Non-Newtonian flow and heat transfer of pineapple juice in a plate heat exchanger

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ABSTRACT

The study of non-Newtonian flow and heat transfer in plate heat exchangers (PHEs) is of great importance for the food industry in order to provide useful correlations for equipment sizing and process design. The objective of this work was to study the thermophysical and flow properties of pineapple juice and also the convective heat transfer coefficients in a PHE. Specific heat and thermal conductivity of pineapple juice were determined in triplicate and were linearly correlated with temperature ($17.4 \leq T \leq 85.8$ °C) and soluble solids content ($11.0 \leq X_s \leq 52.4$ ºBrix). That the soluble solids content showed a negative effect, while the temperature showed a positive effect on these properties. Results from previous density measurements and rheological characterization are also reported. The pseudoplastic behaviour was well characterized by the rheological power-law model. Nusselt numbers for pineapple juice convective heat transfer in a PHE with 50º chevron plates were obtained for different flow rates and inlet temperatures. A countercurrent arrangement with three flow channels was used, where cold pineapple juice flowed in the middle channel and hot distilled water flowed in the two adjacent channels. Temperatures and flow-rates were recorded. The overall heat transfer coefficient was determined for each experimental run. Obtained Nusselt numbers were well correlated with the generalized power-law Reynolds number ($0.13 \leq Re_g \leq 3.58$) and they differ from predictions for Newtonian fluids in the same Reynolds range.

Keywords: thermal processing; heat transfer; plate heat exchanger; non-Newtonian flow; thermophysical properties

INTRODUCTION

Pineapple is a popular fruit worldwide and is of great commercial importance in the tropics. However, in many developing countries the variety of pineapple products (canned fruit, canned juice or frozen juice concentrate) is still limited. Thermal processing is required for the industrialization of pineapple pulp and juice for destruction of microorganisms and inactivation of enzymes. Adequate heat treatment levels must be reached with minimum alteration of nutritional and sensorial characteristics. For the correct process design it is essential to understand thermophysical properties, heat transfer coefficients and flow characteristics of the product. Moreover, the influence of temperature and soluble solids content over these properties must be also known [1,2].

The study of non-Newtonian flow and heat transfer in plate heat exchangers (PHEs) is of great importance for the food industry since various processes include this device, such as cooling and heating applications in milk, citrus juices and tropical fruit pulp pasteurization and concentration processes. The main advantages of PHEs are their arrangement flexibility, ease of maintenance and cleaning and high heat exchange rate [3, 4].

The objective of this work was to determine thermophysical (density, thermal conductivity and specific heat) and flow properties (viscosity and rheology) of pineapple juice for a considerable range of temperature and soluble solids content, as well as to study the heat transfer of pineapple juice in a PHE in order to obtain a correlation for the determination of the convective coefficient.

MATERIALS & METHODS

Pineapple (*Ananas comosus* L.) fruits, variety Smooth Cayenne, were purchased from a local market at São José do Rio Preto (State of São Paulo, Brazil) and stored at 7 ºC prior to use. A batch of concentrated pineapple juice, with 63.8 % solid content and 5.4 % of pulp content, was prepared in a pilot plant finisher with a single stage evaporator and sieved through a 1.6 mm-mesh. Experimental measurements were performed using concentrated juice diluted in distilled water to obtain soluble solids content of X_s = 11.0, 17.7, 23.5, 33.2, 37.9, 43.2 and 52.4 ºBrix, which was determined with a digital refractometer (Marconi, Piracicaba, Brazil). Studied temperatures were T = 17.4, 36.7, 54.8, 76.2 and 85.8 ºC.

Specific heat (Cp) and the thermal conductivity (λ) were measured using the method described by Bellet et al. [5], based on a cylindrical cell where the test liquid fills the annular space between two concentric cylinders. The inner cylinder contains an electric heater and thermocouples that register the temperature of the walls adjacent to the liquid film. Considering the unsteady heat conduction through the sample, the equation for energy conservation allows the determination of the specific heat. On the other hand, the Fourier equation for steady state heat transfer allows the determination of the thermal conductivity. Obtained results were correlated with temperature and soluble solids content using software Statistica 8 (StatSoft, Tulsa, USA).

Rheological measurements were carried out using an AR 2000 rheometer (TA Instruments, New Castle, USA) with cone and plate geometry (60 mm disc, 4º angle) under controlled stress and temperature. Shear rate range was 0.5 to 300 s^{-1} and both upward and downward tests were performed in duplicate for each temperature and soluble solids content combination. Density was determined by picnometry [2].

A M15 plate heat exchanger (Alfa Laval, Lund, Sweden) with four stainless steel 50º chevron plates was used for the heat transfer tests. The main characteristics of the plate were: length between ports L = 1.154 m, width between gaskets w = 0.438 m, orifice diameter D_P = 0.140 m, plate thickness e_p = 0.6 mm and area enlargement factor Φ = 1.227. The mean flow channel thickness was b = 2.0 mm and the equivalent diameter was $D_{eq} = 2b/\Phi$ = 3.26 mm.

