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Rheology and fluid dynamics properties of sugarcane juice

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ABSTRACT

The sugarcane juice is a relatively low-cost agricultural resource, abundant in South Asia, Central America and Brazil, with vast applications in producing ethanol biofuel. In that way, a good knowledge of the rheological properties of this raw material is of crucial importance when designing and optimizing unit operations involved in its processing. In this work, the rheological behavior of untreated (USCJ, 17.9 °Brix), clarified (CSCJ, 18.2 °Brix) and mixed (MSCJ, 18.0 °Brix) sugarcane juices was studied at the temperature range from 277 K to 373 K, using a cone-and-plate viscometer. These fluids were found to present a Newtonian behavior and their flow curves were well-fitted by the viscosity Newtonian model. Viscosity values lied within the range 5.0×10^{-3} Pa s to 0.04×10^{-3} Pa s in the considered temperature interval. The dependence of the viscosity on the temperature was also successfully modeled through an Arrhenius-type equation. In addition to the dynamic viscosity, experimental values of pressure loss in tube flow were used to calculate friction factors. The good agreement between predicted and measured values confirmed the reliability of the proposed equations for describing the flow behavior of the clarified and untreated sugarcane juices.

1. Introduction

Sugarcane is an abundant and relatively low cost agricultural resource, largely produced in tropical and sub-tropical regions of the planet. This raw material contains about 80–85% of water and its dry matter presents an average composition of approximately 30% sucrose and 70% pre-processed ligno-cellulosic materials [1]. In previous years, sugarcane, either in the form of cane juice or cane molasses, has been widely used as feedstock for producing ethanol fuel in tropical and sub-tropical countries [2]. The sugarcane ethanol has the advantage of generating energy from a clean and renewable resource and contributes to reduce both air pollution and greenhouse gas emission, when compared to fossil fuels [3]. So, one important focus in current research and development applied in fuel ethanol production is the engineering of process to improve the productivity, by optimizing the unit operations involved in the productive chain [3,4]. Indeed, in preliminary steps of ethanol production, numerous unit operations requiring the knowledge of fluid rheology and dynamics (e.g., pumping, heating, cooling, sedimentation, etc.) are applied. For this purpose, the knowledge of rheological properties of the untreated sugarcane juice (USCJ), clarified sugarcane juice (CSCJ) and mixed sugarcane juice (MSCJ) should be of utmost importance to the ethanol industry. A schematic representation of the process line before fermentation step, identifying each type of sugarcane juice, is shown in Fig. 1. As depicted in this figure, the unclarified juice (USCJ) is the material obtained from the sugarcane milling and pre-filtration (to remove bagasse pieces). The clarified (CSCJ) is obtained from the USCJ after its heating and settling; it is the supernatant obtained in this unit operation. Finally, the mixed juice (MSCJ) results from the mixing of USCJ and filtered sugarcane juice (FSCJ), which is the permeate obtained after the filtration of the previously settled juice.

Literature reports a large number of fluids exhibiting a non-Newtonian behavior, such as diverse kinds of sludge [5,6]; and biological fluids, such as sucrose-CMC model solution [7], supersaturated sucrose solutions [8], dairy cattle manure [9] and aqueous solutions of sucrose, glucose and fructose [10]. Moreover, data concerning the influence of temperature on the rheological and flow behaviors of biological fluid products with varied sucrose contents, such as fruit purées [11], coffee extract [12], honey [13], sourcherry juice and concentrate [14] and pineapple juice at different stages of maturity [15] can be found. Nevertheless, to our knowledge, such kind of data for sugarcane juices is not available. Considering this lack of published information on rheology and fluid dynamics of USCJ, CSCJ and MSCJ, this work intended to determine their rheological properties and to develop simple correlations for predicting

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Nomenclature

A	empirical constant in Eq. (14)
D	diameter (m)
ΔP	pressure drop (Pa)
E_a	activation energy for flow (J/mol)
f	friction factor
K	consistency index (Pa s^n)
L	length (m)
n	flow behavior index
R	universal gas constant (8.314 J/mol K)
Re	Reynolds number
Re_g	generalized Reynolds number
T	temperature (K)
v	velocity (m/s)

Symbols

ε	roughness (m)
$\dot{\gamma}$	shear rate (s^{-1})
η	viscosity (Pa s)
ρ	density (kg/m^3)
σ	shear stress (Pa)
σ_0	yield stress (Pa)
σ_w	shear stress at the tube wall (Pa)

Table 1
Soluble solids (SS, °Brix) polarizable sugars (Pol. mass), purity (100 × Pol./°Brix), total solids (%) and pH for the studied sugarcane juices.

