0.640
15.0	0.529	0.541	0.553	0.563	0.574	0.584	0.591	0.599	0.605	0.611	0.615
20.0	0.502	0.515	0.525	0.537	0.547	0.556	0.563	0.570	0.577	0.582	0.587
30.0	0.462	0.472	0.483	0.492	0.501	0.510	0.518	0.526	0.533	0.539	0.545
40.0	0.425	0.437	0.449	0.459	0.468	0.476	0.483	0.490	0.495	0.498	0.502
50.0	0.396	0.407	0.417	0.427	0.435	0.443	0.450	0.456	0.461	0.466	0.469
Cherry											
15.1	0.521	0.532	0.544	0.554	0.565	0.574	0.583	0.592	0.600	0.608	0.615
20.0	0.502	0.513	0.524	0.535	0.544	0.553	0.562	0.571	0.579	0.587	0.595
30.0	0.468	0.478	0.489	0.500	0.510	0.520	0.528	0.537	0.544	0.551	0.558
40.0	0.436	0.447	0.458	0.468	0.477	0.487	0.495	0.503	0.510	0.517	0.523
50.0	0.406	0.418	0.430	0.440	0.450	0.458	0.467	0.474	0.481	0.487	0.492
60.0	0.380	0.390	0.399	0.408	0.417	0.425	0.432	0.439	0.446	0.451	0.456

RESULTS AND DISCUSSION

All experimental k data were obtained as a function of temperature at
fixed concentrations for each juice. The experimental k, temperature and
concentration values for each juice are presented in Table 3. These values are
the averages of 5 to 6 measurements at the same temperature and the same
concentration. Figures 2 and 3 show some of the results in the $k - T$ and $k - x$
projections, respectively, together with values for pure water calculated with
IAPWS formulation (Kestin *et al.* 1984). These figures illustrate the effect of
temperature and concentration on the k of raspberry and cherry juices. Figure 4
compares the concentration and temperature dependences of the k of a series
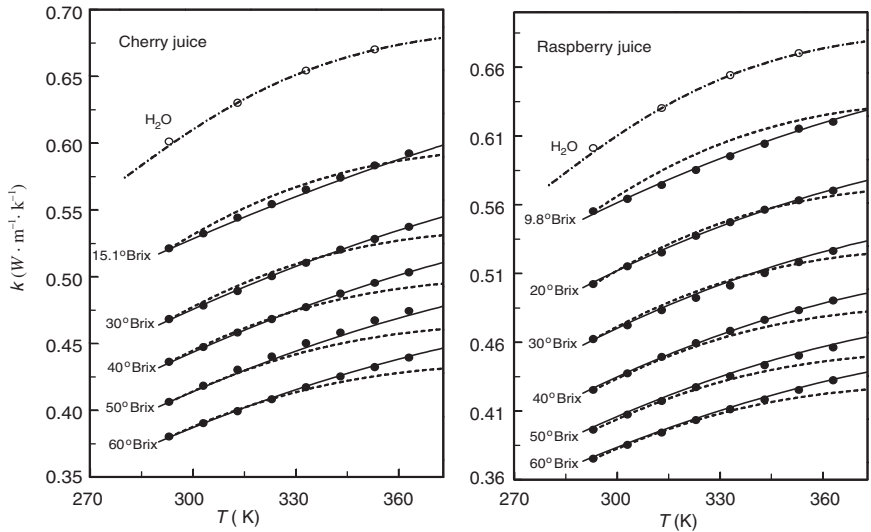
FIG. 2. MEASURED VALUES OF THERMAL CONDUCTIVITY (k) OF CHERRY AND RASPBERRY JUICES AS A FUNCTION OF TEMPERATURE (T) ALONG SELECTED FIXED CONCENTRATIONS
($- \cdot - \cdot - \cdot -$), pure water (IAPWS, Kestin *et al.* 1984); ($- - - -$), Model 3; (——), Model 1. IAPWS, International Association of Properties of Water and Steam.

of juices at the selected temperature of 50C and concentration of 40°Brix. The peach juice has the highest measured values of k among all the juices at the same thermodynamic (T, x) conditions, while raspberry juice exhibits the lowest value. This can be explained by the different chemical compositions of the juices (e.g., contents of the microelements, sugar, or glucose, fructose and sucrose).

