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Thermophysical Properties of Lemon Juice as Affected by Temperature and Water Content

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To design equipment for food processing and estimate process times for refrigerating, freezing, heating, or drying of foods, the thermophysical properties must be known. Since the thermophysical properties of foods are strongly dependent upon chemical composition and temperature, composition and temperature based models provide a means of estimating these properties. In this work, the thermophysical properties of lemon juice were determined at a water mass fraction of (0.381 to 0.900) and a temperature of (273.45 to 353.75) K. Density and thermal conductivity varied from (962.3 to 1282.8) $\text{kg}\cdot\text{m}^{-3}$ and (0.344 to 0.624) $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, respectively. Heat capacity and thermal diffusivity varied from (2446.5 to 4060.1) $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ and $(0.1160\cdot10^{-6}$ to $0.1785\cdot10^{-6})$ $\text{m}^2\cdot\text{s}^{-1}$, respectively. Simple polynomial functions were fitted to the experimental data, and good agreements were obtained. In the tested range, water content showed greater influence on the thermophysical properties.

Introduction

Lemon (C*itrus limon* L.) is one of the citrus fruits that has been increasing its consumption worldwide. It is cultivated in countries with proper temperature and dry climate such as the United States, Argentina, Spain, Italy, and Japan. The production is destined for fresh fruit markets or processing juice units, pectin, and essential oil. Lemon juice, fresh, concentrated and frozen, or dehydrated and powdered, is primarily used for lemonade, carbohydrate beverages, or other drinks. It is also used for confectionary and pharmaceutical products. The lemon cv. Tahiti (*Citrus latifolia*) is produced mainly in tropical countries such as Brazil and Mexico. The state of São Paulo is the largest Brazilian producer with approximately 81.3 % of the total lemon production.[1]

The design and control of equipment for processing such juices are difficult due to the lack of information on the behavior of the thermophysical properties with composition and temperature. Simulation fails since the models derived from the concepts of material conservation need such information. Equipment size is usually overestimated to compensate for this lack of information, leading to a nonideal design with cost implications as well as inferior quality of the product.

In general, modeling, optimization, and control of food processes is difficult due to the complexity of the raw materials and products involved, which affect thermophysical properties such as density ρ, specific heat C_P, thermal conductivity k, and thermal diffusivity α. Besides, these thermophysical properties exhibit substantial changes with temperature and water content during processing. These are the major properties required for designing heat transfer processes, such as refrigeration, freezing, heating, or drying,[2] and for purposes of optimization and control.

An extensive review of existing methods for measurement of thermophysical properties of foods has been done by Reidy and Rippen,[3] Mohsenin,[4] and Singh.[5] Measurements of C_P are often made by means of an adiabatic calorimeter,[6,7] which is a simple technique although it requires a careful calibration. The differential scanning calorimeter is the best technique for experimental determination of C_P of foods but has the disadvantage of being very expensive.[8,9] A simple method can be used to determine k, according to Bellet et al.[10] The great advantage of this technique is that it is possible to determine C_P employing the same device and modeling the unsteady state heat transfer in the system.

Thermal diffusivity can be determined according to its definition, given by the following equation

$$\alpha_{\text{cal}} = \frac{k}{\rho C_P} \tag{1}$$

where α_{cal} is the calculated thermal diffusivity.

This method has the inconvenience of adding up the experimental errors involved in each one of the primary physical quantities. Alternatively, thermal diffusivity can be measured directly using a transient heating technique developed by Dickerson.[11] Singh[5] discusses this and some other approaches used in determining thermal diffusivity of foods as well as the main sources of errors involved.

Thermophysical properties of lemon juice are very scarce in the literature, and an extensive work of the dependence of such properties on temperature and the water content has not yet been published. In an attempt to fill this gap, the objective of this work was to measure the thermophysical properties (ρ, k, C_P, and α) of lemon juice as a function of temperature T and water mass fraction w and to develop simple empirical correlations for predicting these properties.