	°Brix	Pol.	Purity (%)	Total solids (%)	pH
USCJ	17.9	14.7	82.1	19.1	7.2
MSCJ	18.0	14.9	82.8	18.8	6.8
CSCJ	18.2	16.1	88.5	18.2	6.1

these properties under different temperatures. Additionally, the rheological data were used to calculate friction factors for tube flow, based on the widely accepted correlations described above. These results were then compared with those determined from experimental values of pressure loss in tubes.

2. Materials and methods

2.1. Sugarcane juice composition

Sugarcane juices were collected from a local sugarcane company and were quantified in terms of the following parameters. Soluble solids (SS, °Brix mass%) were determined using a digital refractometer (*Pal 3*, *Atago Japan*). Polarizable sugars (Pol., mass%) were determined with a digital polarimeter (*P3000*, *Kruess Optronic*). Purity was calculated as 100 × Pol./°Brix. Values of pH were measured using a digital pH meter-termometer (*Marconi*, *PA 200 P*). Such parameters are those usually employed to characterize the raw sugarcane in a factory. Table 1 presents the values obtained in triplicate for the mentioned quality parameters of untreated sugarcane juice (USCJ), clarified sugarcane juice (CSCJ) and mixed sugarcane juice (MSCJ), as previously detailed in Fig. 1. The soluble solids parameter includes sugars and organic acids; Pol. refers to sucrose content in the solution.

2.2. Rheological properties

Rheological measurements were carried out using an AR 2000 rheometer (TA Instruments, New Castle, DE) with cone-and-plate geometry (60 mm disc, 4° angle) under controlled stress and temperature. Shear rate range was 4–180 s^{-1} and both upward and downward tests were performed in triplicate for each temperature for every juice. The experimental procedure was previously tested on a rheological study of solutions of ethylene glycol and chlorobenzene [7]. Fitted rheological models for the dependence of shear rate on shear stress and for the dependence of the obtained rheological parameters on temperature and soluble solids were obtained by non-linear estimation procedure implemented in the software STATISTICA (Version 8.0, StatSoft, Inc., Tulsa, USA, 2007), by minimizing the sum of squared errors. The reliability of the equations was evaluated by the number of parameters, coefficient of determination (R^2) and analysis of residuals.

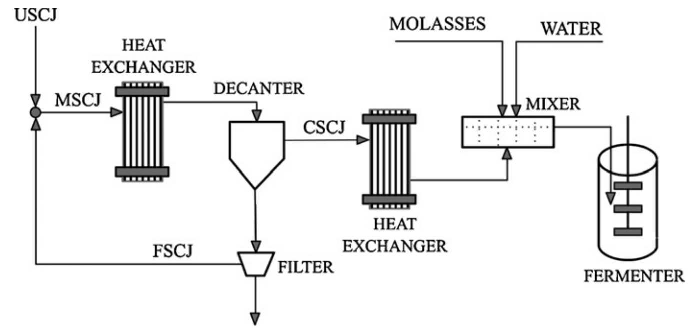

Fig. 1. Schematic representation of the unit operations involved in the processing of sugarcane juice before fermentation.