Temperature Dependence of the k of Fruit Juices

The k of juices increases considerably with increasing temperature. For instance, at temperatures between 20 and 120C, the k of cherry and raspberry juices is significantly (up to 19–20%) affected by temperature at high concentrations (60°Brix) and up to 15–18% at low concentrations (15°Brix) (Fig. 2 and Table 3). For pure water at the same temperature range, the k changes up to 14%. The rate of temperature changes (dk/dT) at low temperatures is higher than that at high temperatures. Figure 2 also demonstrates how the behavior of the temperature dependence of the k of juices depends on concentration. At low concentrations (below 40°Brix), the curvature of the $k - T$ curves is higher than that at high concentrations (above 40°Brix). The k of pure water and
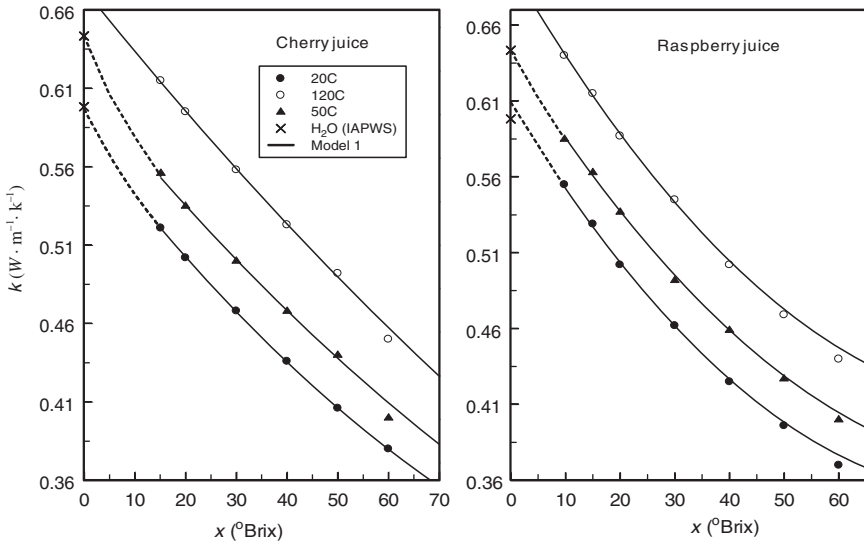
FIG. 3. MEASURED VALUES OF THERMAL CONDUCTIVITY (k) OF CHERRY AND
RASPBERRY JUICES AS A FUNCTION OF CONCENTRATION (x) ALONG
SELECTED ISOTHERMS
(– – – –), extrapolation to zero concentration (pure water).

aqueous solutions increases with temperature and it passes through a maximum between 100 and 200C and it decreases at higher temperatures (Abdulagatov and Magomedov 1999a,b, 2000, 2001, 2004; Abdulagatov *et al.* 2004a,b; Abdulagatov and Azizov 2005). In this study (up to 120C), we did not find any maximum of the k of juices, although a slight decrease in dk/dT at high temperatures is observed (Fig. 2).