The four plates formed three flow channels, where cold pineapple juice flowed in the middle channel and hot distilled water flowed in the two adjacent channels countercurrently. The proposed arrangement does not require a correction factor for the logarithmic mean temperature difference of the exchanger; otherwise this correction factor should be obtained from the mathematical modelling of the PHE [4]. The effective heat transfer area was $A_e = (N_{plate}-2)\cdot L\cdot w\cdot\Phi$ = 1.24 m².

Figure 1 presents the schematic diagram of the experimental setup. Various flow rates and inlet temperatures of pineapple juice with X_s = 24.0 ºBrix were tested in order to wider the range of heat transfer data. Temperatures and flow rates were measured, as shown in Figure 1.

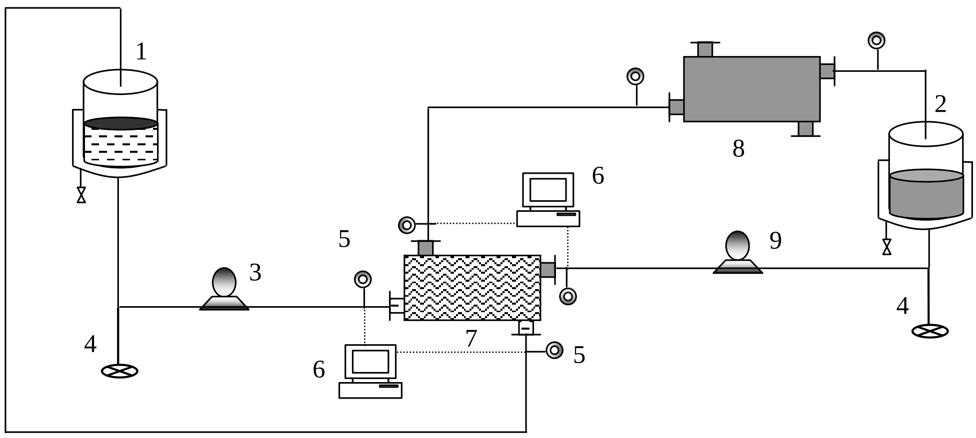

Figure 1. Schematic diagram of the experimental setup: 1) pineapple juice tank; 2) distilled water tank; 3) positive displacement pump; 4) flow meter; 5) temperature transmitters; 6) data acquisition systems; 7) test section-heat exchanger; 8) secondary heat exchanger; 9) centrifugal pump.

The heat exchange rate Q was evaluated for hot and cold sides of the exchanger (Eqs. (1) and (2)) and the overall heat transfer coefficient U was obtained from Eq. (3) using the mean value of Q. In Eqs. (1-3), W is the flow-rate and ΔT_{lm} is the log-mean of the temperature difference. The overall heat transfer coefficient is related to the convective coefficients of hot and cold sides (h_{hot} and h_{cold}) through Eq. (4), where λ_p = 17 W/Km is the plate thermal conductivity. All fluid properties were evaluated at the mean stream temperature.

$$Q = W_{hot} \cdot Cp_{hot} \cdot \left(T_{hot,in} - T_{hot,out}\right) \tag{1}$$

$$Q = W_{cold} \cdot Cp_{cold} \cdot \left(T_{cold,out} - T_{cold,in}\right) \tag{2}$$

$$Q = A_e \cdot U \cdot \Delta T_{lm} \tag{3}$$

$$\frac{1}{U} = \frac{1}{h_{hot}} + \frac{1}{h_{cold}} + \frac{e_p}{\lambda_p} \tag{4}$$

The convective coefficient of the water side of the PHE was obtained according to Sauders [6] for a 50º chevron plate using Eq. (5), where $Nu = h \cdot D_{eq}/\lambda$ is the Nusselt number, $Re = D_{eq} \cdot v \cdot \rho/\mu$ is the Reynolds number, $Pr = Cp \cdot \mu/\lambda$ is the Prandtl number, μ is the fluid viscosity, $v = W/(\rho \cdot b \cdot w \cdot N)$ is the mean velocity in the channel and N is the number of channels per pass. Parameters C and y are: $C = 0.630$ and $y = 0.333$ for $Re < 20$, $C = 0.291$ and $y = 0.591$ for $20 \leq Re \leq 300$ and $C = 0.130$ and $y = 0.732$ for $Re > 300$.

