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Rheological Properties of Pomegranate Juices

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Abstract. Flow behavior of juices of three varieties (Taifi, Banati and Manfaluti) of pomegranate fruit was determined with a concentric-cylinder rotational viscometer. All samples of pomegranate juices behaved as a non-Newtonian fluid at all concentrations (13.7-65.0°Brix) with the shear rate and temperature ranges 10-979 s^{-1} and 25-70°C, respectively. The power law equation ($\tau = K\gamma^n$) was suitable to describe the behavior of the various juices. The flow behavior index (n) was < 1.0 for all concentrations indicating a pseudoplastic (shear-thinning) behavior, the suitability of the power law equation to all experimental data was obtained. The results indicated that the apparent viscosity of pomegranate juices decreased as the temperature was increased. Consistency index of juices was significantly ($P < 0.001$) different for the various pomegranate fruit. The consistency index decreased as concentration decreased and temperature increased.

Introduction

Rheology of fluid is concerned with the flow and deformations of such materials. Obtaining a knowledge of reliable rheological properties of fluid foods is very important because of their influence on processing operations such as those involving heat transfer (heating and cooling), mass transfer, pasteurization, homogenization, and concentration. In recent years, rheological properties of single strength and concentrated fruit juices have been reported [1,2,3,4]. Most of these studies, however, were mainly concerned with the effect of concentration and temperature on the rheological properties of fruit juices under investigation. Nonetheless, earlier studies on rheological properties and flow behaviors of fluid foods have been reviewed by Holdsworth [5], Rao [6], and Rao *et al.* [7].

Temperature is an important factor affecting apparent viscosity of fluid foods and its effect must be understood since many rheological parameters including apparent viscosity are affected by temperature. Most fluid foods are essentially exposed to different temperatures during processing. It is therefore, necessary to control the temperature of fluid foods under study and to report the test temperature.

Very scarce information is available on rheological properties of pomegranate fruit juice. These properties are especially useful in the food industry in determining processing parameters such as piping design and the pumping requirements for a fluid transport system. The objectives of this work were to determine the flow curves for juices of three different pomegranate fruit varieties and to determine the effect of temperature, concentration, and variety on rheological parameters of pomegranate fruit juices.

Materials and Methods

The fruit

Pomegranate fruit varieties used in this work included Taifi, Banati, and Manfaluti. Healthy fruits were obtained from Agricultural Research and Experiment Station at King Saud University during the 1992 growing season. Fruits were stored in a cold room at 5°C and 90-95% r.h. for two weeks.

The preparation of single strength juices

For the preparation of fresh juices, approximately 35, 45 and 50 Kg of fully ripe fruit samples of the varieties Taifi, Banati, and Manfaluti, were respectively selected, peeled and separated into peel and edible portions. The edible portions were separately weighted and were used for the extraction of single strength juices using an electric extractor (Moulinex, type 140.6.03). Extracted juices were immediately filtered through one layer of cheese cloth. At the end of the extraction process, juices were also passed through three layers of the cloth and weighted as final extracts. Total solids (TS) and densities (ρ) of fresh juices were as follows: 13.7°Brix and 1.032 (g/cm^3) for Taifi, 16.7°Brix and 1.042 (g/cm^3) for Banati, and 15.0°Brix and 1.034 (g/cm^3) for Manfaluti.

The preparation of concentrations

Parts of the pomegranate fruits extracts were concentrated by evaporation using a climbing film evaporator designed to operate as either a batch or continuous evaporator (Climbing film and Natural Circulation Evaporator, Corning Process Systems, Stone, England). In the system, about 12, 16 and 17 Kg of extract samples from the three pomegranates passed up into the calandria where the volatile component (water) was vaporized. The vapors rising up the calandria and so doing pulled a thin turbulent film of liquid up the calandria wall. The conditions of the evaporation process were as follows: operating vacuum = 0.6 bar gauge, water pressure = 1.5 bar gauge, steam pressure = 1.5 bar gauge, feed flow rate = 0.5 l/min, feed inlet temperature = 40°C.

Feed outlet temperatures were 64, 58, and 65°C for Taifi, Banati, and Manfaluti, respectively. The highest concentrations obtained for the three pomegranates were 69.3, 73.6, and 77.9°Brix, respectively. Juices of intermediate concentrations were prepared by diluting highest concentrations with the water collected in the receiver in the evaporator. These concentrations were 13.7, 25, 45, and 65°Brix for Taifi, 16.7, 25, 45, and 65°Brix for Banati, and 15.0, 25, 45, and 65°Brix for Manfaluti.