A number of correlation equations have been developed in the literature to calculate and predict the k of liquid foods as a function of temperature (Fernández-Martin and Montes 1972; Cuevas and Cheryan 1978; Choi and Okos 1983a; Constenla *et al.* 1989; Telis-Romero *et al.* 1998; Gratão *et al.* 2005). Because of the lack of a theoretical background on the temperature and concentration dependency of k for liquids and liquid mixtures, empirical and semiempirical correlation equations and prediction techniques are commonly used (Millat *et al.* 1996). Several widely used models for the temperature dependence of the k are shown in Table 4. Here, we examined the applicability of these models for the k of our tested fruit juices. The Model 1 (quadratic polynomial in temperature [T], Table 4) was used by many authors (Venart and Prasad 1980; Horvath 1985; Abdulagatov and Magomedov 1999a,b, 2000, 2001, 2004) to represent experimental k data of liquids and liquids mixtures in
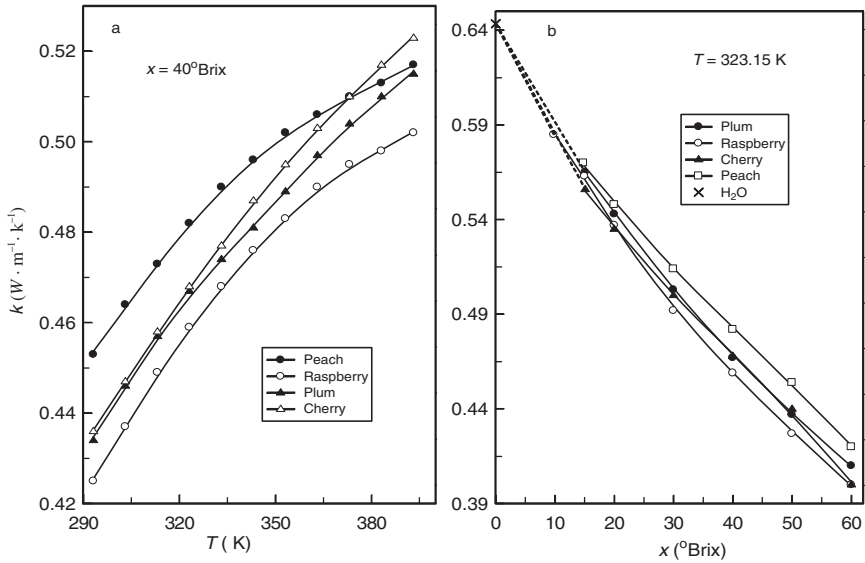
FIG. 4. COMPARISON OF THE TEMPERATURE AND CONCENTRATION DEPENDENCE OF
THE MEASURED VALUES OF THERMAL CONDUCTIVITY (k) OF VARIOUS JUICES
($-$ $-$ $-$ $-$), extrapolation to zero concentration (pure water).

a wide temperature range (room temperature [20C] to 400C). Model 2 (linear
temperature dependence) is applicable only in a limited temperature range
(22–75C) (basically at low temperatures, Assael *et al.* 1988, 1989). Model 3 is
preferable for the prediction of the temperature dependence of k of solution at
fixed composition (Riedel 1951; Vargaftik and Osminin 1956) just by knowing
the thermal conductivity of aqueous solution (k_0) at a reference temperature
(T_0) and pure water thermal conductivity ($k_W(T)$) as a function of temperature.
This model was applied for the present k measurements of fruit juices.

The comparison between the predictions using Model 3 and the present
experimental result for k of cherry and raspberry juices is shown in Fig. 2
(dashed lines). The agreement between predicted and measured values of k is
about 0.25 to 1.50% at high concentrations and 0.7 to 1.5% at low concentra-
tions. This model can be used to estimate the temperature dependence of the k
of fruit and vegetable juices.

Concentration Dependence of the k of Fruit Juices

Figure 3 shows the effect of concentration on the k of juices at various
fixed temperatures. The k of cherry and raspberry juices monotonically
decreased almost linearly with concentration. A small curvature of the $k - x$

TABLE 4.
MODELS FOR PREDICTION OF THERMAL CONDUCTIVITY OF LIQUIDS*

No.	Models for temperature dependence	References
1	$k(T) = a_0 + a_1T + a_2T^2$	Venart *et al.* 1980; Horvath 1985; Abdulagatov and Magomedov 1999a,b, 2000, 2001, 2004;
2	$k(T) = (T_0)(1 + \alpha\Delta T)$	Assael *et al.* 1988, 1989
3	$k(T) = k_{sol}(T_0)[k_w(T)/k_w(T_0)]$	Riedel 1951; Vargaftik and Osminin 1956
	Models for concentration dependence	
4	$k(x) = k_W + a_1x$	Riedel 1949; Kolarov and Gromov 1973; Choi and Okos 1983b; Constenla *et al.* 1989; Lau *et al.* 1992; Telis-Romero *et al.* 1998; Gratão *et al.* 2005
5	$k(x) = k_W + a_1x + a_2x^2$	Ziegler and Rizvi 1985
6	$k(x) = k_W(1 + a_1x + a_2x^2)$	Chiquillo 1967; Losenicky 1969; Horvath 1985; Abdulagatov and Magomedov 1999a,b, 2000, 2001, 2004; Ramires and Nieto de Castro 2000; Abdulagatov *et al.* 2004a,b; Abdulagatov and Azizov 2005
	Combined models for temperature and concentration dependences	
7	$k(T, x) = k_W(T)[1 - (a_0 + a_1T + a_2T^2)x - (c_0 + c_1T + c_2T^2)x^2]$	Pepinov and Guseynov 1993
8	$k(T, x) = \sum\limits_{i=0}^{2}\sum\limits_{j=0}^{2} a_{ij}\Delta T^j x^i$	Ramires and Nieto de Castro 2000
9	$k(T, x) = k_W(T)[1 - a(x + 2 \times 10^{-4}x^3)] - 2 \times 10^{-8}Tx$	Abdulagatov and Magomedov 1999a,b, 2000, 2001, 2004
10	$k(T, x) = a_0 + a_1x + a_2x^2 + b_1T$	Alloush *et al.* 1982