$$Nu = C \cdot Re^{y} \cdot Pr^{0.33} \tag{5}$$

Equation (4) provided the convective coefficient and, consequently, the Nusselt number, for the juice side of the exchanger. Since the rheological behaviour of the pineapple juice could be well represented by the power law model, the generalized power-law viscosity was used for the calculation of the Reynolds and Prandtl numbers for the juice side of the exchanger. The generalized viscosity is defined in Eq. (6), where K is the consistency coefficient, n is the flow index and ξ and υ are geometric parameters. Fort these study, the values for parallel plates where used, which are $\xi = 12$ and $\upsilon = 2$ [3,4].

$$\mu_g = K \cdot \xi^{n-1} \left(\frac{v}{D_{eq}} \right)^{n-1} \left(\frac{\upsilon \cdot n + 1}{(\upsilon + 1) \cdot n} \right)^{n} \tag{6}$$

The concept of the generalized Reynolds number was originally defined by Metzner and Reed [7] for correlation with the friction factor in circular pipes using data collected from various Newtonian and non-Newtonian power-law fluids. Subsequently, the concept of generalized Reynolds number was extended to turbulent flow and also heat transfer, with satisfactory results.

RESULTS & DISCUSSION

Rheological data indicated that the pineapple juice showed non-Newtonian pseudoplastic behaviour in the temperature and soluble solids content range studied. Upward and downward results showed no time-dependent behaviour. Power law model was fitted to all rheograms for determination of the consistency coefficient (K) and the flow behaviour index (n). Results for flow properties and density of the pineapple juice are available elsewhere [2].

Specific heat and thermal conductivity where determined in triplicate for the proposed temperature and soluble solids content range. These properties where linearly correlated with T and X_s and the results are presented in Figures 1 and 2. It can be seen that the soluble solids content had a negative effect, while temperature had a positive effect on these properties.

Table 1 summarizes the obtained correlations for thermophysical and flow properties of pineapple juice, where R = 8.3145 J/mol.K is the universal gas constant, r^2 is the coefficient of determination.

Table 1. Thermophysical and flow properties of pineapple juice ($17.4 \leq T \leq 85.8$ °C; $11.0 \leq X_s \leq 52.4$ ºBrix).

Property	Correlation	r^2
Density [2]	$\rho(\text{kg/m}^3) = 998 - 0.35T + 4.71X_s$	0.987
Specific heat	$Cp(\text{J/kg.K}) = 4111 + 1.93T - 26.7X_s$	0.994
Thermal conductivity	$\lambda(\text{W/K.m}) = 0.520 + 7.55 \cdot 10^{-4}T - 3.98 \cdot 10^{-3}X_s$	0.973
Consistency index (power-law) [2]	$k(\text{Pa.s}^n) = 6.40 \cdot 10^{-8} \exp\left(\frac{1.89 \cdot 10^4}{R(273+T)} \right) X_s^{2.95}$	0.997
Behaviour index (power-law) [2]	$n = (1.275 + 2.59 \cdot 10^{-3}T) X_s^{-0.231}$	0.996

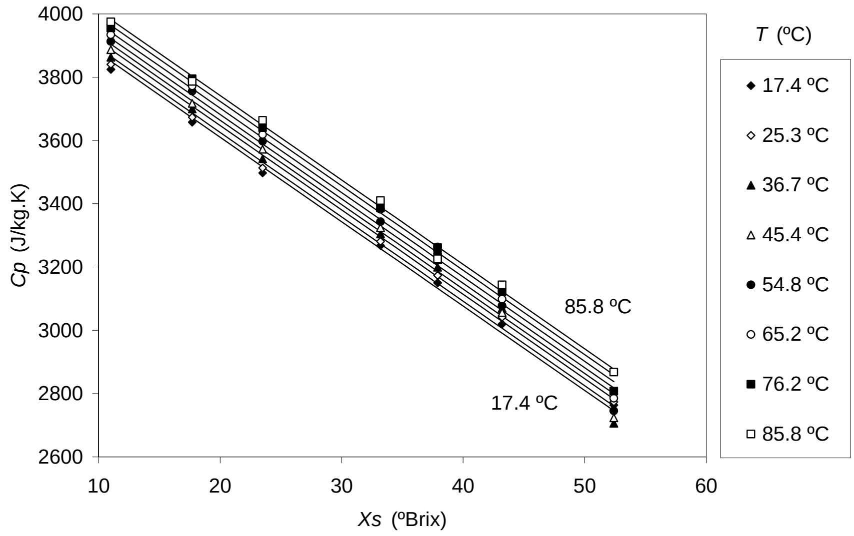

Figure 1. Specific heat of pineapple juice a function of soluble solids content and temperature.

