J. Agr. Sci. Tech. (2013) Vol. 15: 961-971

Modeling of Rheological Characteristics of "MalasYazdi" (*Punicia granatum* L.) Pomegranate Juice

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ABSTRACT

Flow characteristics and rheological parameters of "Malas Yazdi" pomegranate (*Punica granatum* L.) juice were investigated using rotational viscometer at different temperatures (10, 20, 30, 40, 50, 60 and 70ºC) and concentrations (12, 22, 32, 42 and 52º Brix). The experimental data had the best fitness with Herschel-Bulkley model and the values of flow behavior index (n) varied between 0.97 and 1.45 at all temperatures and concentrations, revealing the shear thickening nature of pomegranate juice. The activation energy of flow (E_a) calculated with respect to apparent viscosity at 40 rpm increased from 9.07 to 24.05 kJ mol^{-1} as the juice concentration increased from 12 to 52º Brix. Power equation indicated that consistency coefficient increased non-linearly with concentration increase. A mathematical model was developed to describe the influence of temperature and soluble solids on the consistency coefficient of pomegranate juice for the studied conditions.

Keywords: Apparent viscosity, Consistency coefficient, Pseudoplastic, Shear-thickening.

[DOR: 20.1001.1.16807073.2013.15.5.8.3]

INTRODUCTION

Rheology concerns the flow and deformation of a substance under applied forces; and attempts to define a relationship between the stress acting on a given material and the resulting deformation and/or flow that take place. These rheological properties, in addition to chemical and physical properties, have several applications in the field of food acceptability, food processing and food handling (Barbosa-Canovas, *et al*., 1996; Molwane and Gunjal, 1985; Rao, *et al.,* 1984). Rheological data are also needed for computation in any unit operation involving flow (e.g. pump sizing, filtration, extrusion, etc); and serve significant role in the analysis of flow conditions in many food processing operations such as pasteurization, concentration and dehydration (Memnune *et al*., 2007). Rheological properties are determined by measuring force and deformation as a function of time. Several equations have been used to describe the flow behavior of foods, for example, linear (Newtonian or Bingham), power law (Ostwald-de-Waele), power law with yield stress (Herschel Bulkey) and Casson models (Marcotte, *et al.,* 2001). Moreover, temperature has an important influence on the flow characteristics of foods. The effect of temperature on the apparent viscosity at a specified shear rate is generally expressed by an Arrhenius-type model (Rao and Anantheswaran, 1982). As every fruit juice is composed of soluble solids in an aqueous phase, its rheological behavior will be influenced by the concentration and chemical composition of the solids. Heating processes significantly change the thermo-physical properties of fruit juices. It is necessary to study thermodynamic and transfer

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properties of fruit juices, particularly viscosity in order to understand and control the juice production processes. Knowledge of the viscosity has great importance in fruit juice industry. Since the fruit juices are subjected to different temperatures and concentrations during processing, storage, transport, marketing and consumption, the viscosity is studied as a function of temperature and concentration. Fruit Juices vary greatly in their rheological behavior and their viscosity is a function of temperature and concentration. Thus, there is a great practical interest to study the effect of temperature and concentration on viscosity of fruit juices at various conditions.

The pomegranate (*Punica granatum* L.) fruit, native of Iran, is extensively cultivated in Spain, Egypt, Russia, France, Argentina, China, Japan, USA and India (Patil and Karade, 1996). In Iran, the fruit is known as "Anar" which has been grown since ancient period. The versatile adaptability, table and therapeutic values, and long shelf life are the features responsible for its cultivation on a wide scale (Dhandar and Singh, 2002). Pomegranate is commercially grown for its sweet-acidic taste of the arils. The fruit is consumed directly as fresh seeds and fresh juice which can also be used in beverages, jellies, and flavoring and coloring agents (Ewaida, 1987). The edible part of the fruit contains considerable amounts of acids, sugars, vitamins, polysaccharides, polyphenols, and important minerals. In a study performed by Sadeghi *et al.* (2009), it was made clear that the highest potent antioxidant activity in different Iranian pomegranate seed cultivars was in *Sour white peel* cultivars. There are numerous varieties which differ from each other regarding shape, size, taste, color, and anthocyanins content. Malas Yazdi, Shirin Shahvare Yazd, Ardestani Torshe Semnan, Pust Syahe Yazd and Malase Porbarij Stahban are some of popular pomegranate varieties in Iran. Rheological properties of fruit juices appear to be strongly dependent on their varieties, stage of ripening, and concentration of juice and temperature variation. Typical values of flow behavior index, consistency coefficient and activation energy of flow are rather limited considering the varieties of pomegranate fruits. However, published values of these indices may not be accurate since factors such as variety, ripeness, processing methods, instrumental method, to name few, may influence the rheological properties (Magerramov *et al.*, 2007). "Malas Yazdi" variety is well-known for its unique taste, color and high anthocyanin content and the juice of this variety has high quality (Tehranifar *et al.*, 2010). Up to now, there is not any published data about rheological properties of "Malas Yazdi" variety.