Experimental Section

Materials. Lemon juice was extracted from Lemons cv. Tahiti with the following chemical composition (mass fraction): water, 88.0 %; total soluble solids (organic acids and sugars), 9.8 %; protein, 1.0 %; dietary fiber, less than 0.1 %; and ash, 0.4 %;

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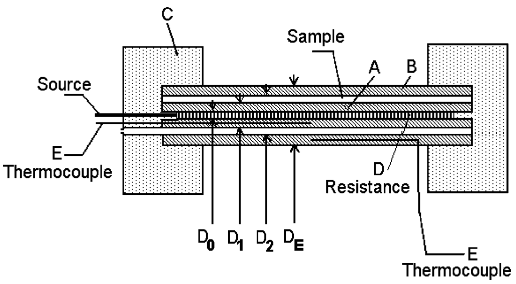

Figure 1. Cross section of the cell used for thermal conductivity and specific heat measurements.

total titratable acidity (expressed as citric acid), 0.69 %; density of 1064.4 $\text{kg}\cdot\text{m}^{-3}$; and pH of 2.98. All the experimental measurements were made using samples from the same batch of concentrated lemon juice (37.4 % water mass fraction). The concentration process was performed using a rotoevaporator, under vacuum. In the industrial practices, it is usual to characterize fruit juices mainly according to their water and soluble solids contents. To obtain different concentrations, concentrated juice was diluted with distilled water, and an analytical balance (Shimadzu AUX220, Japan) was used with an uncertainty of ± 0.0001 g. The standard uncertainty of the concentration measurements was ± 0.52 %. A complete factorial design was conducted with eight levels of T [(273.45 to 353.75) K] and eight levels of w (0.381 to 0.90). The thermophysical properties were measured in triplicate for each value of T and w adding up 192 experiments. All statistical analysis was performed using the GLM (General Linear Model) procedure, while fitted functions were obtained by using the REG (REGression) procedure from the SAS statistical package.[12] The suitability of the fitted functions was evaluated by the level of significance (p), the coefficient of determination (R^2), and residual analysis.

Apparatus and Methods. (a) Thermal Conductivity. Thermal conductivity at various T and w was measured using the method described by Bellet et al.,[10] based on a cylindrical cell, where the liquid whose properties are being determined fills the annular space between two concentric cylinders. The equipment, shown in Figure 1, presented the following physical characteristics: two coaxial copper cylinders (A and B), 180 mm length, separated by a 2 mm annular space, which was filled with the sample; 50 mm thick covers (C) made of a low thermal conductivity material (0.225 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) to prevent axial heat transfer; an inner cylinder (A) containing a heater (D) made with a constantan wire (resistance 15 Ω), electrically insulated by a varnish and coiled around a copper stick; two thermocouples type T (E) to measure temperature differences between the two cylinders, located at half-length of the cell. The wires were placed inside 0.5 mm gaps, parallel to the cell axis.

To keep the external temperature constant, the cell was immersed in a constant temperature water bath (MK70, MLW, Dresden, Germany) controlled within ± 0.05 K. The power input to the heater resistance was made by means of a microprocessed, stabilized source (ETB-252, Entelbra, Sao Paulo, Brazil), which permitted us to adjust the current with a stability of 0.05 %. An HP data logger model 75.000-B, an interface HP-IB, and an HP PC running a data acquisition program written in IBASIC monitored temperatures with a standard uncertainty of ± 0.6 K.

(b) Specific Heat (C_P). The apparatus described above was also used to measure specific heat. Considering unsteady heat conduction through an isotropic, homogeneous medium, the equation of energy conservation was written for the system. The solution of the differential equation with the proper boundary conditions is presented in detail by Bellet et al.[10]

(c) Density (ρ). Gravimetric determination of lemon juice density at different temperatures and concentrations was conducted using an analytical balance with a given uncertainty of ± 0.0001 g and a standard volumetric pycnometer.[8] The pycnometer was previously calibrated with distilled water, at each temperature.

(d) Thermal Diffusivity (α). Thermal diffusivity was determined using the method proposed by Dickerson.[11] The experimental apparatus consisted of a cylindrical cell ($24.75\cdot10^{-3}$ m internal radius and $248.5\cdot10^{-3}$ m length) made of chromium-plated brass with two nylon covers with thermal diffusivity of $1.09\cdot10^{-7}\ \text{m}^2\cdot\text{s}^{-1}$, which is similar to most liquid food products. Two thermocouples type T were fixed at the center and on the external surface of the cell. The cell was immersed in a well-agitated thermostatic bath (MK70, MLW, Dresden, Germany) heated at a constant rate, and the evolution of temperatures at the wall and at the center of the cell was monitored. Temperatures were monitored employing the same data acquisition system previously specified.