Rheological measurements and calculations

The rheological properties of the fresh juices and concentrated samples were measured with a concentric-cylinder rotational viscometer (HAAKE, Type VT 181, Karlsruhe, Berlin, Germany). The viscometer was connected to both a heating bath circulator and a frequency converter to make up an integrated system as described by Hassan [1]. It allows the continuous measurements of the shear stress (torque)-shear rate (angular speed) data. In the apparatus, each sample was placed into the annular spaces between the two concentric cylinders of a sensor system, while the inner cylinder was rotating at a defined speed the torque required was measured. Sensor systems used were the system NV for fresh juices and low-viscosity concentrations and the systems MVI, MVII, and MVIII for higher concentrations. The speed of the rotating inner cylinder ranged between 5.6 and 181 rpm with the capability to alternate between two fixed rotor speeds which differ by their 1:4 ratio. Temperatures used in this work were 25, 40, 50, 60, and 70°C. The temperature of the sample was kept constant using the heat bath circulator.

Fluid foods exhibit two types of behavior, namely Newtonian and non-Newtonian. Newtonian fluids normally obey Newton's law of viscosity which is defined by the following equation:

$$\tau = \mu \gamma \tag{1}$$

where τ is the shear stress (N m^{-2}), γ is the shear rate (s^{-1}), and μ is the viscosity (N s m^{-2}). Fluids that are not obeying Newton's law of viscosity are called non-Newtonians and are described by the following power law equation:

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

where K is the consistency index (N s^n m^{-2}), and n is the flow behavior index (dimensionless). The rheological parameters K and n can be determined by plotting the logarithm of shear stress versus the logarithm of shear rate on ordinary paper. The slope of the best fit line gives the flow behavior index (n). The consistency index (K) is obtained from the intercept.

Results and Discussion

The flow curves

The relationships between shearing stress (τ) and rate of shear (γ) are shown in Figs. 1-3. The results indicated a pronounced curvilinear relationship for most concentrations of pomegranate juices within the temperature range 25-70°C. At the 65°Brix concentration level of Taifi and Manfaluti pomegranates and at the temperature of 25°C, the relationship between shear stress and shear rate was very close to a linear relationship. The concentrated Banati juice at the concentration level of 65°Brix and within the temperature range 25-70°C had a more pronounced linear relationship particularly at temperature 25°C. This result was similar to the relationship of higher concentrations i.e. 65 and 78°Brix of a date water extract at the temperature range 24.8-69.5°C [1]. The results also indicated a decrease in the shear stress as the temperature increased for all juice concentrations of the various pomegranate fruit.

The regression analysis were performed to determine the flow behavior index (n) and the consistency index (K) of equation (2). The results were summarised as functions of variety, temperature, and concentration in Table 1. The flow behavior index (n) of the power law equation was less than 1.0 for all concentrations indicating a pseudoplastic (shear-thinning) behavior and the acceptability of the power law equation to all experimental data obtained.

Effect of temperature, concentration and variety on rheological parameters

The effect of temperature on the apparent viscosity of Taifi, Banati, and Manfaluti pomegranate fruit juices at different concentrations and at different shear rates are shown in Figs. 4-6.

The viscosities of all juices were calculated at selected shear rates within the shear rate range 10-969 (s^{-1}) and at the temperature range 25-70°C.

As shear-thinning (pseudoplastic) fluids, pomegranate juices exhibited a decrease in apparent viscosity with increasing shear rate. At the shear rate 10 (s^{-1}),

