

DENSITY, THERMAL EXPANSION COEFFICIENT, AND RHEOLOGICAL BEHAVIOUR OF MEAT EXTRACT UNDER DIFFERENT TEMPERATURES AND SOLIDS CONCENTRATIONS

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Meat extract is a product with a high aggregated value obtained by concentrating cooking broth from meat products. To optimize project design and processing, we determined experimental values of the density and rheological behaviour of meat extract. We evaluated the influences of temperature and solids concentration on the studied parameters. Different concentrations and temperatures were selected based on the main processing steps, ranging from 0–60 g_{soluble solids}/100 g_{solution} and 2–98 °C. The model best fitted to density was derived and a thermodynamic relation was applied to calculate the thermal expansion coefficient. Meat extract density had a linear dependence on temperature and quadratic dependence on solids content, while the thermal expansion coefficient remained approximately constant at $5.33 \times 10^{-4} \text{ m}^3 \cdot \text{m}^{-3} \cdot \text{K}^{-1}$. Concerning rheological analyses, meat extract had Newtonian behaviour from 1.5–20 g_{soluble solids}/100 g_{solution} at the temperature range studied. From 30–60 g_{soluble solids}/100 g_{solution}, the Power-Law model was better fitted to the data and the consistency coefficient and flow behaviour index could be calculated. Both parameters were sensitive to changes in temperature and concentration. Apparent viscosity increased with increasing the meat extract concentration and lowering the temperature. The dependence of rheological parameters on temperature was expressed through an Arrhenius-type equation.

Keywords: beef broth, specific mass, consistency coefficient, flow behaviour index, viscosity

INTRODUCTION

Meat extract, obtained from bovine meat cooking broth concentrate, is a highlighted byproduct of the meat industry due to its high iron and protein content. This product has attracted the interest of food and pharmaceutical companies for producing condiments, dried seasonings, sauces, and medicines. The yield of 0.03 kg of extract per kg of meat, combined with the abundance and low costs of meat in South America, have resulted in the creation and expansion of meat extract processing plants.^[1]

Although meat extract is an important source of protein, fat, essential amino acids, minerals, vitamins, and other nutrients,^[2] there are very few comprehensive studies on this product, especially regarding the steps that involve energy consumption. The intense energy demands for thermal treatment and cooking broth concentration from 1.5 to around 80 g_{soluble solids}/100 g_{solution} are the main reasons for its aggregate value. During sterilization (Figure 1a), the broth with 1.5 g_{soluble solids}/100 g_{solution} is pumped through a heat plate exchanger and kept at 121 °C for 3 min in the holding coil. After being sterilized, the broth is sent to a counter-current multiple-effect evaporating system at a concentration of up to 60 g_{soluble solids}/100 g_{solution} (Figure 1b). To reach 80 g_{soluble solids}/100 g_{solution}, the meat extract is subjected to discontinuous processing in a vacuum boiler after evaporation.

An alternative for reducing the inherent processing costs is to optimize the plant design and operational conditions by using exact values of the physical properties at each of several processing steps. Density and viscosity are two of the most relevant physical properties for the design and optimization of unit operations which involve heat transfer and fluid transport, such as mixing,

pasteurization, concentration, and dehydration.^[3] The thermal expansion coefficient, also known as the volumetric expansion coefficient, is one of the most important thermodynamic properties of materials,^[4] representing the density change caused by a change in temperature at constant pressure. Knowledge of how density varies with concentration and temperature is important for the food industry,^[5] but there is no published data describing the effects of concentration and temperature on meat extract density.

Rheological measurements allow for evaluation of product quality and structure, as well as the necessary energy for fluid pumping and transport.^[6] Rheological parameters are obtained by fitting theoretical models to the rheograms. Several mathematical models have been used to fit data of shear stress versus shear rate, including Newton (one parameter), Power-Law and Bingham (two parameters), and Herschel-Bulkley (three parameters). The Power-Law (or Ostwald-de Waele) model is considered most representative regarding the number of comprised parameters.^[7] Furthermore, temperature has an important influence on the flow characteristics of foods. Different temperatures are found in the majority of food processing operations, thus the rheological properties must be studied as a function of temperature.^[3] To evaluate the effect of temperature on rheological parameters, an

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Can. J. Chem. Eng. 94:988–994, 2016