Results and Discussion

Specific heat, thermal conductivity, thermal diffusivity, and density of lemon juice with w of (0.381, 0. 443, 0.522, 0.594, 0.650, 0.712, 0.794, and 0.90) were determined in triplicate at (273.45, 282.25, 295.35, 304.25, 314.95, 327.05, 339.65, and 353.75) K, adding up to 192 experimental values of each thermal property.

Tables 1 include experimental values and respective standard deviations between triplicate measurements for ρ, k, C_P, and α of the system studied as related to T and w.

Polynomial models for the thermophysical properties as a function of T and w were fitted to the experimental data. According to Fikiin and Fikiin,[13] the influence of the different solid components of foods on thermophysical properties is usually negligible, and the food material can be seen as a system formed by only two components, water and solids. The quadratic complete model was first analyzed, and the nonsignificant parameters were eliminated based on the t (student) test and $p > 0.05$. The final models are presented by a polynomial like eq 2. Table 2 shows the coefficients of eq 2 for ρ, C_P, k, and α.

$$\Psi = \beta_0 - \beta_1(T/\text{K}) - \beta_2 w + \beta_3 w^2 + \beta_4(T/\text{K})\cdot w \tag{2}$$

where Ψ is the thermophysical property.

The agreement between experimental and calculated values for the thermophysical properties was very good. Figures 2 to 5 show the relative deviations between observed and predicted values of ρ, C_P, k, and α. In all cases, despite its simplicity, eq 2 with the associated parameters in Table 2 was found to represent accurately the physical properties of lemon juice in the studied range of T and w, with the determination coefficient (R^2) superior to 0.98. The present properties all lie within ± 4 % of the correlations and agree well with most of the observed data.

The properties studied here varied from (962.3 to 1282.8) $\text{kg}\cdot\text{m}^{-3}$ for density, (0.344 to 0.624) $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for thermal conductivity, (2446.5 to 4060.1) $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ for heat capacity, and ($0.116\cdot10^{-6}$ to $0.178\cdot10^{-6}$) $\text{m}^2\cdot\text{s}^{-1}$ for thermal diffusivity. The reported values are of the same order of magnitude as the values reported by Telis-Romero et al.[14] for orange juice.

It was observed that ρ decreased with both T and w. The variables k and C_P increased linearly with T and w, and α

Table 1. Density ρ, Thermal Conductivity k, Heat Capacity C_P, and Diffusivity α of Lemon Juice and Associated Standard Deviation of Triplicate Measurements for Different Temperatures and Water Contents