2.3. Pressure loss measurements

The apparatus shown schematically in Fig. 2 consists of a heat transfer section, where sugarcane juice was heated or cooled by flowing through a large thermostatic bath, kept at constant temperature. The heat transfer test section was composed by a set of three horizontal copper circular tubes with internal diameters of 6.3 mm, 7.8 mm and 10.2 mm and thickness of 1.4 mm. The total length of the section was 3.1 m providing a maximum length-to-diameter ratio (L/D) of 492. Differential pressure transmitters were used to measure static pressure at five different positions along the equipment (620, 1240, 1860, 2480, and 3100 mm from the heated tube inlet). Sugarcane juice was pumped by a peripheral pump (KSB model P-500, Brazil) at temperatures between 313 K and 373.4 K and between 273 K and 310 K using a gear pump (KSB model Triglav, Brazil). The wall temperature of the tube was kept constant by a thermostatic bath of silicon oil (Marconi, Brazil), which was pumped by means of a centrifugal pump (KSB model C-1010, Brazil). A static mixer was placed at the end of the equipment to homogenize the sugarcane juice at final temperature (T_m). A HP data logger, an interface HP-IB and a PC running a data acquisition and control program written in IBASIC (Navcon Engineering Network, Fullerton, CA, USA, 2007) to monitor temperatures and pressures. Measurements were accomplished to 134 different conditions for laminar flow and 148 conditions for turbulent flow. After the adjustment of the desired flow rate, the differential pressure data were recorded (10 data at intervals of 5 min).

2.4. Theoretical models

Non-Newtonians fluids do not present a direct proportionality between shear stress and shear rate. To describe their rheological behavior, different flow models are commonly used. One of the most frequently used is the Ostwald-de-Waele model, better known as the Power-Law model [16], given by Eq. (1):

$$\sigma = K\dot{\gamma}^n \tag{1}$$

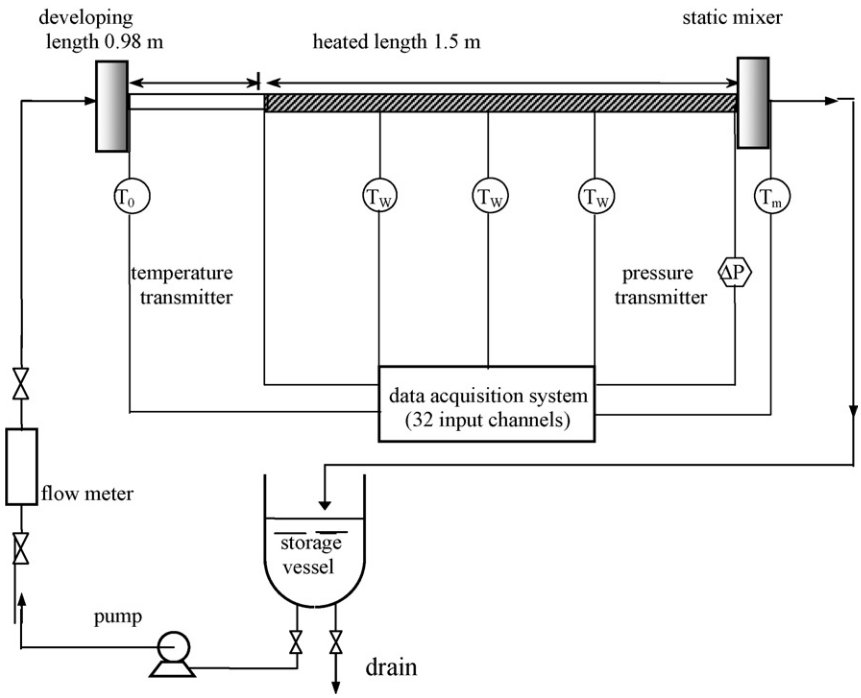

Fig. 2. Schematic diagram of the experimental setup used in the pressure loss measurements. T_0 = initial temperature; T_w = wall temperature; T_m = final temperature; ΔP = pressure drop.

In Eq. (1) σ is the shear stress, $\dot{\gamma}$ is the shear rate, K is the consistency index and n is the flow behavior index. In cases in which $n = 1$, K changes to η and Eq. (1) becomes the Newtonian model of the viscosity, expressed in Eq. (2):

$$\sigma = \eta\dot{\gamma} \quad (2)$$

In this case, η is a constant of proportionality between the shear stress applied on the fluid and the corresponding shear rate. This constant is the dynamic viscosity of the Newtonian fluid. The rheological parameters K, n and η, are influenced by water content and temperature. In order to quantify the effect of temperature on the viscosity of Newtonian fluids, an Arrhenius-type equation, given by Eq. (3), is frequently employed [17–19].

$$\eta = A_0 \exp\left(\frac{E_a}{RT}\right) \quad (3)$$

In this expression, A_0 is an empirical constant, R is the ideal gas constant, T is the absolute temperature and E_a is the activation energy for flow. E_a represents the energy barrier that must be overcome before the elementary flow process can occur.