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DOI 10.1002/cjce.22468

Published online in Wiley Online Library

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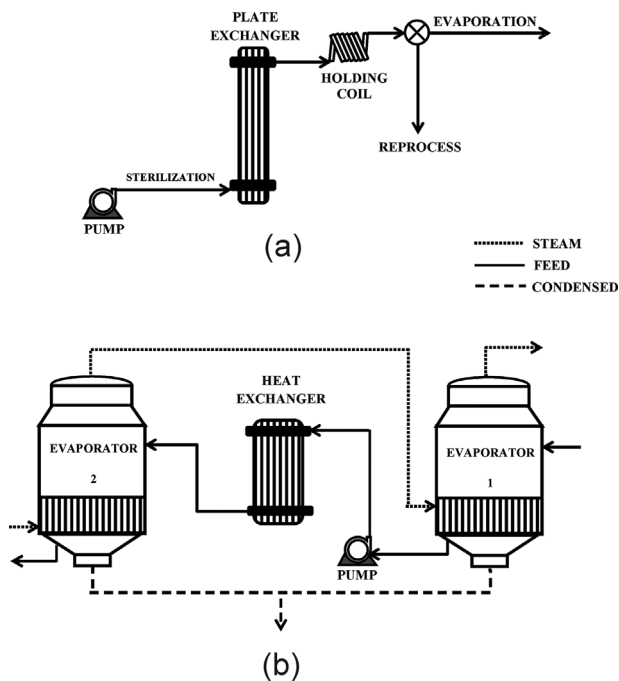


Figure 1. Partial flowcharts of meat extract processing: (a) broth sterilization; (b) broth concentration in a double effect evaporator system.

Arrhenius-type equation is often used, mainly in foodstuffs with high solids concentrations.^[8]

Based on the above considerations, the present study aims to determine the thermal expansion coefficient, the experimental values of density, and rheological properties of meat extract over the temperature and concentration ranges found in industrial processing, especially during sterilization and concentration. The efficiency of the obtained models to represent these properties is analyzed with statistical tools.

EXPERIMENTAL

Samples Preparation and Characterization

Meat extract at 80 g_{soluble solids}/100 g_{solution} (thermally treated and hermetically sealed) was supplied by JBS (Brazil). The raw material comprised 15.9 g/100 g water, 64.4 g/100 g protein, 19.1 g/100 g ash, and 0.6 g/100 g fat.^[9] The samples used for density and rheological measurements were prepared by diluting the original batch with distilled water, attaining concentrations ranging from 1.5–60 g_{soluble solids}/100 g_{solution} (1.5, 8, 12, 20, 30, 40, 50, and 60 g_{soluble solids}/100 g_{solution}).

Density Measurements

Density was measured in triplicate using a digital electronic density meter (Anton Paar, DMA-4500M model, Austria). Fifty mL samples were inserted into the density meter and the temperature range was established by the equipment as ranging from 5–95 °C.

Rheological Measurements

A rotational rheometer (AR-G2, TA Instruments, USA) equipped with concentric cylinders (5920 μm gap) was used to investigate the rheological behaviour of meat extract at 8 concentrations (1.5, 8, 12, 20, 30, 40, 50, and 60 g_{soluble solids}/100 g_{solution}) and 11 temperatures (2, 10, 20, 30, 40, 50, 60, 70, 80, 90, 98 °C). For each rheological test, 19.6 mL of meat extract was pipetted into the concentric cylinder cup. Steady flow runs were carried out over a

continuously increasing shear rate ranging from 2.5–315 s⁻¹. The Rheology Advantage software version 5.7.1 and the Universal Analysis 2000 data acquisition system version 4.7 (TA Instruments, USA) were used.

Data Modelling and Evaluation

The average density values ρ (kg·m⁻³) were correlated with absolute temperature T (K) and solids content X (g_{soluble solids}/100 g_{solution}) using non-linear fitting with first-, second-, and third-degree polynomials, using OriginPro 8.0 software (OriginLab Corporation, USA). Equation (1) presents a generic form of a third-order polynomial model:

$$\rho = a_0 + a_1X + a_2T + a_3X^2 + a_4T^2 + a_5X^3 + a_6T^3 \quad (1)$$

To identify the significant differences between the evaluated models, an F-test was applied to compare pairs of models.^[10]

The thermal expansion coefficient ($\beta/\text{m}^3 \cdot \text{m}^{-3} \cdot \text{K}$), at constant pressure, was calculated by Equation (2),^[11] using adjusted linear models of density as a function of only temperature for each fixed concentration value.

$$\beta = \rho \left(\frac{\partial(1/\rho)}{\partial T} \right)_p = - \left(\frac{1}{\rho} \right) \left(\frac{\partial \rho}{\partial T} \right)_p \quad (2)$$