T / K	w	ρ / $(\mathrm{kg \cdot m^{-3}})$	k / $(\mathrm{W \cdot m^{2} \cdot K^{-1}})$	C_P / $(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$	$10^6\alpha$ / $(\mathrm{m^2 \cdot s^{-1}})$
273.45	0.900	1000.6 ± 1.3	0.527 ± 0.003	3843.6 ± 11.0	0.139 ± 0.002
282.25	0.900	1004.2 ± 2.3	0.542 ± 0.005	3828.1 ± 27.4	0.142 ± 0.004
295.35	0.900	993.4 ± 2.7	0.564 ± 0.006	3938.1 ± 33.3	0.156 ± 0.005
304.25	0.900	982.5 ± 1.7	0.569 ± 0.003	3923.3 ± 11.3	0.155 ± 0.003
314.95	0.900	979.0 ± 1.8	0.582 ± 0.003	3951.0 ± 11.3	0.159 ± 0.003
327.05	0.900	974.1 ± 3.2	0.591 ± 0.007	3929.5 ± 34.6	0.162 ± 0.006
339.65	0.900	963.4 ± 2.0	0.604 ± 0.006	4027.9 ± 27.3	0.174 ± 0.004
353.75	0.900	967.7 ± 1.2	0.621 ± 0.003	4051.4 ± 11.6	0.171 ± 0.002
273.45	0.794	1053.0 ± 2.4	0.498 ± 0.005	3524.1 ± 25.2	0.132 ± 0.003
282.25	0.794	1043.2 ± 2.8	0.511 ± 0.005	3582.1 ± 21.7	0.143 ± 0.004
295.35	0.794	1031.8 ± 1.9	0.525 ± 0.003	3616.0 ± 10.4	0.144 ± 0.003
304.25	0.794	1038.5 ± 1.3	0.542 ± 0.003	3639.0 ± 10.5	0.148 ± 0.002
314.95	0.794	1023.8 ± 3.1	0.546 ± 0.005	3630.4 ± 26.0	0.150 ± 0.005
327.05	0.794	1038.6 ± 3.7	0.574 ± 0.006	3722.0 ± 28.3	0.162 ± 0.006
339.65	0.794	1003.6 ± 3.0	0.566 ± 0.003	3730.6 ± 10.8	0.159 ± 0.005
353.75	0.794	1018.4 ± 1.3	0.589 ± 0.003	3767.1 ± 10.8	0.162 ± 0.002
273.45	0.712	1084.1 ± 2.9	0.468 ± 0.005	3295.1 ± 29.1	0.128 ± 0.004
282.25	0.712	1072.3 ± 2.3	0.488 ± 0.005	3478.8 ± 55.6	0.139 ± 0.003
295.35	0.712	1080.9 ± 1.4	0.503 ± 0.003	3384.9 ± 11.0	0.139 ± 0.002
304.25	0.712	1062.1 ± 2.7	0.506 ± 0.003	3407.9 ± 11.2	0.143 ± 0.004
314.95	0.712	1084.0 ± 2.8	0.528 ± 0.006	3389.5 ± 32.9	0.144 ± 0.004
327.05	0.712	1048.9 ± 2.3	0.529 ± 0.005	3489.4 ± 23.7	0.155 ± 0.004
339.65	0.712	1072.5 ± 1.9	0.553 ± 0.003	3499.2 ± 11.4	0.153 ± 0.003
353.75	0.712	1038.2 ± 2.5	0.548 ± 0.003	3535.5 ± 11.6	0.155 ± 0.004
273.45	0.650	1106.7 ± 2.0	0.446 ± 0.002	3162.7 ± 10.3	0.127 ± 0.003
282.25	0.650	1127.3 ± 2.9	0.467 ± 0.005	3164.2 ± 25.3	0.129 ± 0.004
295.35	0.650	1113.2 ± 3.0	0.484 ± 0.004	3250.7 ± 24.7	0.140 ± 0.004
304.25	0.650	1105.2 ± 3.3	0.487 ± 0.006	3198.7 ± 31.0	0.137 ± 0.005
314.95	0.650	1091.2 ± 2.2	0.499 ± 0.004	3291.1 ± 22.3	0.147 ± 0.003
327.05	0.650	1106.0 ± 1.5	0.517 ± 0.002	3300.9 ± 10.8	0.145 ± 0.002
339.65	0.650	1094.0 ± 1.3	0.525 ± 0.003	3333.4 ± 10.9	0.148 ± 0.002
353.75	0.650	1073.5 ± 2.1	0.527 ± 0.003	3369.8 ± 11.0	0.150 ± 0.003
273.45	0.594	1147.5 ± 3.1	0.428 ± 0.005	2972.7 ± 28.8	0.123 ± 0.004
282.25	0.594	1119.2 ± 2.9	0.434 ± 0.003	3045.7 ± 18.4	0.132 ± 0.004
295.35	0.594	1154.0 ± 1.9	0.465 ± 0.002	3069.5 ± 10.0	0.132 ± 0.002
304.25	0.594	1119.9 ± 4.5	0.460 ± 0.005	3061.5 ± 24.5	0.133 ± 0.006
314.95	0.594	1132.5 ± 0.8	0.481 ± 0.001	3120.0 ± 5.1	0.139 ± 0.001
327.05	0.594	1126.8 ± 0.8	0.490 ± 0.001	3130.3 ± 10.5	0.142 ± 0.001
339.65	0.594	1129.3 ± 2.1	0.507 ± 0.004	3214.9 ± 13.9	0.142 ± 0.003
353.75	0.594	1109.7 ± 3.4	0.504 ± 0.006	3177.0 ± 19.3	0.152 ± 0.005
273.45	0.522	1190.0 ± 0.8	0.407 ± 0.001	2839.0 ± 5.6	0.122 ± 0.001
282.25	0.522	1199.4 ± 1.9	0.421 ± 0.001	2843.2 ± 4.6	0.125 ± 0.002
295.35	0.522	1186.5 ± 0.8	0.434 ± 0.001	2877.0 ± 4.6	0.129 ± 0.001
304.25	0.522	1173.4 ± 3.0	0.439 ± 0.003	2900.0 ± 14.4	0.129 ± 0.004
314.95	0.522	1169.3 ± 3.2	0.451 ± 0.005	2946.7 ± 24.3	0.138 ± 0.005
327.05	0.522	1163.4 ± 2.9	0.460 ± 0.004	2958.8 ± 14.7	0.134 ± 0.004
339.65	0.522	1150.7 ± 3.1	0.466 ± 0.005	2991.3 ± 20.7	0.143 ± 0.004
353.75	0.522	1155.8 ± 0.8	0.476 ± 0.002	2987.1 ± 16.3	0.140 ± 0.001
273.45	0.443	1251.1 ± 1.9	0.379 ± 0.001	2626.5 ± 5.2	0.118 ± 0.002
282.25	0.443	1239.4 ± 0.9	0.386 ± 0.001	2632.0 ± 4.3	0.120 ± 0.001
295.35	0.443	1225.8 ± 3.1	0.397 ± 0.003	2665.8 ± 13.2	0.122 ± 0.003
304.25	0.443	1223.1 ± 3.4	0.406 ± 0.004	2688.8 ± 18.6	0.130 ± 0.004
314.95	0.443	1234.9 ± 1.3	0.420 ± 0.001	2698.3 ± 9.0	0.128 ± 0.001
327.05	0.443	1233.9 ± 2.2	0.434 ± 0.003	2774.5 ± 10.4	0.129 ± 0.002
339.65	0.443	1215.4 ± 1.0	0.436 ± 0.001	2780.1 ± 2.2	0.133 ± 0.001
353.75	0.443	1194.2 ± 1.4	0.436 ± 0.001	2778.8 ± 15.2	0.134 ± 0.002
273.45	0.381	1271.8 ± 1.5	0.346 ± 0.002	2459.6 ± 11.4	0.117 ± 0.002
282.25	0.381	1282.0 ± 1.1	0.359 ± 0.001	2466.3 ± 2.0	0.118 ± 0.001
295.35	0.381	1268.0 ± 0.7	0.369 ± 0.000	2500.1 ± 2.0	0.121 ± 0.001
304.25	0.381	1265.1 ± 1.8	0.377 ± 0.002	2523.0 ± 6.2	0.121 ± 0.002
314.95	0.381	1260.7 ± 0.9	0.385 ± 0.001	2533.7 ± 5.0	0.125 ± 0.001
327.05	0.381	1248.7 ± 1.4	0.395 ± 0.001	2607.1 ± 9.7	0.127 ± 0.001
339.65	0.381	1257.2 ± 0.8	0.403 ± 0.001	2579.4 ± 14.1	0.127 ± 0.001
353.75	0.381	1257.0 ± 2.5	0.415 ± 0.001	2650.7 ± 2.1	0.130 ± 0.003