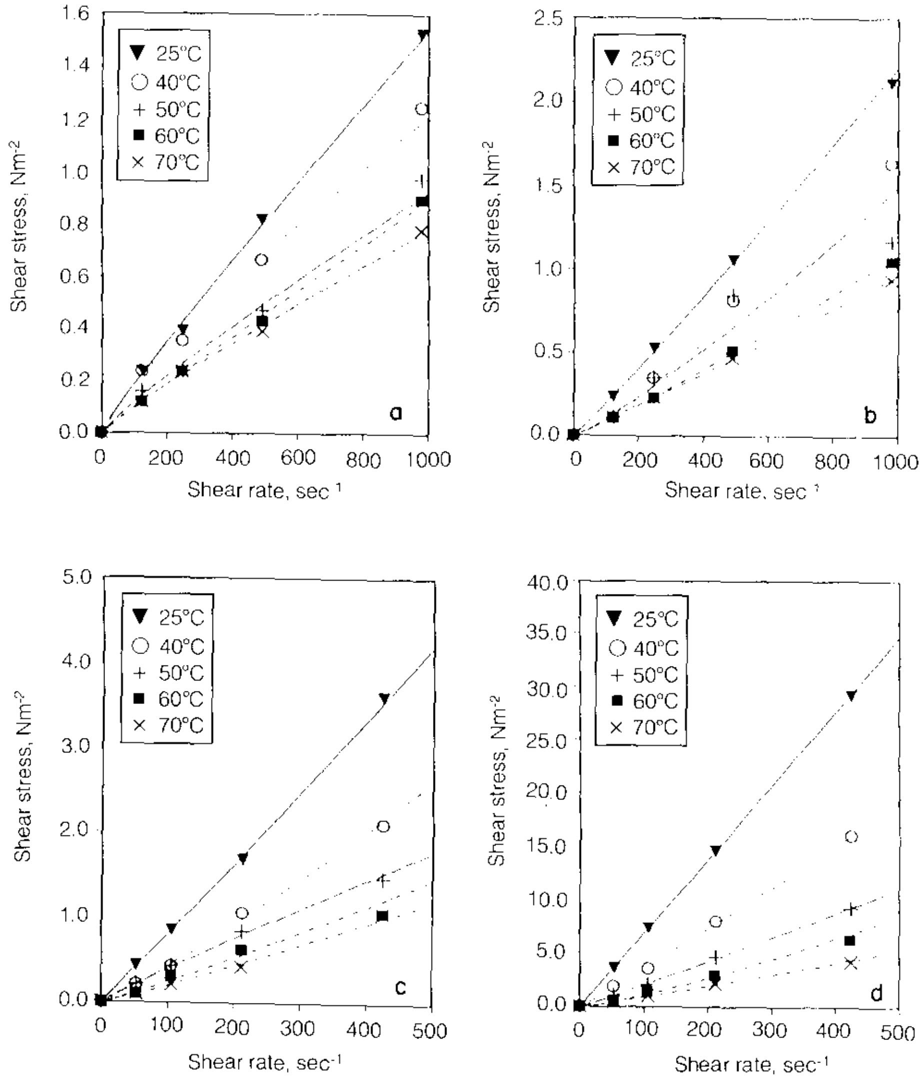

Fig. 1. Relationships of shear stress (τ) vs. shear rate (γ) of Taifi pomegranate juices: (a) 13.7°Brix; (b) 25°Brix; (c) 45°Brix; and (d) 65°Brix.

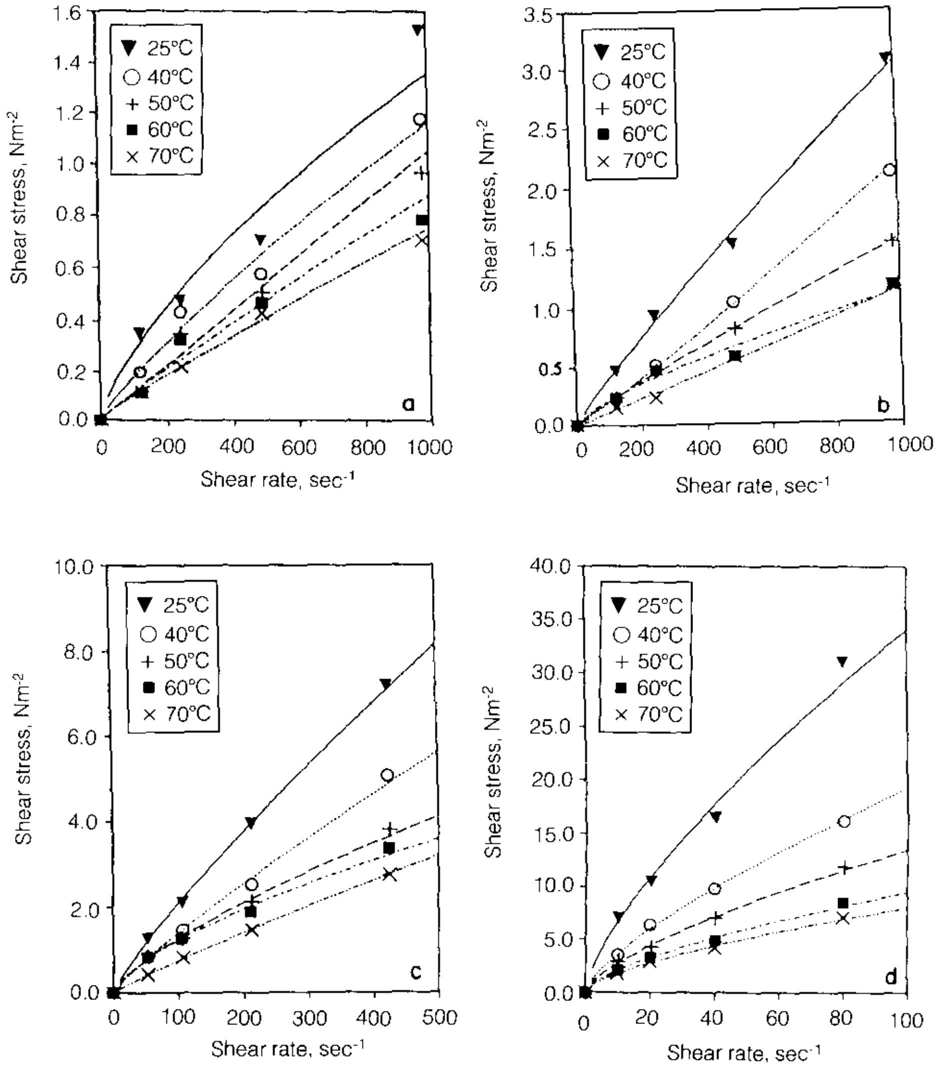

Fig. 2. Relationships of shear stress (τ) vs. shear rate (γ) of Banati pomegranate juices: (a) 16.7°Brix; (b) 25°Brix; (c) 45°Brix; and (d) 65°Brix.