Although many works have been reported for other fruit juices but only a few describe the physicochemical characteristics of pomegranate juice (Sadeghi *et al.*, 2009; Alighourchi and Barzegar, 2009). Yasoubi *et al.* (2007) studied the total Phenolic contents and Antioxidant activity of pomegranate (*Punica granatum* L.) peel extracts. They observed that pomegranate peel extract possessed a relatively high antioxidant activity and might be considered as a rich source of natural antioxidant. Turfan *et al.* (2011) investigated anthocyanin and colour changes during processing of pomegranate (*Punica granatum* L., cv. Hicaznar) juice from sacs and whole fruit and reported that clarification of pomegranate juice caused a loss of 4% of ACNs in juice from sacs (JFS) and a loss of 19% in juice from whole fruit (JFWF).The objective of this study was to investigate the flow behavior of pomegranate juice as well as modeling of its rheological data using flow equations. The effect of soluble solids concentration and temperature on flow behavior was also described.

MATERIALS AND METHODS

Preparation of Pomegranate Juice

Fresh and fully ripe "Malas Yazdi" variety of pomegranate (*Punica granatum* L.) was procured in early October 2009 from the local market. Pomegranate juice was obtained from fresh pomegranates by cutting, pressing, filtration and clarification. According to Bodbodak *et al.* (2010), pectolitic enzyme (120 ppm)-gelatin (300ppm)-bentonit (200ppm)-silica sol (500 ppm) treatment was an effective treatment for clarification of pomegranate juice. Since pomegranate bioactive compounds such as

[DOR: 20.1001.1.16807073.2013.15.5.8.3]

anthocyanins, phenols are sensitive to high temperature, the juice was concentrated to 70±1° Brix using a rotary glass vacuum evaporator (HB4 basic, IKA WERKE) at temperatures below 50ºC. Samples with lower soluble solids contents were obtained by diluting the concentrated juice with distilled water.

Analytical Methods

A pH-meter (827 pH lab, Metrohm, Switchzerland) was used to measure the pH of the pomegranate fresh juice and concentrate and gave values of 3.01 and 2.61 at 20°C, respectively. Total acidity was determined by potentiometric (827 pH lab, Metrohm, Switchzerland) titration with NaOH 0.1N until pH 8.1. The acidity of the fresh juice and concentrate were 1.07 and 4.03 g 100 g^{-1} (citric acid), respectively. The density was determined in capillary tube pycnometer (10 ml capacity) (Thomas Glass Pycnometer Bottle, 10ml Capacity, +/-0.04 Specific Gravity) after stabilizing the temperature in a thermostatic bath (U30 Memert, Germany) at 20°C (±0.1). The density of fresh juice and concentrate were 1.02 and 1.16 (g cm^{-3}), respectively. Soluble solid contents of the samples were determined by a temperature compensating type Refractometer (CETI, ABBE, Belgium) at 25ºC before viscosity measurement and was expressed as ºBrix. Before conducting the tests, the prepared samples were stirred for 3 min to ensure uniformity. The Soluble solid content of fresh juice was 14.3º Brix.