One important application of rheological parameters is to calculate the pressure drop during flow, which is usually made through the friction factor, f [20]. The friction factor is defined as:

$$f = \frac{2\sigma_w}{\rho v^2} \quad (4)$$

In this expression, ρ is the fluid density, v is the average flow velocity, and σ_w is the stress in the wall, given by:

$$\sigma_w = \frac{D\Delta P}{4L} \quad (5)$$

where D is the tube diameter and ΔP is the pressure drop observed in a length L of the tube.

For laminar flow, the friction factor can be obtained from a simple function of the generalized Reynolds number (Re_g), which is identical to the dimensionless form of the Hagen–Poiseuille equation [21]:

$$f = \frac{16}{Re_g} \quad (6)$$

Re_g can be expressed as [21]:

$$Re_g = \frac{D^n v^{(2-n)}\rho}{8^{(n-1)}K}\left(\frac{4n}{1+3n}\right)^n \quad (7)$$

Eqs. (6) and (7) can be used for both non-Newtonian and Newtonian fluids. For these last, indeed, $K \equiv \eta$ and $n = 1$, so that the generalized Reynolds number Re_g becomes the well-known expression $Re = Dv\rho/\eta$.

Under turbulent flow conditions, the correlations to estimate the friction factor are semi-empirical. For Newtonian fluids flowing in rough pipes with $Re > 4000$, the Colebrook equation is commonly used (Eq. (8)). This is an empirical modification of the von Karman equation to include the effect of wall roughness [21]:

$$\frac{1}{\sqrt{f}} = -4\log\left(\frac{\varepsilon/D}{3.7} + \frac{1.255}{Re\sqrt{f}}\right) \quad (8)$$

where ε/D is the relative roughness of the tube. Eq. (8) is derived from data obtained with Newtonian fluids, such as water or liquids containing low molar mass solutes, under turbulent conditions of flow, within tubes with varying values of roughness (ε) [21]. Foust et al. [22] proposed an empirical relation which approaches to Eq. (8), and has the advantage of being simpler, as it is explicit in f:

$$f = \frac{0.0460}{Re^{0.2}} \quad (9)$$

3. Results and discussion

3.1. Rheological properties

In order to get an accurate evaluation of the rheological characteristics of sugarcane juices, the densities (ρ) of UCSJ, MSCJ and CSCJ were previously evaluated [23]. Density values showed a linear

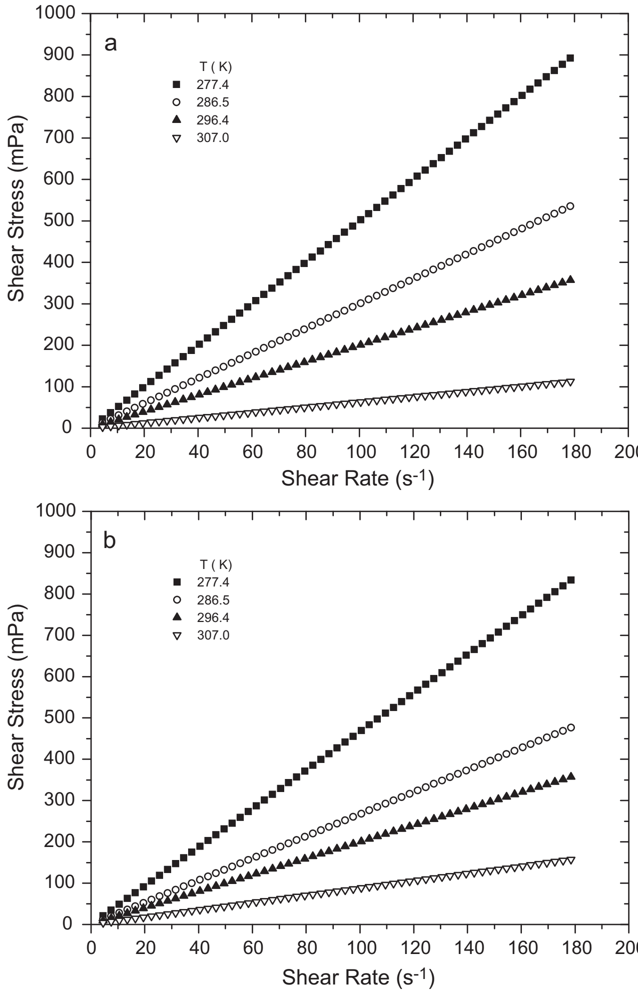

Fig. 3. Rheograms obtained for USCJ and CSCJ at different temperatures.