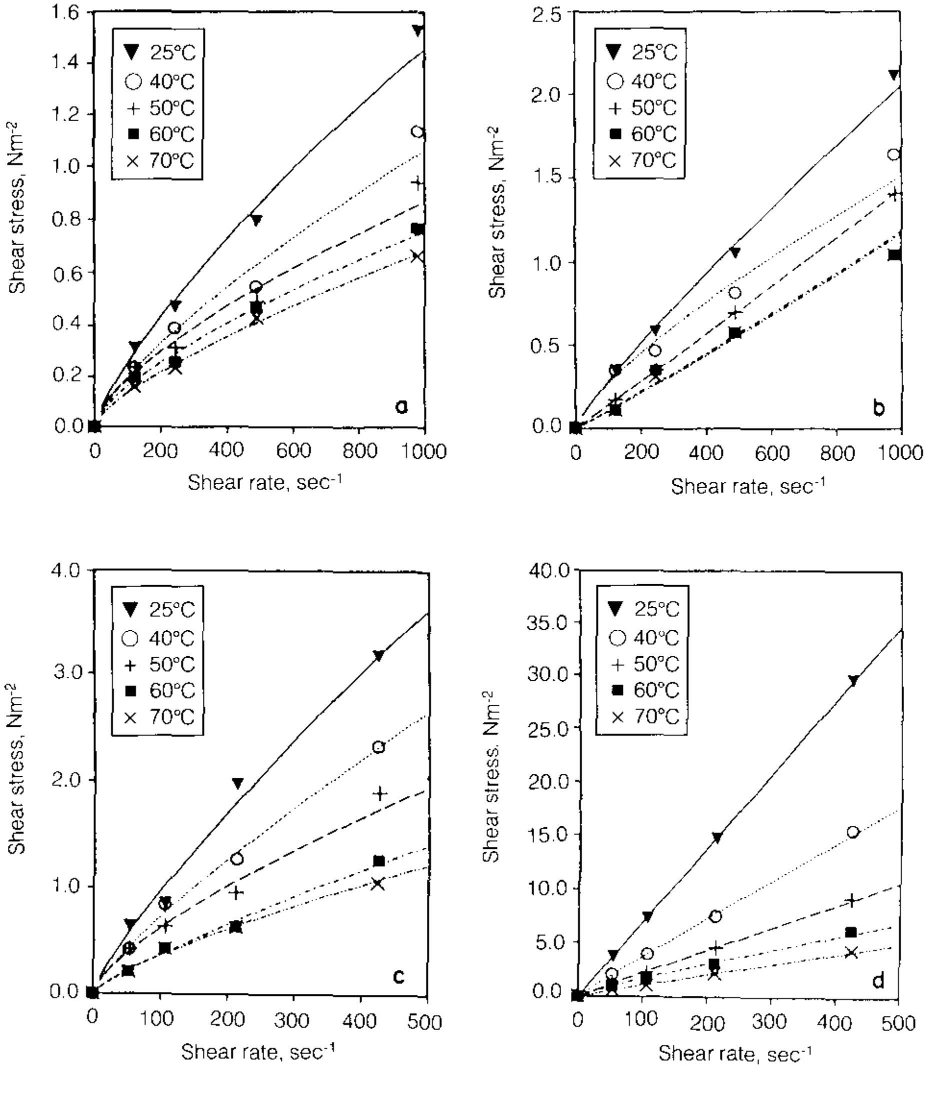

Fig. 3. Relationships of shear stress (τ) vs. shear rate (γ) of Manfaluti pomegranate juices: (a) 15.0°Brix; (b) 25°Brix; (c) 45°Brix; and (d) 65°Brix.

Table 1. Mean values of the flow behavior index (n), the consistency index (*K*), and the correlation coefficients (R^2) for juices of pomegranate fruits

Fruit	Temperature (°C)	Concentration (°Brix)	n	*K* ($N\,s^n\,m^{-2}$)	R^2
Taifi	25	13.7	0.796	5.581×10^{-3}	0.99
	40		0.791	5.027×10^{-3}	1.00
	50		0.780	3.778×10^{-3}	0.99
	60		0.777	3.443×10^{-3}	0.99
	70		0.775	3.282×10^{-3}	0.99
	25	25.0	0.803	6.678×10^{-3}	0.99
	40		0.790	4.749×10^{-3}	0.99
	50		0.784	4.132×10^{-3}	0.99
	60		0.779	3.630×10^{-3}	0.99
	70		0.777	3.477×10^{-3}	0.99
	25	45.0	0.842	1.8×10^{-2}	0.99
	40		0.823	1.1×10^{-2}	0.99
	50		0.817	9.623×10^{-3}	0.99
	60		0.804	6.845×10^{-3}	0.99
	70		0.797	5.760×10^{-3}	0.99
	25	65.0	0.912	1.07×10^{-1}	1.00
	40		0.891	6.3×10^{-2}	0.99
	50		0.873	4.0×10^{-2}	0.99
	60		0.857	2.6×10^{-2}	0.99
	70		0.847	2.0×10^{-2}	0.99
Banati	25	16.7	0.798	6.107×10^{-3}	0.99
	40		0.799	4.833×10^{-3}	0.99
	50		0.781	3.923×10^{-3}	0.99
	60		0.779	3.741×10^{-3}	0.99
	70		0.774	3.238×10^{-3}	0.99
	25	25.0	0.819	1.0×10^{-2}	1.00
	40		0.803	6.614×10^{-3}	0.99
	50		0.797	5.799×10^{-3}	1.00
	60		0.792	5.133×10^{-3}	0.99
	70		0.784	4.202×10^{-3}	0.99