* $\Delta T = T - T_0$, where T_0 is the reference temperature (25C); α is the linear thermal conductivity gradient.

curves at high concentrations was noted. The k considerably decreases (up to 38–48%) with concentration at low temperatures (20C) and up to 35–43% at high temperatures (120C). The most often used models for the concentration dependence of k_0 are given in Table 4.

Model 4 (linear relation) is commonly used for the concentration dependence of k and juices (Riedel 1949; Kolarov and Gromov 1973; Choi and Okos 1983b; Constenla *et al.* 1989; Lau *et al.* 1992; Telis-Romero *et al.* 1998; Gratão *et al.* 2005). However, as Fig. 3 shows, the linear dependence of the k is valid only at low concentrations (below 30°Brix). At high concentrations, the quadratic term (Model 5) is required to accurately describe the experimental data (Ziegler and Rizvi 1985). Figure 5 shows the concentration dependence of the relative k, $(k_{juice}/k_W - 1)$ versus concentration x for two selected
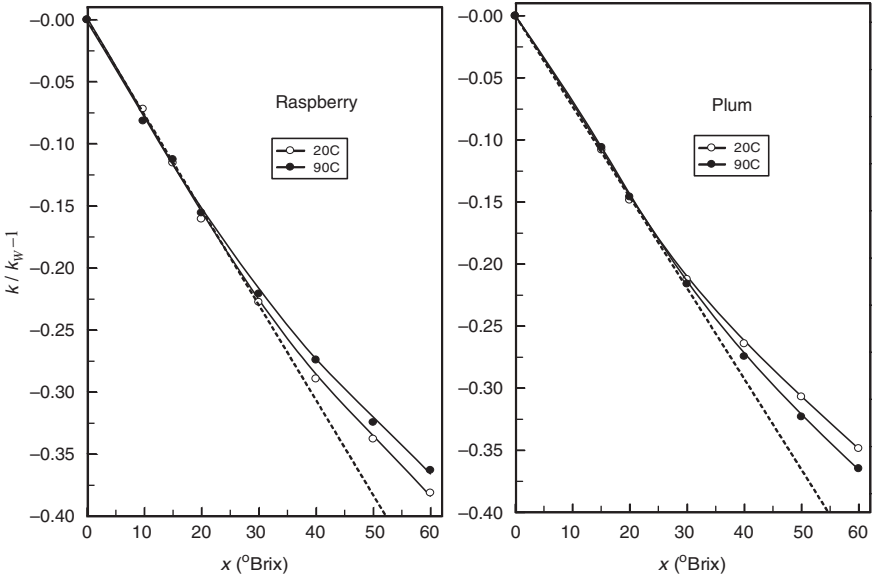
FIG. 5. RELATIVE THERMAL CONDUCTIVITY ($k_{juice}/k_W - 1$) OF RASPBERRY AND PLUM JUICES AS A FUNCTION OF CONCENTRATION (x) AT TWO FIXED TEMPERATURES (– – – –), linear extrapolation to high concentrations.

temperatures. k, ($k_{juice}/k_W - 1$) varies linearly with concentration x only at a concentration up to 30°Brix and is almost independent of temperature (a function of concentration only). At high concentrations (above 30°Brix or from 30 to 60°Brix), the nonlinear (quadratic term) behavior of concentration dependence of the k is observed, ($k_{sol}/k_W - 1$) = $a_1 x + a_2 x^2$ (see Model 6).