Rheological Measurements and Analysis

The rheological measurements were carried out using a rotational type Brookfield Viscometer (Model LVDV-II Brookfield Engineering Laboratories, Inc. USA). A sample of pomegranate juice of desired concentration was loaded into cylindrical sample chamber (ULA-31Y) of 16 mL capacity for all experiments and was allowed to equilibrate at the desired temperature using a circulating water jacket (Model ULA-40Y Brookfield Engineering Laboratories). The rheological parameters of pomegranate juices with different total soluble solids of 12, 22, 32, 42 and 52º Brix and temperatures of 10, 20, 30, 40, 50, 60 and 70ºC (± 0.1ºC) were studied using spindle YULA-15 at rotational speeds between 10 and 200 rpm in accordance to viscometer rpm working range. Different rheological models (Newtonian, Power Law, Herschel-Bulkley and Casson) were used to find out the best equation to relate shear rate to shear stress data of pomegranate juice. Fluids that follow Newton's law of viscosity [Equation (1)] are called Newtonian fluids. The slope of the shear stress versus shear rate graph, which is viscosity, is constant and independent of shear rate in Newtonian fluids (Rao and Rizvi, 1986):

$$\tau = \eta \gamma^{\circ} \tag{1}$$

Where, τ is shear stress (Pa), η is viscosity (Pa.s), and γ° is shear rate (s^{-1}).

The Oswald de Waelle model, commonly referred to as Power Law model [Equation (2)], has been used extensively in studies on handling and heating/cooling of foods because it gives good description of fluid flow behavior in the shear rate range that is easily measured by most rheological instruments. However, it exhibits poor fitting for data obtained at a wide range of shear rates. This model is in the following form:

$$\tau = K \gamma^{\circ n} \tag{2}$$

Where, τ is shear stress (Pa), K is consistency index (Pa s^n), γ° is shear rate (s^{-1}) and n is the dimensionless flow behavior index. Sometimes, for some foods, experimental data are not adjusted to the Power Law model with great precision since these foods have yield stress (Ditchfield *et al.*, 2004). If the foodstuff has a finite yield stress, the yield term can be included in the Power Law model to yield the Herschel-Bulkley (HB) model:

$$\tau = \tau_0 + K \gamma^{\circ n} \tag{3}$$

Where, τ_0 is yield stress (Pa), and n is a dimensionless flow behavior index. The

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yield stress can be determined by means of graph as explained by Steffe (1996), or calculated by using model. The Casson model, Equation (4), gives the yield stress (as square of the intercept) when the square roots of τ and γ are plotted against each other on linear coordinates (Rao, 1999):

$$\sqrt{\tau}=\sqrt{\tau_{\circ}}+K\sqrt{\dot{\gamma}} \qquad (4)$$

Statistical Analysis

The experimental Shear stress–shear rate data was fitted to the different rheological models (Newtonian, Power Law, Herschel-Bulkley, and Casson models). Modeling of data was performed with non-linear and multiple regression analysis functions and parameters associated with different models estimated from the experimental data using SAS software 9.1 (2001). There are several criteria such as coefficient of determination (R^2), mean square error (MSE) and residual plotting to evaluate the fitting of a model to experimental data. The average percent difference between the experimental and predicted values or the mean relative deviation modulus (P) has also been used as a measure of model adequacy:

$$\mathrm{P}=\frac{100}{n}\sum_{i=1}^{n}\frac{\left|\mathrm{MR}_{\mathrm{measured}}-\mathrm{MR}_{\mathrm{predicted}}\right|}{\mathrm{MR}_{\mathrm{measured}}} \qquad (5)$$

RESULTS AND DISCUSSION

Comparison of Selected Rheological Models

The viscosity of fresh juice was 2.15 (cP) at 25°C. The best model describing the rheological behavior of pomegranate juice was chosen as the one with the highest coefficient of determination (R^2) and the mean square error (MSE) and mean relative deviation modulus (P). The accuracy of the rheological parameters measurements strongly depends on the uncertainty of each individual measurement that affects the overall determination. In this study, the measurement of the following basic quantities are needed: Temperature and concentration. In order to investigate the reproducibility of the results, three replicates were made for all experiments and the average reproducibility was ±2.7%. The results of the statistical analysis for the four models showed that acceptable R^2 of greater than 0.95 were obtained for all four models fitted to all runs, while Herschel-Bulkley model presented higher values than the other rheological models. An examination of *MSEs* showed that the Casson model gave the superior fit to the experimental data compared to others models due to its lower values. *P* value indicates the deviation of the observed data from predicted line. *P* value lower than 10%, is recommended for the selection of models (Yanniotis *et al*., 2006). Herschel-Bulkley model showed lower *P* values than the other models and also lower than 10%. Based on statistical evaluation and overall suitability of the models considered, the Herschel-Bulkley model was selected to describe the rheological behavior of pomegranate juice (Table 1). Memnune *et al.* (2007) studied the rheological behaviour of carob pekmez and the Herschel-Bulkley model was found to be the best to describe the rheological property with the coefficient of determination higher than 0.998.