Table 1. (Continued)

Fruit	Temperature (°C)	Concentration (°Brix)	n	K ($N\,s^n\,m^{-2}$)	R^2
Banati	25	45.0	0.871	3.8×10^{-2}	1.00
	40		0.858	2.7×10^{-2}	1.00
	50		0.852	2.4×10^{-2}	0.99
	60		0.850	2.3×10^{-2}	0.99
	70		0.838	1.6×10^{-2}	1.00
	25	65.0	0.974	5.34×10^{-1}	0.99
	40		0.954	3.17×10^{-1}	0.99
	50		0.943	2.40×10^{-1}	0.99
	60		0.932	1.85×10^{-1}	0.99
	70		0.926	1.57×10^{-1}	0.99
Manfaluti	25	15.0	0.799	6.099×10^{-3}	1.00
	40		0.789	4.839×10^{-3}	0.99
	50		0.785	4.348×10^{-3}	0.99
	60		0.780	3.846×10^{-3}	0.99
	70		0.776	3.432×10^{-3}	1.00
	25	25.0	0.806	7.407×10^{-3}	1.00
	40		0.800	6.374×10^{-3}	0.99
	50		0.790	4.870×10^{-3}	0.99
	60		0.783	4.042×10^{-3}	0.99
	70		0.783	4.042×10^{-3}	0.99
	25	45.0	0.844	1.9×10^{-2}	0.99
	40		0.835	1.5×10^{-2}	1.00
	50		0.828	1.3×10^{-2}	0.99
	60		0.813	8.829×10^{-3}	1.00
	70		0.811	8.447×10^{-3}	1.00
	25	65.0	0.913	1.09×10^{-1}	1.00
	40		0.892	6.5×10^{-2}	1.00
	50		0.875	4.2×10^{-2}	1.00
	60		0.864	3.2×10^{-2}	1.00
	70		0.851	2.3×10^{-2}	0.99