The rheological behaviour was evaluated by fitting different models to flow curves, such as Herschel-Bulkley for non-Newtonian inelastic fluid (Equation (3)), where τ is shear stress (Pa), $\dot{\gamma}$ is the shear rate (1/s), and η_{app} (Pa·s) is the apparent viscosity.^[12]

$$\tau = \tau_0 + k\dot{\gamma}^n \text{ for } |\tau| > \tau_0, \text{ considering } \dot{\gamma} \neq 0 \quad (3a)$$

$$\eta_{app} = k\dot{\gamma}^{n-1} + \frac{\tau_0}{\dot{\gamma}} \quad (3b)$$

Model parameters include yield stress τ_0 (Pa), consistency coefficient k (Pa·s ^{n}), and flow behaviour index n . The three other following models can be derived from Herschel-Bulkley.^[12]

- (i) Power-Law model (Ostwald-de Waele): shear-thinning behaviour ($n < 1.0$) or shear-thickening ($n > 1.0$) in the absence of yield stress ($\tau_0 = 0$) as shown in Equation (4):

$$\tau = k\dot{\gamma}^n \quad (4a)$$

$$\eta_{app} = k\dot{\gamma}^{n-1} \quad (4b)$$

- (ii) Bingham model: linear dependence between shear rate and shear stress ($n = 1$) in the presence of yield stress, as shown by Equation (5), where η_B (Pa·s) is the plastic viscosity:

$$\tau = \tau_0 + \eta_B\dot{\gamma} \text{ for } |\tau| > \tau_0, \text{ considering } \dot{\gamma} \neq 0 \quad (5a)$$

$$\eta_{app} = \eta_B + \frac{\tau_0}{\dot{\gamma}} \quad (5b)$$

- (iii) Newton model: purely viscous fluid with $\tau_0 = 0$ and $n = 1.0$, as seen in Equation (6), where Newtonian viscosity μ (Pa·s) is equal to apparent viscosity:

$$\tau = \mu\dot{\gamma} \quad (6)$$

The most important variables that influence rheological parameters of foodstuffs are τ_0 , n , k , μ , η_{app} , η_B , temperature, and composition.^[13] To quantify the effect of temperature, an Arrhenius-type equation was used (Equation (7)), where A_0 is a pre-exponential factor, E_a is the activation energy ($\text{J} \cdot \text{mol}^{-1}$), R is the universal gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), and T is the absolute temperature (K).

$$\tau_0, k, n, \eta_B, \eta_{app}, \mu = A_0 \exp\left(\frac{E_a}{RT}\right) \quad (7)$$

The concentration dependence can be expressed by adding specific components of this variable in exponential or potential form. Equations (8–10) describe simultaneous dependence on temperature and solids concentration.^[14,15]

$$\tau_0, k, n, \eta_B, \eta_{app}, \mu = \phi_1 + \phi_2 \exp\left(\frac{E_a}{RT}\right) X^{\phi_3} \quad (8)$$

$$\tau_0, k, n, \eta_B, \eta_{app}, \mu = \exp\left(\phi_1 + \phi_2 X + \frac{E_a}{RT}\right) \quad (9)$$

$$\tau_0, k, n, \eta_B, \eta_{app}, \mu = \phi_1 \exp\left(\phi_2 X + \phi_3 X^2 + \frac{E_a}{RT}\right) \quad (10)$$

where ϕ_1 , ϕ_2 , and ϕ_3 are empirical parameters.

The choice of the best model for both density and rheological parameters was established based on the determination coefficient (R_{adj}^2), root mean square error (RMSE), and analysis of variance (ANOVA) at a 95 % confidence level, using the software STATISTICA 10 (StatSoft, USA).

RESULTS AND DISCUSSION

Density and Thermal Expansion Coefficient

The experimental mean values of density increased with increasing solids concentration and decreasing temperature (Figure 2), behaving like other fluid foods, such as banana purée,^[5] orange juice concentrate,^[16] and honey.^[17]