dependence on temperature and the mean experimental error was ±30 kg/m^3 at 277.4 K ≤ T ≤ 373.4 K. Eq. (10) for UCSJ presented to the experimental data with R^2 = 0.910, Eq. (11) for MSCJ was fitted R^2 = 0.937 and Eq. (12), for CSCJ, with R^2 = 0.978. The mean absolute error found for density determination was 0.6%.

$$\rho = 1297.7 - 0.390T \quad \text{(UCSJ)} \tag{10}$$

$$\rho = 1177.7 - 0.347T \quad \text{(MSJC)} \tag{11}$$

$$\rho = 1179.7 - 0.354T \quad \text{(CSJC)} \tag{12}$$

In these equations, ρ is given in kg m^{-3} and T in K. Before the rheological measurements, the accuracy of the viscometer was checked by comparing the measured viscosity of ethylene glycol and chlorobenzene with data previously presented by Perry et al. [24]: the maximum relative error (Eq. (10)) observed was 1.82%, whereas the maximum standard deviation of experimental replicates was 3.90%. In the studied ranges of temperature (277.4–373.5 K) and soluble solids content (18.2–19.1 (w/w) %), the sugarcane juices showed Newtonian behavior, as indicated by the linear dependence of the shear stress on the shear rate shown in Fig. 3. The Ostwald-De Waele (Power Law) model was also used, but the detected n value was equal to 1, further confirming that the fluids behavior was Newtonian. The dynamic viscosities determined for the studied sugarcane juices (UCSJ, MSCJ and CSCJ), measured in triplicate, are reported in Table 2. These data show that the viscosity varied from 0.044 × 10^{-3} Pa s to 5.0 × 10^{-3} Pa s and, as expected, an increase in the temperature induces the reduction of the sugarcane juice viscosities, as occurs with some fruit juices [14,15,25]. The Newtonian behavior of sugarcane juice may be attributed to the low molar mass of the solutes. The found viscosity magnitudes are comparable to literature values concerning sugar solutions and fruit juices with similar soluble solids contents. For example, considering sugar solutions with about 20 mass%, from 278 K to 361 K [10], viscosity values varied as follows: for sucrose, from 3.15 × 10^{-3} Pa s to 0.55 × 10^{-3} Pa s; for fructose, from 2.95 × 10^{-3} Pa s to 0.51 × 10^{-3} Pa s; for glucose, they lied in the range 3.11 × 10^{-3} Pa s to 0.54 × 10^{-3} Pa s. Considering Josapine pineapple juice with about 14 mass% sucrose (°Brix), from 278 K to 338 K [15], viscosity varied from 47 × 10^{-3} Pa s to 24 × 10^{-3} Pa s. Finally, according to Nindo et al. [26], for blueberry juices with 20 °Brix, viscosities varies from 3 × 10^{-3} Pa s to 1 × 10^{-3} Pa s; for raspberry juices with the same °Brix, the values varied from 3.5 × 10^{-3} Pa s to 0.7 × 10^{-3} Pa s (293–333 K).

Table 2
Average and standard deviation values for viscosity (η) of the studied sugarcane juices at different temperatures (considering three independent measurements for each juice at each temperature).

T/K	Viscosity (η) ×10^3/Pa s	
	Average	Standard deviation
Untreated Sugarcane Juice (USCJ). SS = 19.1%		
277.4	5.000	1.000
286.5	3.000	0.000
296.4	2.000	0.000
307.0	0.980	0.035
317.4	0.630	0.009
328.2	0.390	0.007
340.4	0.230	0.015
352.0	0.130	0.016
364.1	0.087	0.003
373.4	0.070	0.010
Mixed Sugarcane Juice (MSCJ). SS = 18.8%		
277.4	4.670	0.577
286.5	2.670	0.577
296.4	2.000	0.000
307.0	0.880	0.009
317.4	0.520	0.011
328.2	0.330	0.015
340.4	0.190	0.008
352.0	0.120	0.002
364.1	0.075	0.001
373.4	0.055	0.002
Clarified Sugarcane Juice (CSCJ). SS = 18.2%		
277.4	4.000	0.000
286.5	2.000	0.000
296.4	1.000	0.000
307.0	0.750	0.009
317.4	0.450	0.005
328.2	0.270	0.002
340.4	0.160	0.005
352.0	0.100	0.002
364.1	0.060	0.006
373.4	0.044	0.002