Table 2. Coefficients of Equation 2

	β_0	β_1	β_2	β_3	β_4	R^2
$\rho/(\mathrm{kg \cdot m^{-3}})$	1582.28203 ± 10.15165	−0.4419 ± 0.0257	−891.38227 ± 33.14545	272.44025 ± 25.86346	0.0	0.990
$k/(\mathrm{W \cdot m^{2} \cdot K^{-1}})$	0.20923 ± 0.00248	0.000966 ± 0.000023	0.37379 ± 0.0036	0.0	0.0	0.985
$C_P/(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$	1415.65004 ± 9.32724	2.45612 ± 0.08533	2695.9344 ± 13.5325	0.0	0.0	0.995
$10^6\alpha/(\mathrm{m^2 \cdot s^{-1}})$	0.09809 ± 0.00109	0.0	0.04787 ± 0.00179	0.0	0.00046155 ± 0.0000164	0.924

decreased linearly with w and increased with T. In all cases, w presented a larger impact on the thermal properties of lemon juice than T. This fact was also reported in other works.[2,14,15]

Thermal diffusivities were also calculated according to the definition given by eq 1 and with the fitted polynomial function given by eq 2. The relative average error between the calculated

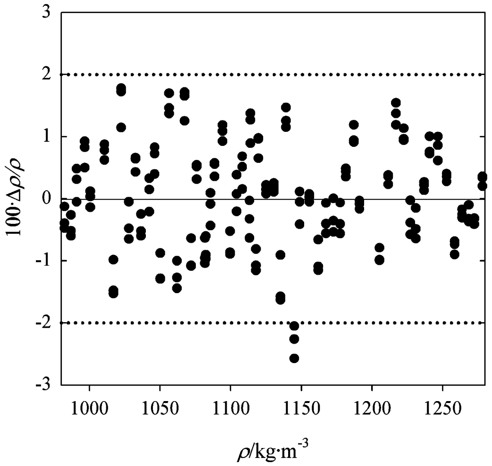

Figure 2. Fractional deviations $\Delta\rho = (\rho_{\text{obs}} - \rho_{\text{pred}})$ of the observed densities ρ_{obs} of lemon juice as a function of ρ_{obs}. ···, uncertainty of eq 2.