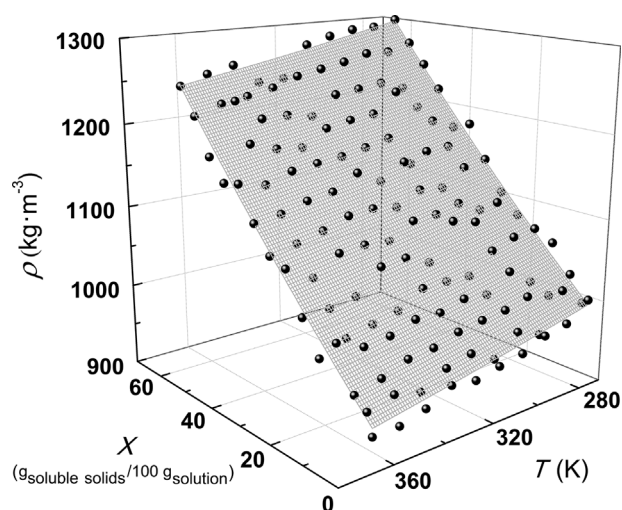


Figure 2. Experimental values of meat extract density as affected by temperature (K) and solids concentration ($\text{g}_{\text{soluble solids}}/\text{100 g}_{\text{solution}}$). The surface represents the best fitted model (Equation 10).

Non-linear regressions were done using polynomials of different degrees, taking into account the complete set of experimental results. The statistical parameters showed that meat extract density had a linear dependence on temperature and quadratic dependence on solids content (both with $p_{\text{value}} < 0.05$). According to Table 1, the adjusted determination coefficients were similar to all tested models, which were able to predict experimental data with $> 98\%$ accuracy. An analysis of variance (ANOVA) presented significant differences between first- and second-degree polynomials ($F_{\text{value}}=5.18$, $F_{\text{critical}}=2.9957$) and first- and third-degree polynomials ($F_{\text{value}}=2.69$, $F_{\text{critical}}=2.2141$). No significant differences were observed when comparing polynomials of second and third degree (where $F_{\text{value}}=0.25$ was lower than $F_{\text{critical}}=2.9957$). In this way, the second-order polynomial could be considered the simplest model for representing density variation as a function of temperature and solids concentration.

In contrast, Table 1 shows that coefficient α_4 is small, indicating little contribution from the quadratic temperature term. This concurs with the results of Aguado and Ibarz,^[18] who verified that second-order equations were representative of apple juice density as a function of soluble solids and temperature, while linear equations were able to predict density only as a function of temperature.

Since linear models have been shown to be satisfactory for representing density only as a function of temperature at fixed concentration, linear correlations were obtained for each concentration (Equation (11)), with α_0 and $\alpha_1 = f(X)$. These equations and their derivatives were inserted into Equation (2) to obtain the thermal expansion coefficient for each value of meat extract concentration studied.

$$\rho|_X = f(T) = \alpha_0 + \alpha_1 T \quad (11)$$

Thermal expansion coefficients were also calculated as a function of temperature range and their behaviour concurs with Guignon et al.^[19] and Prieto et al.,^[20] i.e. β -values increased with increasing temperature at pressures close to atmospheric pressure. The deviations between the minimum and maximum values of β from the mean value of the temperature range were $\leq 7.8\%$, suggesting that the thermal expansion coefficient is constant along the temperature range studied.

Means of β were plotted against meat extract concentration in Figure 3 (left), with error bars representing the intervals of β found at lower and higher temperatures. Observing data behaviour, it was not possible to detect a clear trend according to solids concentration. In those cases, an average and constant thermal

Table 1. Adjustment parameters from polynomial regressions using Equation (1)

Coefficients	1 st degree polynomial	2 nd degree polynomial	3 rd degree polynomial
α_0	1160.4725	1246.5385	2336.8495
α_1	4.9469	4.4102	4.5488
α_2	-0.5858	-1.0967	-11.3239
α_3	0	0.0093	0.00307
α_4	0	7.9085×10^{-4}	0.0326
α_5	0	0	7.0358×10^{-5}
α_6	0	0	-3.2830×10^{-5}
R_{adj}^2	0.9866	0.9874	0.9872
RMSE	11.3044	10.8937	10.8775