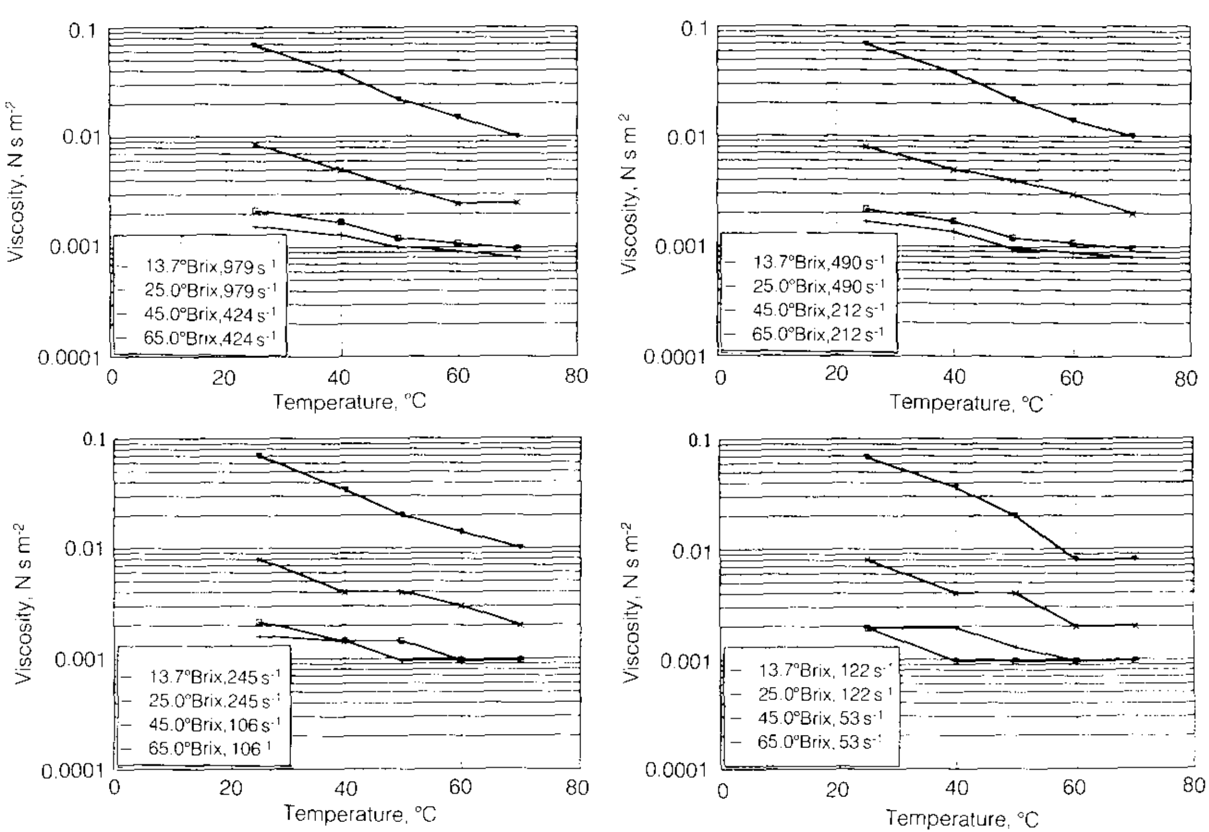

Fig. 4. Effect of temperature on viscosity of Taifi pomegranate juices at different shear rates.

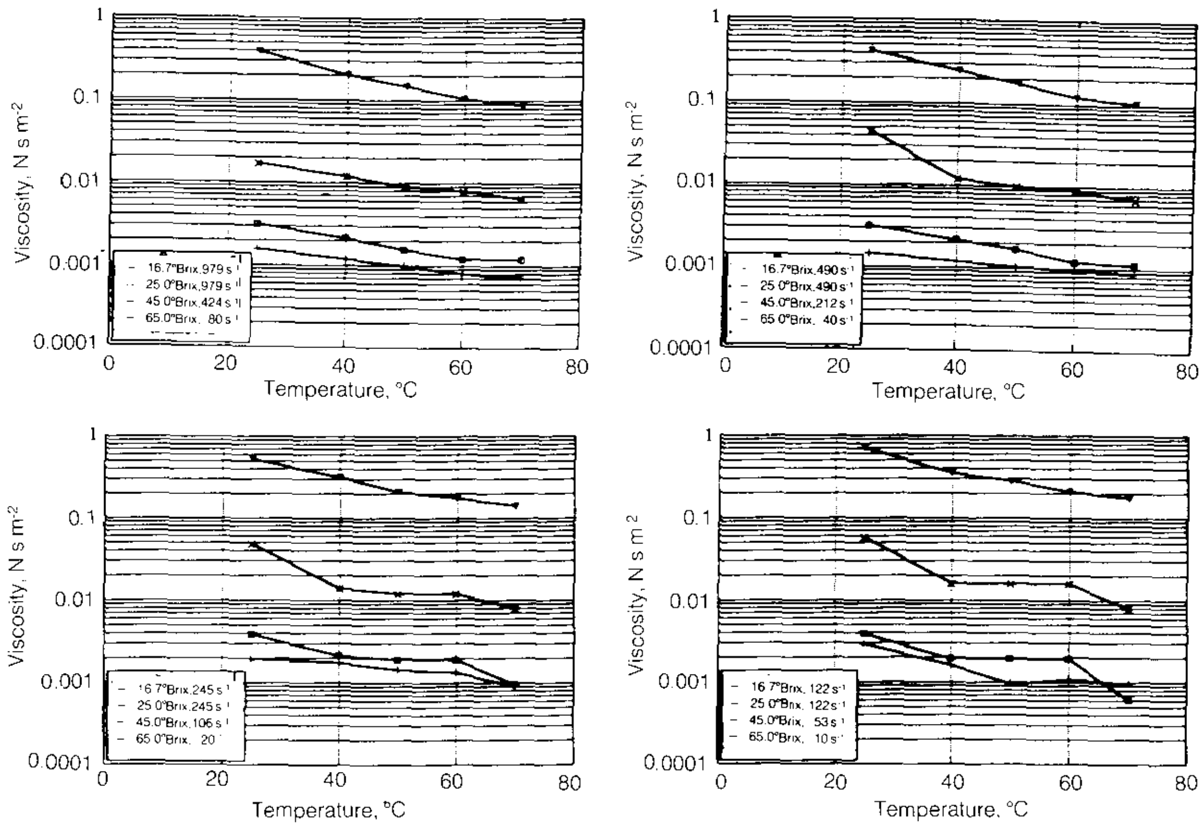

Fig. 5. Effect of temperature on viscosity of Banati pomegranate juices at different shear rates.