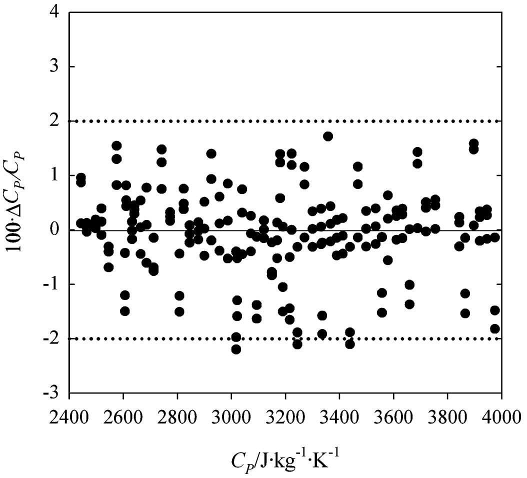

Figure 3. Fractional deviations $\Delta k = (k_{\text{obs}} - k_{\text{pred}})$ of the observed densities k_{obs} of lemon juice as a function of k_{obs}. ···, uncertainty of eq 2.

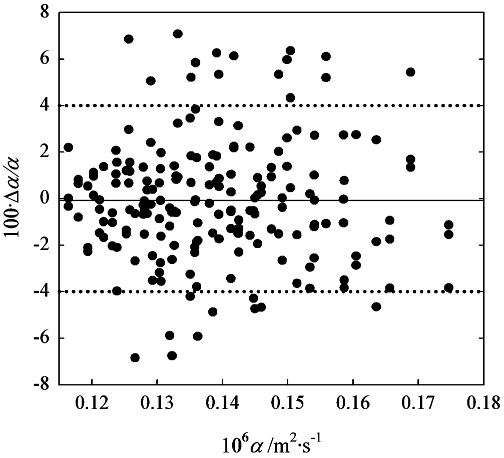

Figure 4. Fractional deviations $\Delta C_P = (C_{P,\text{obs}} - C_{P,\text{pred}})$ of the observed densities $C_{P,\text{obs}}$ of lemon juice as a function of $C_{P,\text{obs}}$. ···, uncertainty of eq 2.

values given by these equations was 3.2 %, indicating that Dickerson's method constitutes an easy and adequate technique for measuring thermal diffusivity of lemon juice.

Conclusions

In this paper, the effect of T and w on the thermophysical properties (ρ, C_P, k, and α) of lemon juice were studied. Simple polynomial functions were successfully fitted to the experimental data, thus thermophysical properties estimation for lemon juice using the models developed in this work is recommended, considering the range of T and w investigated. k and C_P increased with increasing T and w. On the other hand, ρ of lemon juice decreased with increasing w and T, and α decreased with w. The water mass fraction showed a higher influence on the thermophysical properties than T.

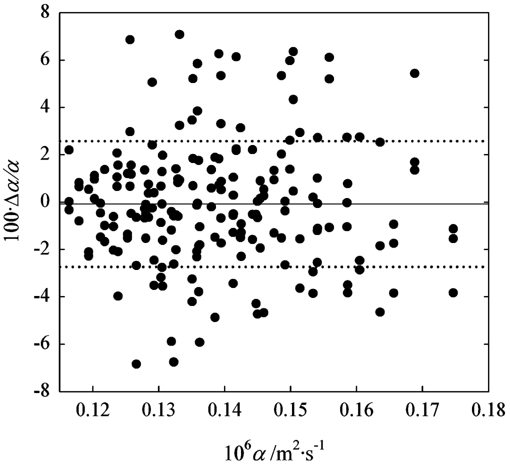

Figure 5. Fractional deviations $\Delta\alpha = (\alpha_{\text{obs}} - \alpha_{\text{pred}})$ of the observed densities α_{obs} of lemon juice as a function of α_{obs}. ···, uncertainty of eq 2.

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