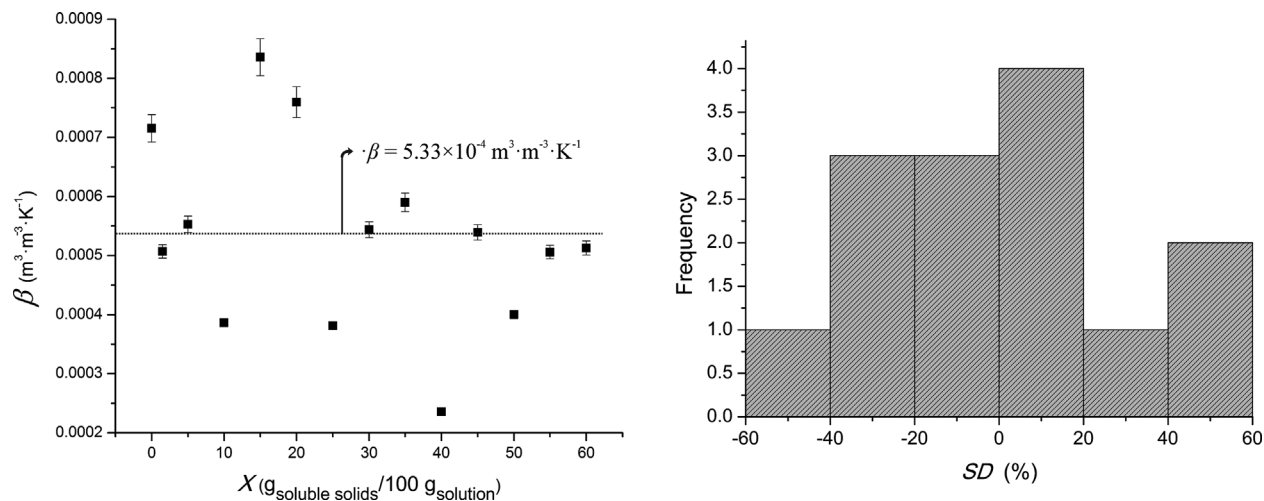


Figure 3. Left: thermal expansion coefficient as affected by solids concentration; error bars represent maximum and minimum values of β in the temperature range at fixed concentration. Right: histogram of deviations from the average value calculated in the solids concentration interval.

expansion coefficient was calculated and the corresponding standard deviation (SD) distribution was found to be normal around zero in the histogram (Figure 3). Although some variations occurred, they can be justified by the lack of fitting obtained

for linear correlations of density versus temperature at some concentration values. Considering the distribution of errors and the absence of trends, the thermal expansion coefficient could be considered constant and equal to $5.33 \cdot 10^{-4} \text{ m}^3 \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ for the

Table 2. Fitting parameters from rheograms to the Power-Law model

X (g _{soluble solids} /100 g _{solution} , °Brix)	Power-Law model T (°C)											
		2	10	20	30	40	50	60	70	80	90	98
1.5	k	0.0015	0.0012	0.0012	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003
	n	1.0056	0.9970	0.9658	1.0155	1.0130	1.0213	1.0211	1.0058	1.0062	0.9983	0.9981
	R^2_{adj}	0.9999	0.9987	0.9977	0.9992	0.9999	0.9982	0.9982	0.9999	0.9999	0.9987	0.9987
8	k	0.0025	0.0018	0.0014	0.0013	0.0010	0.0008	0.0007	0.0006	0.0005	0.0005	0.0004
	n	0.9970	1.0155	1.0155	1.0129	1.0078	1.0057	0.9969	0.9970	0.9967	0.9658	0.9657
	R^2_{adj}	0.9987	0.9992	0.9992	0.9999	0.9981	0.9999	0.9987	0.9988	0.9987	0.9977	0.9976
12	k	0.0048	0.0032	0.0024	0.0019	0.0015	0.0013	0.0012	0.0010	0.0009	0.0005	0.0005
	n	0.9657	1.0130	1.0129	1.0129	1.0212	0.9971	0.9657	0.9658	0.9656	1.0157	1.0128
	R^2_{adj}	0.9977	0.9999	0.9999	0.9999	0.9982	0.9987	0.9977	0.9977	0.9977	0.9992	0.9999
20	k	0.0094	0.0054	0.0040	0.0030	0.0023	0.0020	0.0012	0.0009	0.0008	0.0006	0.0005
	n	0.9657	1.0155	1.0078	1.0078	1.0057	0.9656	1.0154	1.0153	1.0128	1.0129	1.0215
	R^2_{adj}	0.9977	0.9992	0.9981	0.9981	0.9999	0.9977	0.9992	0.9992	0.9999	0.9999	0.9981
30	k	0.0329	0.0264	0.0215	0.0088	0.0051	0.0027	0.0014	0.0012	0.0011	0.0011	0.0008
	n	0.9604	0.9212	0.8621	0.9126	0.8974	0.8451	0.8526	0.8249	0.7769	0.7464	0.7716
	R^2_{adj}	0.9999	0.9949	0.9900	0.9957	0.9999	0.9999	0.9993	0.9999	0.9942	0.9883	0.9936
40	k	0.1059	0.0994	0.0517	0.0401	0.0318	0.0214	0.0175	0.0166	0.0172	0.0160	0.0129
	n	0.8826	0.8320	0.8742	0.8642	0.8143	0.8280	0.8067	0.7976	0.7613	0.7445	0.7541
	R^2_{adj}	0.9948	0.9896	0.9952	0.9999	0.9999	0.9992	0.9999	0.9999	0.9942	0.9883	0.9941
50	k	0.4311	0.2478	0.1876	0.1261	0.0827	0.0487	0.0323	0.0280	0.0269	0.0199	0.0217
	n	0.8061	0.8422	0.8330	0.8159	0.7966	0.7783	0.7436	0.7426	0.7447	0.7814	0.7603
	R^2_{adj}	0.9893	0.9948	0.9999	0.9999	0.9992	0.9999	0.9941	0.9941	0.9941	0.9999	0.9942
60	k	0.4205	0.3899	0.3412	0.2529	0.1667	0.1270	0.1056	0.0838	0.0802	0.0608	0.0622
	n	0.9134	0.9076	0.8669	0.8619	0.8765	0.8476	0.8191	0.8199	0.8208	0.8518	0.8268
	R^2_{adj}	0.9964	0.9999	0.9999	0.9999	0.9999	0.9946	0.9894	0.9895	0.9895	0.9946	0.9896