In order to obtain the flow behavior index (n), consistency index (K) and yield stress (τ_0) values, Equation (3) was analyzed by non-linear regression, and *n, K* and yield stress (τ_0) values at different temperatures are given in Table 2. As shown in Table 2, *n, K* and τ_0 values ranged from 0.97 to 1.45, 0.0013 to 0.1188 and 0.001 to 0.068, respectively. Pomegranate juice exhibited a slight shear-thickening behavior because the values of flow behavior index (n) (especially at 12, 22 and 32 Brix) were more than 1 but, at Brix 42 and 52, flow indices are close to 1. As well, the representative curves of shear stress versus shear rate for pomegranate juice at 10–70°C and 12–52° Brix all indicate shear-thickening behavior (Figure

Table 1. Statistical results obtained for Herschel Bulkey model.

Concentration (°Brix)	T (°C)	$R^{2\,a}$	$MSE^{\,b}$	P ^{c} (%)
12	10	0.984	0.01601	9.61
	20	0.985	0.01410	9.54
	30	0.984	0.01830	8.31
	40	0.984	0.02000	11.03
	50	0.989	0.01540	6.34
	60	0.983	0.02412	10.49
	70	0.986	0.02105	8.81
22	10	0.994	0.00041	4.87
	20	0.993	0.00631	5.17
	30	0.991	0.00814	6.23
	40	0.989	0.01230	10.15
	50	0.986	0.01826	10.08
	60	0.981	0.02671	11.91
	70	0.980	0.02634	12.84
32	10	1.000	0.00010	0.66
	20	1.000	0.00012	0.84
	30	1.000	0.00054	2.39
	40	0.997	0.00325	3.47
	50	0.991	0.00957	6.92
	60	0.983	0.01920	10.07
	70	0.983	0.02610	10.61
42	10	1.000	0.00004	1.73
	20	1.000	0.00012	1.18
	30	0.999	0.00093	3.52
	40	0.999	0.00046	1.54
	50	1.000	0.00012	1.31
	60	0.998	0.00157	3.69
	70	0.995	0.00431	5.10
52	10	1.000	0.00001	0.48
	20	1.000	0.00001	0.96
	30	1.000	0.00023	2.29
	40	0.999	0.00045	1.22
	50	1.000	0.00026	1.63
	60	0.996	0.00293	2.55
	70	0.999	0.00120	2.42

^{a} Coefficient of determination; ^{b} Mean Square Error, ^{c} Mean relative deviation modulus.

Table 2. Rheological parameters of Herschel-Bulkley model describing flow behaviors of pomegranate juices at different concentrations and temperatures.

Concentration (°Brix)	T (°C)	K^a (Pa s^n)	n^b	$\tau_0{}^c$ (Pa)
12	10	0.0074	1.18	0.044
	20	0.0076	1.17	0.064
	30	0.0053	1.23	0.062
	40	0.0033	1.31	0.049
	50	0.0026	1.34	0.002
	60	0.0018	1.40	0.020
	70	0.0013	1.45	0.040
22	10	0.0191	1.04	0.052
	20	0.0150	1.08	0.065
	30	0.0128	1.10	0. 3 0
	40	0.0053	1.25	0.020
	50	0.0031	1.34	0.046
	60	0.0028	1.34	0.040
	70	0.0028	1.33	0.030
32	10	0.0404	0.98	0.022
	20	0.0321	0.99	0.029
	30	0.0262	1.03	0.011
	40	0.0120	1.23	0.021
	50	0.0106	1.14	0.060
	60	0.0059	1.23	0.045
	70	0.0044	1.28	0.048
42	10	0.0750	0.97	0.051
	20	0.0573	0.99	0.032
	30	0.0478	1.00	0.068
	40	0.0317	1.02	0.021
	50	0.0273	1.03	0.001
	60	0.0231	1.04	0.042
	70	0.0189	1.05	0.025
52	10	0.1510	0.99	0.048
	20	0.1188	1.00	0.031
	30	0.0757	1.01	0.033
	40	0.0566	1.04	0.016
	50	0.0323	1.05	0.024
	60	0.0287	1.02	0.054
	70	0.0244	1.03	0.033

^{a} Consistency index (Pa s^n); ^{b} Flow behavior index, ^{c} Yield stress (Pa).