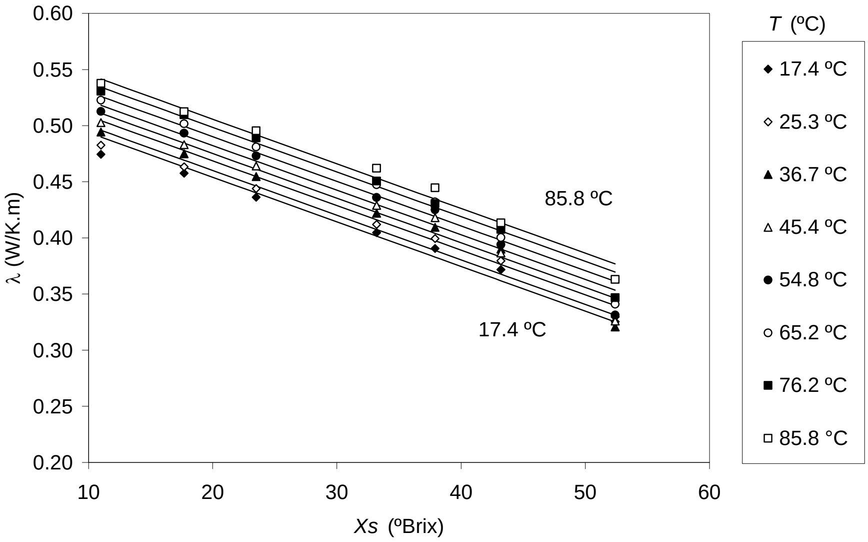

Figure 2. Thermal conductivity of pineapple juice a function of soluble solids content and temperature.

The number of experimental runs with the heat exchanger was 68, the achieved ranges of Reynolds numbers and overall heat transfer coefficient were: $26 \leq Re_{water} \leq 522$; $0.13 \leq Re_{juice} \leq 3.58$; $6.0 \leq U \leq 100$. Figure 3 brings the Nusselt/Reynolds plot for the juice side of the exchanger. It was possible to adjust to a correlation analogue to Eq. (5) in order to obtain $C = 0.0182$ and $y = 0.960$.

The adjusted parameters differ from those presented by Saunders [6] for a Newtonian fluid in the PHE, which are $C = 0.630$ and $y = 0.333$. This represents a large reduction on the predicted convective coefficient for the juice flow using the generalized power-law Reynolds and Prandtl numbers. This difference was also observed by Carezzato et al. [4] when evaluating the convective coefficients of water (Newtonian) and CMC solutions (pseudoplastic, power-law) in a small-scale PHE with flat-plates ($A_e = 0.0050$ m²). This emphasizes the importance of studying the heat transfer of non-Newtonian fluids in heat exchangers to obtain more reliable correlations for equipment sizing and process design.

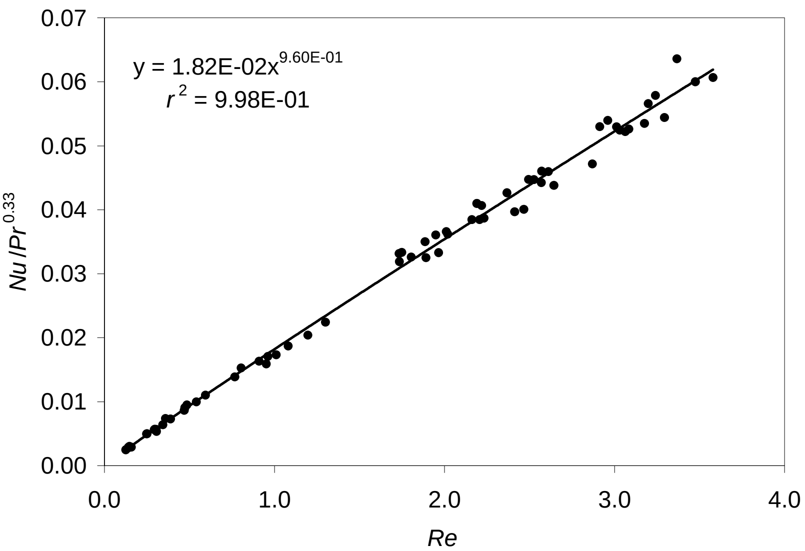

Figure 3. Nusselt/Reynolds plot for the juice side obtained from the experimental runs.

CONCLUSIONS

A major contribution of this work was to determine the thermophysical and flow properties of pineapple juice and to correlate them with temperature ($17.4 \leq T \leq 85.8$ °C) and soluble solids content ($11.0 \leq X_s \leq 52.4$ ºBrix). The rheological model that best represented the pseudoplastic behaviour was the power-law model. The correlations presented in Table 1 are very useful for the design of processing equipment. Moreover, the convective heat transfer coefficient of pineapple juice (24 ºBix) in a PHE with 50º chevron plates was determined and a Nusselt/Reynolds correlation was obtained. Because of the non-Newtonian behaviour, generalized forms of dimensionless numbers Reynolds and Prandtl were necessary. Correlations for non-Newtonian heat transfer of food products in PHEs are rather scarce and extensively required in the design of heat transfer operations dealing with similar pseudoplastic products.

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