complete range of temperatures and concentrations studied. This value is similar to the average data published by Guignon et al.^[19] for water, and whole and skim milk.

A constant value of β can be useful in thermodynamic applications to avoid the complexity of calculations, e.g. integrating two functions at the same time such as specific volume and thermal expansion coefficient.

Rheological Behaviour

Tables 2 shows the rheological parameters resulting from the Power-Law model fitting, indicating that the complete set of flow curves could be accurately described by this model.

Samples of meat extract with solids contents up to 20 $g_{\text{soluble solids}}/100 g_{\text{solution}}$ resulted in values of flow behaviour index close to unity, indicating that meat extract may be considered a Newtonian fluid at these concentrations. For solids contents $> 30 g_{\text{soluble solids}}/100 g_{\text{solution}}$, however, Power-Law fitting to the rheograms showed $n < 1$, characterizing flow curves that are downwardly concave and consequently representing a fluid with shear-thinning behaviour. Bingham and Herschel-Bulkley models were discarded as the corresponding fitting results showed meaningless physical parameters ($\tau_0 < 0$).

A similar trend of two main rheological behaviours has been observed for concentrated coffee extract, which had a Newtonian domain up to 24 $g_{\text{soluble solids}}/100 g_{\text{solution}}$, and shear-thinning from 25–51 $g_{\text{soluble solids}}/100 g_{\text{solution}}$.^[14] In this work, the non-Newtonian behaviour could be attributed to the presence of high molar mass compounds dispersed in the fluid phase, such as proteins.

The results also indicated that the higher the solids content and lower the temperature, the greater the viscosity and consistency coefficient values. Similar behaviour was observed for apple juice,^[21] date syrup,^[6] honey,^[17] concentrated soursop juice,^[22] carrot juice,^[23] and other fluid food products.^[12] According to Hassan and Hobani,^[24] due to energy increments, the distance between product molecules increases, weakening intermolecular bonds. Furthermore, higher temperatures associated with shearing induce molecular rearrangement and the product becomes easy-flowing.

Newtonian domain (1.5–20 $g_{\text{soluble solids}}/100 g_{\text{solution}}$)

Based on the general recognition that exponential models result in suitable fitting of rheological parameters as a function of solids concentration and temperature,^[25–27] Equations (8–10) were used to adjust experimental data of meat extract viscosity at concentrations from 1.5–20 $g_{\text{soluble solids}}/100 g_{\text{solution}}$ and temperatures from 2–98 °C (Figure 4). Table 3 shows the fitting parameters obtained for the different equations, which express viscosity in Pa·s. Although all equations were well-fitted, Equation (10) was shown to be the most suitable for representing Newtonian viscosity as a function of both solids content and absolute temperature. This best adjustment (Figure 4) confirms that viscosity is more dependent on solids concentration than temperature.