The dynamic viscosity was also expressed as functions of temperature, using an Arrhenius-type model. The resulting functions are represented by Eqs. (13), (14) and (15), respectively, for USCJ, MSCJ and CSCJ. The model was able to adjust the experimental data with coefficient of determination (R^2) above 0.990 in the three cases. Dynamic viscosities estimated by Eqs. (13)–(15) exhibited good agreement with the corresponding experimental values.

$$\eta = 5.91 \times 10^{-10} \exp\left(\frac{E_a}{RT}\right), \quad R^2 = 0.998 \quad \text{(USCJ)} \tag{13}$$

$$\eta = 4.65 \times 10^{-10} \exp\left(\frac{E_a}{RT}\right), \quad R^2 = 0.992 \quad \text{(MSCJ)} \tag{14}$$

$$\eta = 0.14 \times 10^{-10} \exp\left(\frac{E_a}{RT}\right), \quad R^2 = 0.994 \quad \text{(CSCJ)} \tag{15}$$

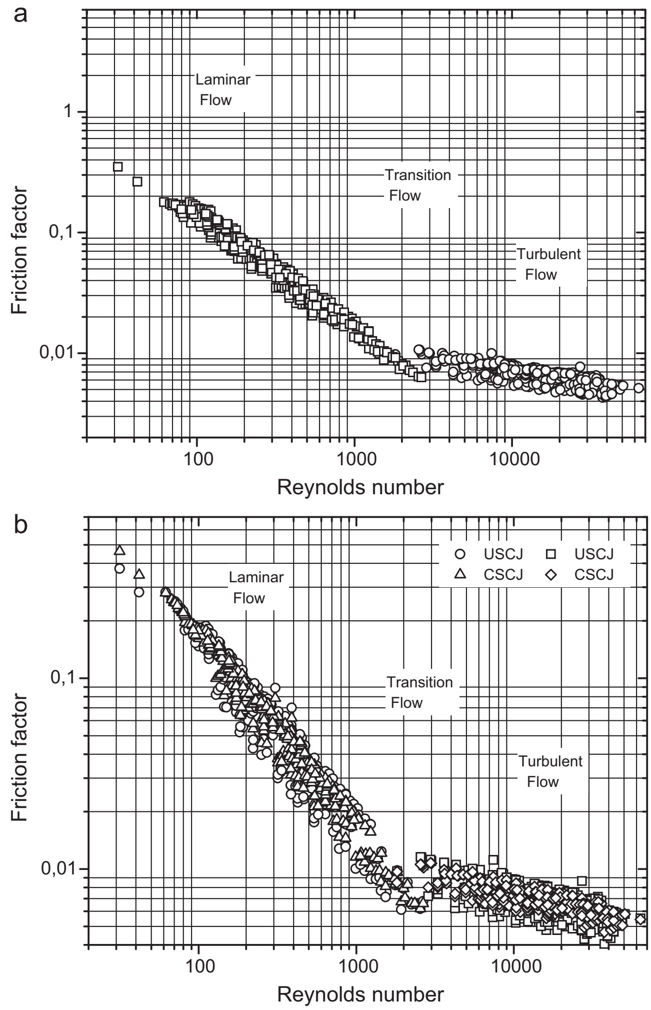

Fig. 4. Experimental friction factors obtained for (a) ethylene glycol and (b) for the USCJ and CSCJ sugarcane juices.

Eqs. (13)–(15) are Arrhenius-type. So, the activation energies for flow (E_a) could be calculated. According to Holdsworth [27], the higher the value of activation energy, the larger is the effect of temperature on the considered property. The calculated values for E_a for the three studied fluids were: 36,796.5 J/mol for USCJ, 37,182.5 J/mol for MSCJ and 44,912.9 J/mol for the CSCJ.