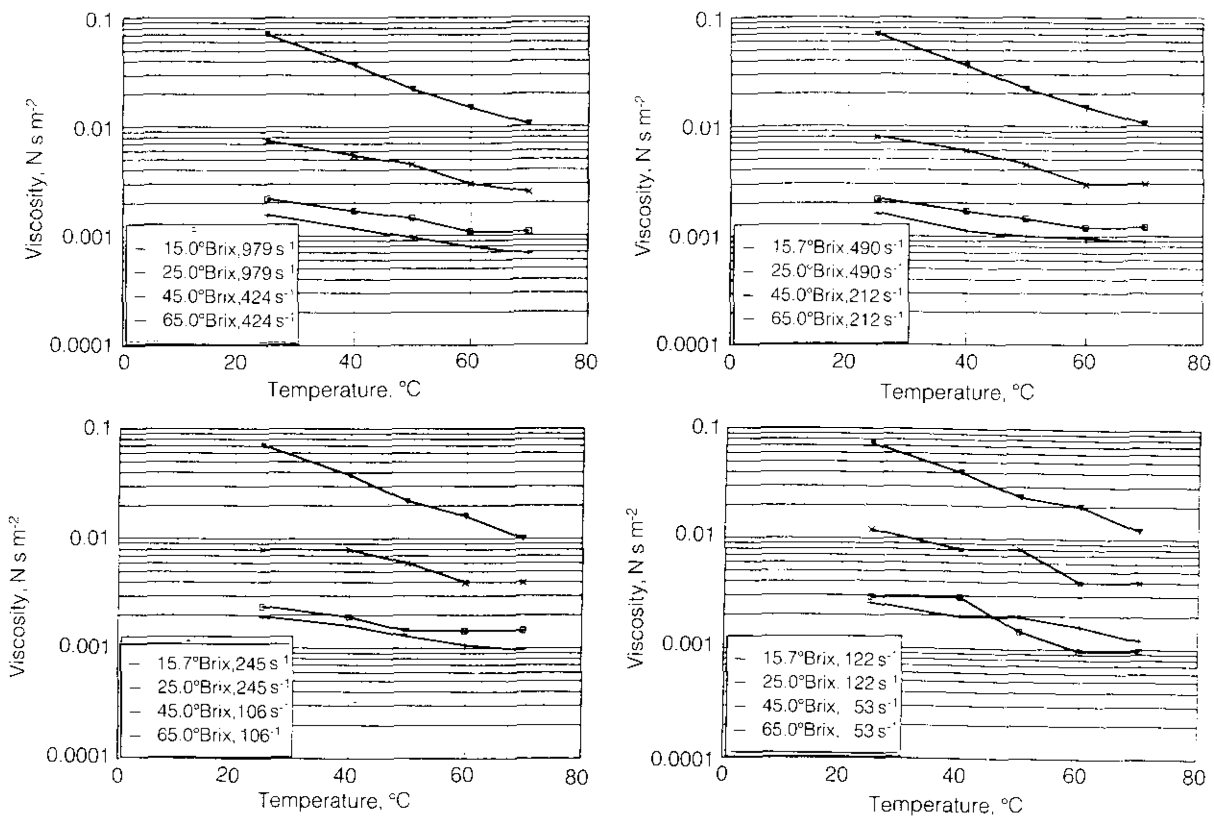

Fig. 6. Effect of temperature on viscosity of Manfaluti pomegranate juices at different shear rates.

the apparent viscosities of the 65°Brix Banati juice were 0.704 (N s m^{-2}) at 25°C and 0.176 (N s m^{-2}) at 70°C. At the shear rate 53 (s^{-1}), the apparent viscosities of the 65°Brix Taifi and Manfaluti juices were 0.070 and 0.072 (Ns m^{-2}) at 25°C, and 0.010 and 0.012 (Ns^n m^{-2}) at 70°C, respectively. The results indicated that the apparent viscosity of pomegranate juices decreased as the temperature was increased.

The effect of temperature and concentration on the consistency index (*K*) was also studied, Figures 7-8 shows the effect of concentration on consistency index of Taifi, Banati, and Manfaluti juices at different concentrations and at temperature 25°C and 70°C. At both temperatures, the magnitudes of consistency index for Banati juices at all concentrations were the highest and for Taifi juices at all concentrations were the lowest. Consistency index of juices decreased as concentration decreased and temperature increased. The multiple comparison procedure (Duncans' test) was used to test the consistency index. The analysis indicated that there was a significant difference ($P < 0.05$) between the Taifi and the Banati pomegranate juices and between the Manfaluti and the Banati pomegranate juices (Table 2).

Conclusions

The quantitative characterization of the rheological properties of fluid foods from the shear rate-shear stress data is of particular interest in process design, quality control, and consumer acceptability. The effect of temperature and concentration on apparent viscosity can be very useful in the concentration of fluid foods. The consistency index is used as a quality control parameter. Based on results of this study, the following summarizes the main conclusions:

1. A curvilinear relationships were found between the shear stress (τ) and rate of shear (γ) for most concentrations of pomegranate juices within the temperature range 25-70°C.
2. The shear stress was decreased as the temperature increased for all juice concentrations of the various pomegranate fruit.
3. The pomegranate juice behaved as a non-Newtonian fluid at all concentrations with the temperature range 25-70°C.
4. There was a decrease in the apparent viscosity of pomegranate juices with increasing temperature.
5. The consistency index of juices was decreased as concentration decreased and temperature increased.