Using the original Arrhenius-type equation (Equation (8)), the calculated values of activation energy ranged from 15.32–23.36 kJ/mol, showing higher values with increasing concentration, as observed for other food products.^[6,8,28]

Non-Newtonian domain (30–60 $g_{\text{soluble solids}}/100 g_{\text{solution}}$)

In the non-Newtonian domain, the dependence of the consistency coefficient and flow behaviour index on variations in temperature

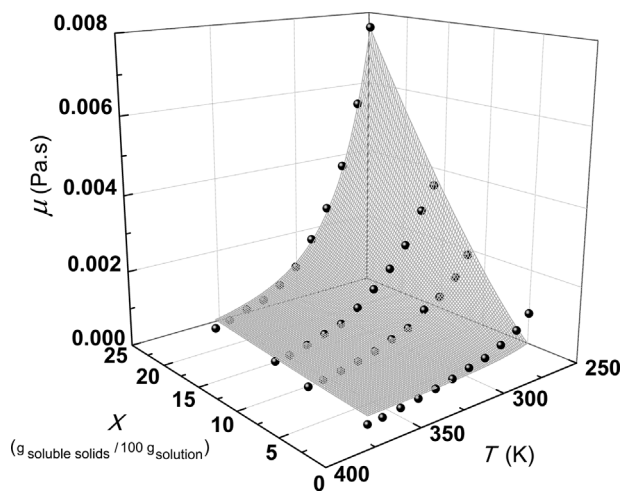


Figure 4. Newtonian viscosity of meat extract as affected by temperature and solids content. The surface represents the best fitted model (Equation 10).

Table 3. Adjustment parameters of Equations (8–10) for Newtonian domain (1.5–20 $g_{\text{soluble solids}}/g_{\text{solution}}$, 1.5–20 °Brix)

Coefficients	Equation (8)	Equation (9)	Equation (10)
ϕ_1	4.463×10^{-4}	-15.7169	1.25×10^{-7}
ϕ_2	1.7×10^{-9}	0.0797	0.1143
ϕ_3	1.2451	-	-0.0013
E_a (J·mol ⁻¹)	26 415.68	21 139.87	21 118.81
R_{adj}^2	0.9783	0.983 68	0.9853
RMSE	2.15×10^{-4}	1.89×10^{-4}	1.77×10^{-4}

and solids content (Figure 5) was also modelled by Equations (8–10), although the consistency coefficient seems to be more affected by temperature than the flow behaviour index.^[29–31] The results of the fitting procedure appear in Table 4. Both non-Newtonian parameters (consistency coefficient and flow behaviour index) could be better fitted to Equation (10), presenting higher R_{adj}^2 and lower RMSE, similar to what was observed in the Newtonian domain. Regarding the activation energy values for the consistency coefficient and for the flow behaviour index found with Equation (10), we confirmed that the consistency coefficient is more dependent on temperature than the flow behaviour index.

Adjusting the original Arrhenius equation (Equation (8)) resulted in energy activation values ranging from 17.55–30.54 kJ·mol⁻¹, but the trend of higher E_a values with increasing concentration observed in the Newtonian domain was not evident in the non-Newtonian interval. This same lack of adjustment was observed in previous studies when modelling the consistency coefficient as a function of concentration.^[22,32–34]

The difficulty in applying theoretical models to correlate rheological parameters with temperature in concentrations $> 30 g_{\text{soluble solids}}/100 g_{\text{solution}}$ could be explained by attributing these deviations from the ideal to physicochemical changes that may occur in macromolecules in suspension, such as protein coagulation and denaturation. Changes in the composition and structural organization of macromolecules are probable when products with high solids concentrations, such as meat extract, are subjected to intense thermal treatment.^[23]