3.2. Friction factors determination

In order to evaluate the performance of the experimental setup (Fig. 2) for pressure drop measurements, preliminary tests were conducted in the proposed system using the ethylene glycol flow. Pipe dimensions, density values and measured pressure drop were substituted in Eqs. (4) and (5) to calculate the friction factor, f, which was then correlated with the Reynolds number calculated by Eq. (7), using the experimental rheological parameters $K \equiv \eta$ and $n = 1$ for ethylene glycol [24,28]. The experimental results, presented in Fig. 4a, display a good agreement with calculated values, using Eq. (6), for the laminar region, and Eq. (9), for turbulent region.

Experimental friction factors for ethylene glycol were also submitted to nonlinear regression analysis, resulting in Eqs. (16) and (17) for laminar and turbulent flow, respectively.

$$f = \frac{16.54}{Re} \tag{16}$$

$$f = \frac{0.0470}{Re^{0.198}} \tag{17}$$

Eq. (16) was adjusted in the range of $27.5 < Re < 2086.3$ with $R^2 = 0.994$, and the obtained parameters were similar to the theoretical values present in Eq. (6). Taking into account the turbulent region, where $4132.1 < Re < 62{,}232$, Eq. (17) was adjusted with $R^2 = 0.908$. The R^2 values obtained in the present work exhibit the same order of magnitude of those determined by using Eq. (9) [22], confirming the suitability of the experimental apparatus.

Tube flow experiments were also carried out during heating of sugarcane juices and the experimental pressure loss data have been used to calculate the friction factor, according to Eqs. (4) and (5). Densities were evaluated at the average temperature between the initial and the final conditions attained by the sugarcane juice during flow, using Eqs. (10), (11) and (12). The data on the thermophysical properties (thermal conductivity, heat capacity and density) for USCJ, CSCJ and MSCJ were reported elsewhere [23].

The experimental friction factors measured for USCJ and CSCJ in conditions of Newtonian behavior are shown in Fig. 4b. Eq. (18) was adjusted in the laminar region ($41.4 < Re < 1882.6$) for both sugar juices; the obtained parameters were satisfactory well adjusted with $R^2 = 0.969$. In the turbulent region ($4301.5 < Re < 61878$) the resulting Eq. (19) was obtained with $R^2 = 0.878$.

$$f = \frac{17.12}{Re} \tag{18}$$

$$f = \frac{0.0475}{Re^{0.197}} \tag{19}$$

A comparison between the friction factors during laminar flow of Newtonian fluids in circular pipes and the Reynolds number with the analytical solution tend to slightly overestimate the friction factor of the sugarcane juices. According to Steffe and Singh [29], this may be due to wall slip or time dependent changes in rheological properties that can occur in suspension and emulsion type products. For higher Reynolds numbers, the experimental data were compared with those predicted by the correlation showed by Eq. (9), resulting in a good agreement. The average relative error was of 5.77% with a maximum of 9.06%.

It is worthy to mention that data presented in Fig. 4b may be considered of limited importance, because they only confirm the suitability of already widely accepted correlations for predicting friction factors, such as the theoretical equations (6) and (9). On the other hand, the good agreement observed between friction factors calculated from experimental data on pressure loss and those estimated from the measured rheological parameters supports the reliability of the models obtained for describing the rheological properties of untreated (USCJ), clarified (CSCJ) and mixed (MSCJ) sugarcane juices (Eqs. (13)–(15)).

4. Summary and conclusions

Sugarcane juice constitutes one of the most important resources for ethanol fuel production. In this study, the rheological behavior of untreated (USCJ), clarified (CSCJ) and mixed (MSCJ) sugarcane juices was investigated. At temperature range of 277–333 K, they were found to exhibit a Newtonian behavior in flow, with the viscosity values lowering as the temperature was increased. The Newtonian model satisfactorily fitted the experimental flow curves. Friction factors, measured in both laminar and turbulent flows, were found to be well correlated in terms of the Reynolds number. The good agreement between experimental values and values predicted by theoretical equations confirmed the reliability of the proposed equations in describing the rheological properties of the evaluated sugarcane juices. Therefore, the outlined rheological and flow dynamics data, in the considered temperature interval, seem to be reliable to be used in optimization of unit operations and processes involving these sugarcane juices in the ethanol production.

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