1). The apparent viscosity of the pomegranate juice varied with the shear rate. Figure 2 shows this variation for concentrations of 12 and 42° Brix at 70ºC temperature. It was observed that as the shear rate increased, the apparent viscosity increased, signifying the direct relationship existent between the two parameters. It was also observed that apparent viscosity increased at a faster rate at lower solid concentrations than at higher concentrations, which suggested the Shear-Thickening nature of juice at lower concentrations. However, the consistency index (K) decreased as temperature increased. Similar results have also been reported in other studies (Alpaslan and Hayta, 2002; Kaya and Beliba_glı, 2002).

Effect of Temperature on Viscosity of Pomegranate juice

Activation energy is necessary to move a molecule, and as the temperature increases

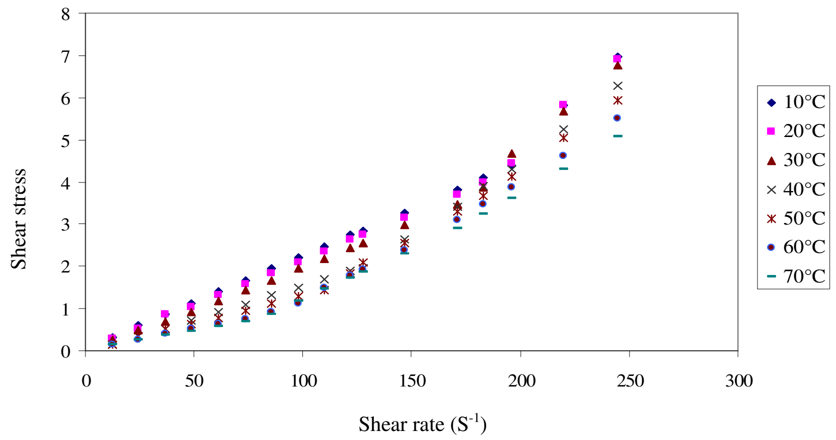
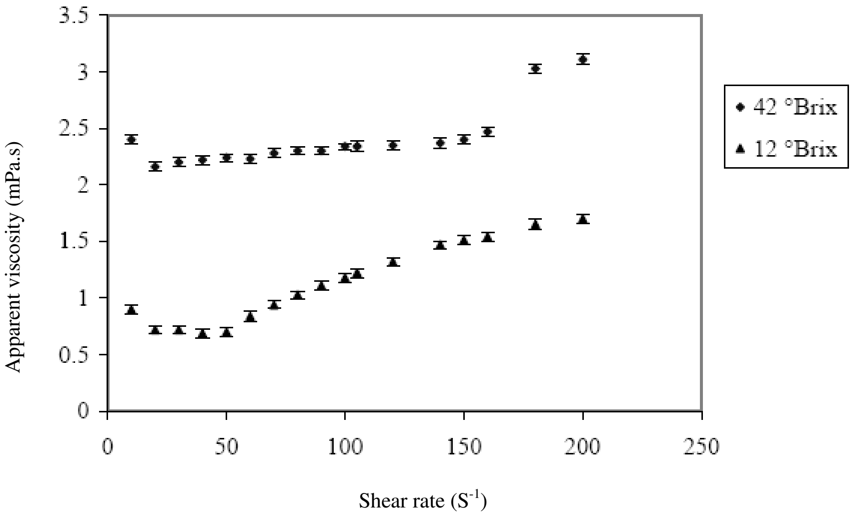


Figure 1. Effect of temperature on rheological behavior of pomegranate juice at 22° Brix.