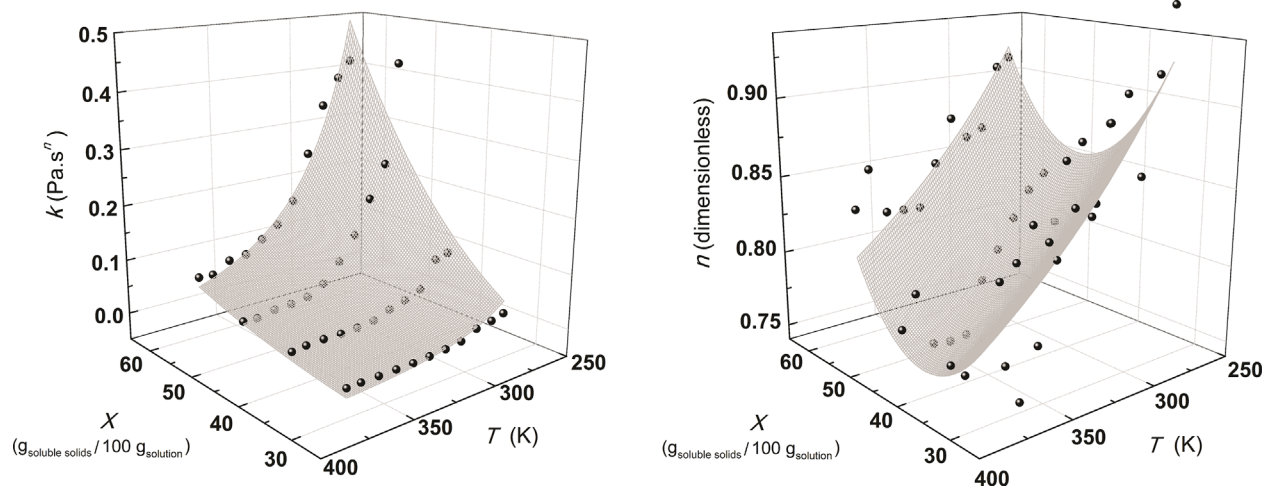


Figure 5. Power-Law parameters of meat extract as affected by temperature and solids concentration: (left) consistency coefficient; (right) flow behaviour index. The surfaces represent the best fitted model (Equation 10).

Table 4. Adjustment parameters of Equations (8–10) for the consistency coefficient in the range of 30–60 g_{soluble solids}/100 g_{solution} (30–60 °Brix)

Coefficients	k (Pa · s ⁿ)			n		
	Equation (8)	Equation (9)	Equation (10)	Equation (8)	Equation (9)	Equation (10)
ϕ_1	-0.0272	-13.4622	4.15×10^{-11}	0.6672	-0.6659	0.9514
ϕ_2	4.43×10^{-9}	0.0634	0.4704	0.0275	-0.0003	-0.0296
ϕ_3	2.6656	—	-0.0039	-0.1937	—	0.0003
E_a (J · mol ⁻¹)	17 551.46	20 563.55	21 219.71	6552.55	1297.64	1301.28
R_{adj}^2	0.9341	0.9093	0.95202	0.5019	0.5040	0.7569
RMSE	0.0285	0.0339	0.0244	0.0369	0.0373	0.0258

CONCLUSIONS

This paper investigates the effects of concentration and temperature on the density and rheological properties of meat extract. A second-degree polynomial model was capable of predicting the density values as a function of temperature and solids content with $R_{adj}^2 = 0.9874$. Linear and quadratic dependence on temperature and solids concentration were observed. Linear models fitted to density data permitted calculation of the thermal expansion coefficient as a function of the variables involved, but the results showed that a constant value of $\beta = 5.33 \cdot 10^{-4} \text{ m}^3 \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ could be adopted in the ranges of concentration and temperature studied.

Meat extract showed two kinds of rheological behaviour: Newtonian for concentrations $\leq 20 \text{ g}_{\text{soluble solids}}/100 \text{ g}_{\text{solution}}$, and shear-thinning for concentrations $> 30 \text{ g}_{\text{soluble solids}}/100 \text{ g}_{\text{solution}}$. Rheological parameters such as viscosity, consistency coefficient, and activation energy could be expressed by an Arrhenius-type equation and its variations, although better adjustments were observed for equations with a quadratic dependence on solid content. In the high-concentration and high-temperature domain, some rheological parameters were difficult to correlate, probably because heating could lead to protein denaturation and consequent changes in the structural properties of the material.

ACKNOWLEDGMENTS

The authors thank the Sao Paulo Research Foundation - FAPESP for financial support (Grant number: 2013/09344-4).

NOMENCLATURE

a_i	fitting parameters of Equation (1)
A_0	pre-exponential factor of Arrhenius equation
E_a	activation energy (J/mol)
k	consistency coefficient (Pa · s ⁿ)
n	flow behaviour index
P	pressure (Pa)
R	universal constant (J/mol · K)
R_{adj}^2	adjusted determination coefficient
RMSE	root mean square error
T	absolute temperature (K)
X	solids content (g _{soluble solids} /100 g _{solution})
α_i	input parameters of Equation (11)
β	thermal expansion coefficient (m ³ · m ⁻³ · K)
$\dot{\gamma}$	shear rate (1/s)
ϕ_i	input parameters of Equations (8–10)
η_{app}	apparent viscosity (Pa · s)
η_B	plastic viscosity (Pa · s)
μ	Newtonian viscosity (Pa · s)
ρ	density (kg/m ³)
τ	shear stress (Pa)
τ_0	yield stress (Pa)

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Manuscript received March 31, 2015; revised manuscript received July 29, 2015; accepted for publication August 10, 2015.