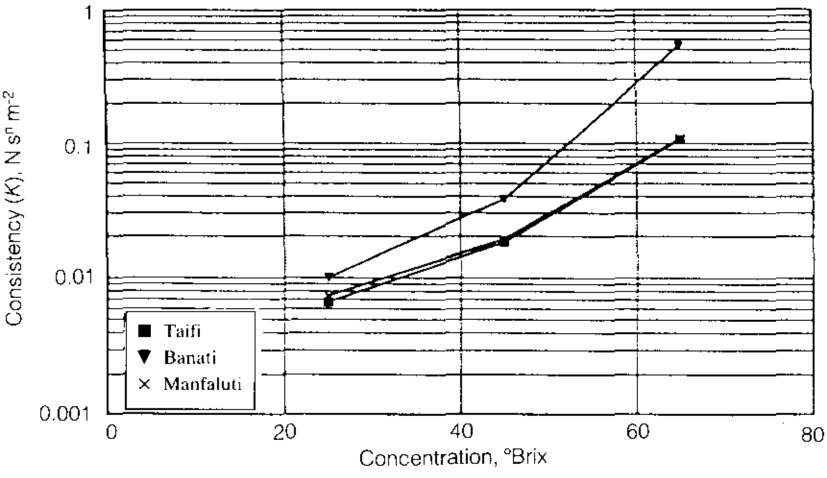

Fig. 7. The relationship between consistency and concentration for various pomegranate juices at 25°C.

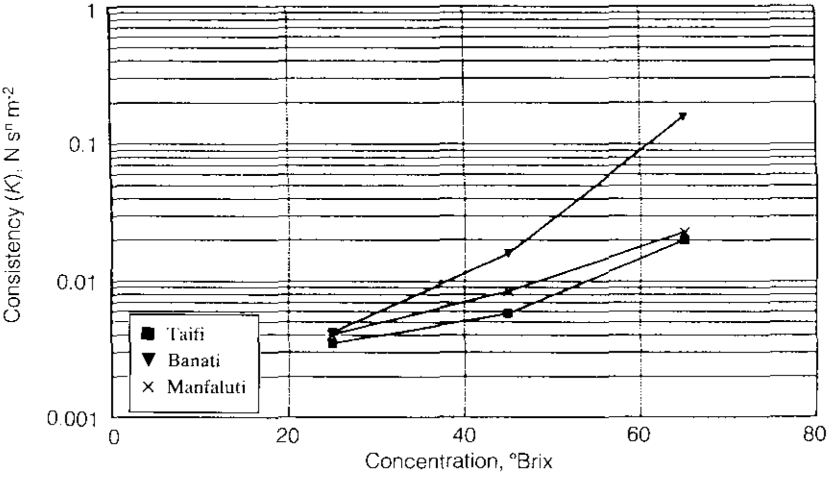

Fig. 7. The relationship between consistency and concentration for various pomegranate juices at 70°C.

Table 2. Effect of variety on consistency index (*K*) at different juice concentrations

Fruit	Concentration, °Brix 25	45	65
Taifi	0.0045	0.0102	0.0512
Banati	0.0063	0.0256	0.2866
Difference	-0.0018*	-0.0154*	-0.2354*
Manfaluti	0.0053	0.0129	0.0542
Banati	0.0063	0.0256	0.2866
Difference	-0.0010*	-0.0127*	-0.2324*

*denotes a statistically significant difference at 5% level.

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الخصائص اللزوجيّة لعصيرات الرمـــان

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ملخص البحث. تمت دراسة سلوك الدفق لعصيرات ثلاثة أنواع من الرمان (الطائفي، البناتي، والمنفلوطي) باستخدام جهاز قياس لزوجة دوراني ذو اسطوانات متداخلة. تشير نتائج هذه الدراسة إلى أنه في حدود تركيزات المستخلصات (١٣,٧-٠ , ٦٥° بركس)، وحدود معدلات القص (١٠-٩٧٩ ثانية$^{-1}$)، وحدود درجات الحرارة (٢٥-٧٠°م) كان سلوك الدفق لعصيرات الرمان سلوكًا غير نيوتوني. وقد وُجد أن معادلة قانون الأس ($\tau = k \gamma^n$) مناسبة لوصف سلوك العصيرات المختلفة. كما تدل قيم دليل سلوك السريان (n) في حدود أقل من ١ أن السلوك غير النيوتوني هو من النوع شبه بلاستيكي. ولقد وُجد أيضًا أن تأثير درجة الحرارة على اللزوجة الظاهرية لعصيرات الرمان كان واضحًا في خفض اللزوجة بارتفاع درجة الحرارة، بينما كان دليل التماسك (K) مختلفٌ اختلافًا معنويًّا بالنسبة لأنواع الرمان الثلاثة.