the liquid flows more easily due to higher activation energy at high temperatures. Besides, Rha (1975) noted that the decrease in viscosity with increasing speed is related to the increasing alignment of constituent molecules. The effect of temperature on the apparent viscosity of pomegranate juice at a specified shear rate (48.9 s^{-1}) was determined by using the Arrhenius model (Costaldo, *et al.*, 1990; Vergnes and Villemarie, 1987):

$$\mu = \mu_o \exp\left(\frac{E_a}{R_g T_a}\right) \qquad (6)$$

Where, μ is the viscosity (Pa s), μ_o is a constant (Pa s), E_a is activation energy (kJ mol^{-1}), R_g is universal gas constant (8.314 kJ mol^{-1} K) and T_a is absolute temperature (K). Applying the linear regression analysis to Equation (6), values of E_a and μ_o were calculated. The Arrhenius equation parameters with correlation coefficients (R^2) and MSEs are given in Table 3. The activation energies of pomegranate juice varied from 9.07 to 24.05 (kJ mol^{-1}) at various concentration levels. As the juice concentration increased from 12 to 52º Brix, the activation energy increased. As it can be seen from the Figure 3, apparent viscosity was affected more by concentration at lower temperatures at 40 rpm. This tendency is similar to other clarified juices (Saracavos, 1970; Rao *et al.*, 1984; Ibarz *et al.*, 1992).

Table 3. Arrhenius model parameters for pomegranate juice at different concentrations at 40 rpm.

Concentration.	E_a^a (Kj mol^{-1})	$\mu_0 b$ (Pa.s)	R^2	MSE^c
12	9.07 ± 0.57	3.36×10^{-5}	0.977	0.0014
22	11.61 ± 1.07	1.84×10^{-5}	0.951	0.0049
32	13.88 ± 0.96	1.12×10^{-5}	0.977	0.0039
42	14.54 ± 0.89	1.37×10^{-5}	0.989	0.0022
52	24.05 ± 1.38	5.58×10^{-7}	0.980	0.0082

[a] Activation energy (kJ mol^{-1}); [b] Model constant (Pa s), [c] Mean Square Error.

Effect of Concentration on Consistency Coefficient

The effect of concentration on consistency coefficient could be described by either an exponential-type or a power-type relationship (Ibarz *et al.*, 1992). For a power-type relationship, the consistency coefficient varies with the concentration raised to a given power:

$$K= K_1C^{A1} \qquad (7)$$

For an exponential-type relationship, the function is exponential:

$$K=K_2 \exp (A_2C) \qquad (8)$$

In both equations, K_1 (Pa s^n), K_2 (Pa s^n), A_1 (dimensionless) and A_2 (dimensionless) are constants and C is the concentration expressed as °Brix. The experimental data were fitted to the linear form of Equations (7) and (8) by linear regression analysis to evaluate constants in Equations (7) and (8). Table 4 shows the parameters of the two equations at different temperatures. Based on the values of the R^2, *MSE* and *P*, the exponential model seems to describe better the effect of the soluble solids on the consistency coefficient of samples. These results were consistent with earlier findings reported for Gazıantep pekmez and tahin-pekmez (Kaya *et al.*, 2005; Arslan *et al.*, 2005). It can be observed from Table 4 that the K_1 decreases as the temperature increases. Also, from Figure 4, it is obvious that the effect of temperature on K is more pronounced at higher concentrations. According to Figure 4, with increase in temperature from 10 to70°C, the concentration dependency of K decreased.

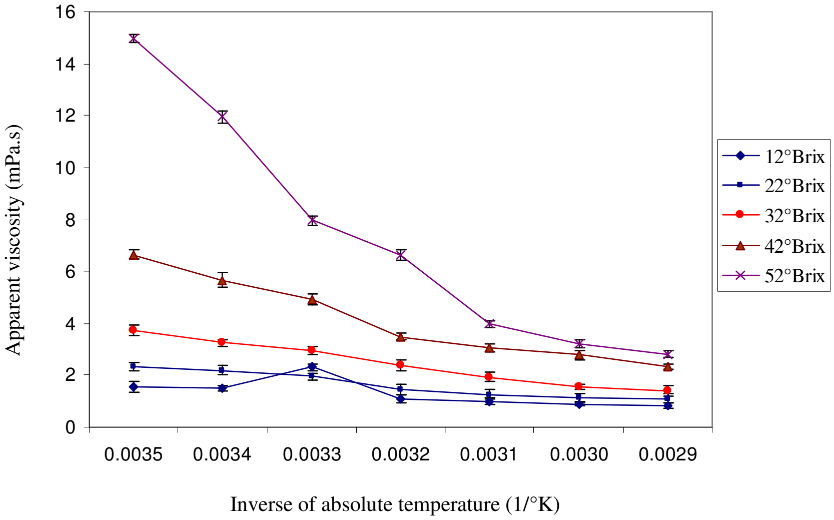


Figure 3. Arrhenius curve of pomegranate juice at different solid concentrations.