Combined Effect of Temperature and Concentration

Different models were proposed by various authors to represent the combined effect of temperature and concentration on k (Model 7 to 10, Table 4). Model 7 reproduced concentration and temperature effects on the k of aqueous systems in the wide temperature and concentration ranges within accuracy of ±0.6%. Models 8 to 10 are different combinations of polynomial functions of temperature and concentration. We developed different models to describe the combined effect of temperature and concentration on the k of fruit juices.

Model I. The effects of temperature and concentration on the k of fruit juices in the present work can be combined by taking into account the concentration dependence of the parameters $a_0(x)$, $a_1(x)$ and $a_2(x)$ in Model 1 (see Table 4) as quadratic functions:

TABLE 5.
VALUES OF PARAMETERS c_i (EQS. 7–9) FOR THE FOUR FRUIT JUICES

Juice	Peach	Plum	Raspberry	Cherry
c_1	0.5888×10^0	0.5905×10^0	0.5835×10^0	0.5601×10^0
c_2	-4.2108×10^{-3}	-5.6132×10^{-3}	-6.0697×10^{-3}	-4.4534×10^{-3}
c_3	6.7985×10^{-6}	2.8382×10^{-5}	3.7629×10^{-5}	1.7796×10^{-5}
c_4	1.9662×10^{-3}	1.0869×10^{-3}	1.2492×10^{-3}	1.0573×10^{-3}
c_5	-8.1694×10^{-5}	6.2466×10^{-6}	1.2418×10^{-5}	1.4187×10^{-5}
c_6	1.2627×10^{-6}	-5.919×10^{-8}	-2.323×10^{-7}	-1.9678×10^{-7}
c_7	-4.8206×10^{-7}	-1.3729×10^{-6}	-2.4189×10^{-6}	-9.4700×10^{-7}
c_8	-7.3754×10^{-8}	-8.8027×10^{-8}	-1.1036×10^{-7}	-8.9423×10^{-8}
c_9	-2.9782×10^{-10}	1.0639×10^{-9}	1.61845×10^{-9}	9.1168×10^{-10}

$$a_0(x) = c_1 + c_2 x + c_3 x^2 \tag{7}$$

$$a_1(x) = c_4 + c_5 x + c_6 x^2 \tag{8}$$

$$a_2(x) = c_7 + c_8 x + c_9 x^2 \tag{9}$$

Model 1 with Eqs. (7–9) was applied to the present experimental data. The derived values of coefficients c_i are given in Table 5. This model reproduced experimental k of peach, plum, raspberry and cherry juices within 0.07, 0.18, 0.20 and 0.13%, respectively.

Model II. Present experimental k data for fruit juices were also fitted to Model 5 (Table 4). The derived equations for the fruit juices are:

$$k = k_W(T) - 5.30 \times 10^{-3} x + 2.50 \times 10^{-5} x^2 \text{ for plum juice}, (R^2 = 0.9005) \tag{10}$$

$$k = k_W(T) - 5.78 \times 10^{-3} x + 3.34 \times 10^{-5} x^2$$
$$\text{for raspberry juice}, (R^2 = 0.9901) \tag{11}$$

$$k = k_W(T) - 4.65 \times 10^{-3} x + 1.35 \times 10^{-5} x^2 \text{ for cherry juice}, (R^2 = 0.9083) \tag{12}$$

$$k = k_W(T) - 4.69 \times 10^{-3} x + 1.65 \times 10^{-5} x^2 \text{ for peach juice}, (R^2 = 0.8965) \tag{13}$$

where the equation for the $k_W(T)$ is:

$$k_W(T) = 0.566 + 1.86 \times 10^{-3} T - 7.363 \times 10^{-6} T^2 \tag{14}$$
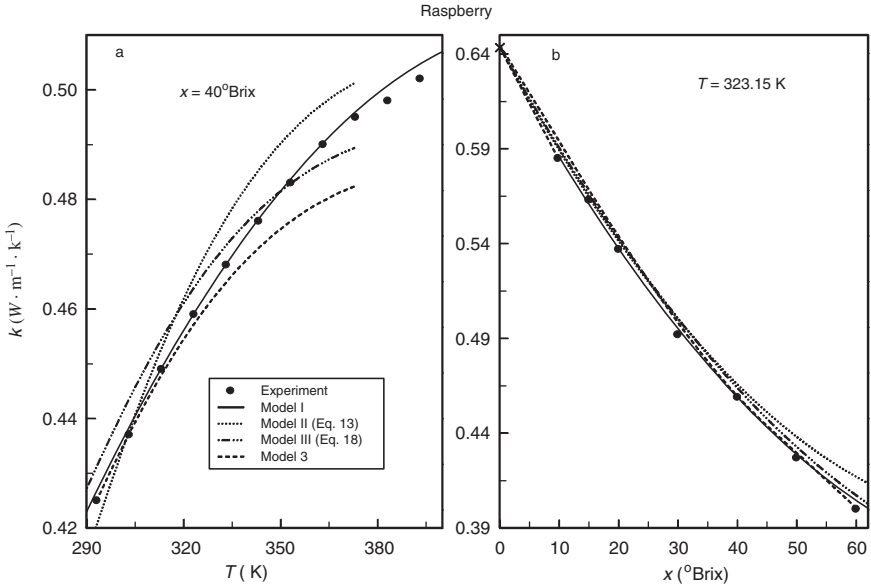
Raspberry

FIG. 6. COMPARISON MEASURED AND CALCULATED VALUES OF THE THERMAL
CONDUCTIVITY (k) OF RASPBERRY JUICE USING VARIOUS MODELS
T, temperature; x, concentration.

This model described the present experimental k data for peach, plum, rasp-
berry and cherry juices within 1.19, 0.68, 1.09 and 1.52%, respectively.

Model III. Model 6 (Table 4) was applied to the present k data for the
juices. The results are given below as:

$$k = k_W(T)(1 - 8.8 \times 10^{-3} x + 5.1 \times 10^{-5} x^2) \text{ for plum juice}, (R^2 = 0.9945) \quad (15)$$

$$k = k_W(T)(1 - 7.2 \times 10^{-3} x + 2.7 \times 10^{-5} x^2) \text{ for peach juice}, (R^2 = 0.9895) \quad (16)$$

$$k = k_W(T)(1 - 8.7 \times 10^{-3} x + 4.3 \times 10^{-5} x^2)$$
$$\text{for raspberry juice}, (R^2 = 0.9916) \quad (17)$$

$$k = k_W(T)(1 - 8.5 \times 10^{-3} x + 4.5 \times 10^{-5} x^2) \text{ for cherry juice}, (R^2 = 0.9852) \quad (18)$$

The accuracy was 0.82, 1.16, 0.90 and 1.44%, respectively, for peach, plum,
raspberry and cherry juices. Figure 6 shows a comparison between experimen-

tal and calculated values using Models I to III. The multiparametric Model I best represents the current experimental k data, but the extrapolation and prediction capabilities of Models II and III are better. Moreover, according to Models II and III, the difference, $k(T, x) - k_W(T)$, and reduced k, $k(T, x)/k_W(T) - 1$, are almost independent of temperature (function of concentration only, see Fig. 5). This means that the temperature dependence of the k of juice is basically governed by the temperature dependence of $k_W(T)$. Therefore, Models II and III allow the prediction of the values of the k of juices at any temperature just by knowing the concentration dependence of $k(T_0, x)$ at a fixed (or reference) temperature T_0.

CONCLUSIONS

The thermal conductivities of four fruit juices (cherry, raspberry, plum and peach) were measured using a coaxial-cylinder (steady-state) technique. The range of temperature and concentration was 20 to 120C and 9.8 to°Brix, respectively. The combined effect of temperature and concentration on the k of fruit juices was studied. New correlation and prediction models for the k of juices were developed. The applicability and predictive capability of the models used previously for aqueous solutions to describe the effect of temperature and concentration on the k of juices was studied. It was found that the prediction Model 3, $k(T) = k_{sol}(T_0)[k_W(T)/k_W(T_0)]$, can be adopted satisfactorily for fruit juices. Therefore, minimal experimental information is needed to predict the k of juices as a function of temperature and concentration. The k of juices can be calculated just by knowing the single k, $(k_{sol}(T_0))$ of juice at a reference temperature $T_0 = 20C$ and pure water data $(k_W(T))$, which facilitates to the prediction of the k of fruit juices. Models I to III are recommended to accurately represent experimental k data for fruit juices in the temperature and concentration ranges used in this study.

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