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Table 4. Effect of soluble solids on the consistency coefficient of samples at different temperatures.

T (°C)	Model: *K*= *K1* (CA1)				Model: *K*= *K2 exp* (A2C)			
	K1^a (Pa.s^n)	*A1*^{b}	R^2	*MSE*	*K2*^{a} (Pa.s^n)	*A2*^{b}	R^2	*MSE*^{c}
10	4.54×10-5	2.01± 0.159	0.981	0.0341	3.41×10-3	0.074±0.004	0.993	0.0121
20	6.57×10-5	1.83± 0.219	0.959	0.0643	3.38×10-3	0.068± 0.001	0.999	0.0021
30	5.22×10-5	1.82± 0.101	0.991	0.0135	2.74×10-3	0.066± 0.005	0.985	0.0223
40	1.85×10-5	1.97± 0.336	0.920	0.1512	1.19×10-3	0.075± 0.005	0.988	0.0218
50	1.51×10-5	1.91± 0.395	0.887	0.2091	9.40×10-4	0.072± 0.011	0.937	0.1156
60	8.29×10-6	2.01± 0.405	0.892	0.2201	6.30×10-4	0.076± 0.009	0.956	0.0896
70	6.14×10-6	2.06± 0.372	0.911	0.1859	5.00×10-4	0.077± 0.009	0.959	0.0859

^{a} Model constants (Pa s^n); ^{b} Model constants (Dimensionless), ^{c} Mean Square Error.

At temperatures of 10 and 20℃, with increasing concentration, *K* enhanced more drastically than other temperatures. However, at 70℃, *K* is independent of concentration or brix.

Effect of Concentration on Activation Energy

For a fixed temperature, flow activation energy depends on soluble solids content. The variation of activation energy with concentration can be described by several models (Giner *et al*., 1996). Two models (power law and exponential models) were used in this study:

$$E_a= A_1C^{B1} \quad (9)$$

and

$$E_a= A_2\exp (B_2C) \quad (10)$$

Where, *C* is the concentration expressed as °Brix and A_1, A_2, B_1 and B_2 are constants. The values of *Ea* and their respective concentrations were fitted to Equations (9) and (10) by the least square methods to obtain the estimates of the parameters of the model. The parameters calculated for these models are given in Table 5. It was found that the exponential model was able to describe better the dependency of E_a on soluble solids content. Also, other studies showed that exponential model could describe dependency of E_a on soluble solids content in Gaziantep pekmez and tahin-pekmez blends (Kaya *et al*., 2005; Arsalan *et al*., 2005)

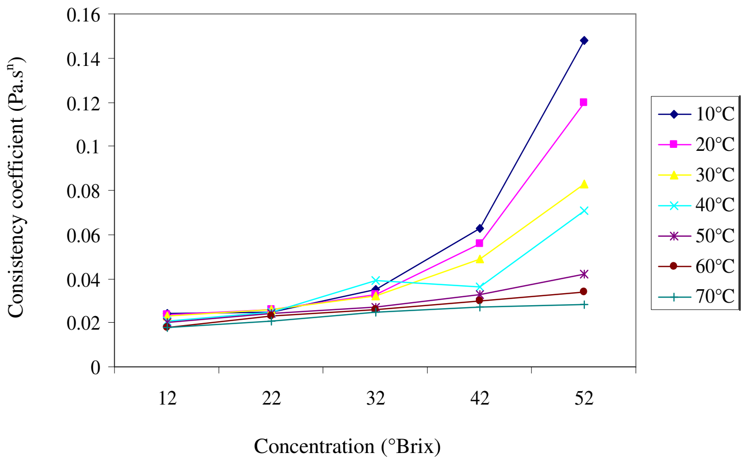

Figure 4. Effect of concentration on consistency coefficient of pomegranate juice.

Table 5. Influence of the soluble solids on the activation energy of flow.

Model	A^a	B^a	R^2	MSE^b
$E_a= A_1C^{B_1}$	3.86	0.41 ± 0.16	0.688	0.0342
$E_a= A_2\exp(B_2C)$	8.94	0.016 ± 0.005	0.818	0.0199

[a] Model constants, [b] Mean Square Error.

Table 6. Combined effect of concentration and temperature on viscosity.

Model[a]	K	D	E_a^b (kJ mol^{-1})	R^2	MSE^c
$K = K_3 \exp(D_1C + \frac{E_a}{R_gT})$	5.06×10^{-8}	0.072 ± 0.0025	26.49 ± 1.45	0.973	0.0451
$K = K_4C^{D2} \exp(\frac{E_a}{R_gT})$	7.58×10^{-10}	1.95 ± 0.1	26.48 ± 2.09	0.944	0.0943

[a] K_3 and K_4, D_1 and D_2 model constants; [b] Activation energy (kJ mol^{-1}), [c] Mean Square Error.

Combined Effect of Temperature and Concentration

For practical engineering applications, it is useful to obtain a simple equation describing the combined effect of temperature and concentration on pomegranate juice consistency coefficient. From the results obtained, the following equations are proposed (Ibarz *et al*., 1992):

$$K = K_3 \exp(D_1C + \frac{E_a}{R_gT}) \tag{11}$$

and

$$K = K_4C^{D2} \exp(\frac{E_a}{R_gT}) \tag{12}$$

Where, K_3, K_4, D_1 and D_2 are constants of the models. Parameters of Equations were obtained by multiple linear regressions and are presented in Table 6. From the results obtained, it seems that equation (11) describes better the combined effect of temperature and concentration. Therefore, for the interval of concentrations and temperatures used, a single equation is proposed to describe the viscosity of clarified pomegranate juice:

$$K = 5.6\times10^{-8} \exp(0.0723C + \frac{3186}{T}) \tag{13}$$

Kaya and Beliba_glı (2005) proposed a similar equation for describing the combined effect of temperature and soluble solids content on the Gaziantep pekmez.

CONCLUSIONS

Pomegranate concentrate and diluted samples followed the Herschel-Bulkley model and showed slight shear thickening behavior. The activation energy values increased with increasing soluble solids concentration and apparent viscosity was affected more by concentration at lower temperatures. The effect of soluble solids on viscosity was best described by an exponential model and with increase in temperature from 10 to70°C, the concentration dependency of *K* decreased. A single equation was formulated to show the combined effect of soluble solids and temperature on consistency coefficient.

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مدل سازی ویژگیهای رئولوژی آب انار (*Punicia granatum* L.) "ملس یزدی"

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چکیده

خصوصیات جریانی و پارامترهای رئولوژیکی آب انار (*Punica granatum L.*) واریته ملس با استفاده از ویسکومتر چرخشی در دماها (°C ۱۰، ۲۰، ۳۰، ۴۰، ۵۰، ۶۰ و ۷۰) و غلظتهای (۱۲، ۲۲، ۳۲، ۴۲ و ۵۲ درجه بریکس) مختلف مورد بررسی قرارگرفت. داده‌های تجربی با بیشترین برازش از مدل هرشل بالکی پیروی کردند و شاخص جریان(n) در تمام دماها و غلظتها بین ۰/۹۷ و ۱/۴۵ قرار داشت که نشان دهنده ماهیت غلیظ شونده با برش آب انار این واریته می باشد. انرژی اکتیواسیون جریان (E_a) با درنظرگرفتن ویسکوزیته ظاهری در ۴۰rpm محاسبه شد و با افزایش بریکس از ۱۲ به°Brix ۵۲ مقدار آن از ۹/۰۷ به kJ/mol ۲۴/۰۵ افزایش یافت. معادله توانی نشان داد که ضریب قوام با افزایش غلظت مواد جامد محلول بصورت غیر خطی افزایش می یابد. برای شرایط بررسی شده مدل ریاضیکه تاثیر دما و مواد جامد محلول را بر ضریب قوام نشان می دهد بطور مناسبی بدست آمد.

[DOR: 20.1001.1.16807073.2013.15.5.8.3]