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Rheological Behavior of Mango Juice throughout the Production Process

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Abstract*: The need for studying the flow behavior of the treated juice in the three main parts of the process (After mixing, after Pasteurization and after cooling) is essential in predicting the pumping power requirement. In the present paper, the rheological properties of mango juice are determined at the end of three steps in the production line: First, after the mixing step, second after homogenization and finally after cooling. The following properties determined, Brix concentration, Acidity of solution, and the rheological properties. Mixed juice showed Bingham behavior with values of yield stress decreasing with increased temperature. The activation energy was determined to equal about 24 kJ.mol^{-1}. Samples collected after the homogenization step exhibited shear thinning behavior with an almost constant flow index of 0.525. The activation energy was determined as 10.93 kJ.mol^{-1}. The juice samples collected from that step exhibited a mild thixotropic behavior. The results of the third step involving cooling of the homogenized juice revealed that the liquid reverted to Bingham behavior with values of consistency index decreasing with increased temperatures. The calculated activation energy equals 11.22 kJ.mol^{-1}.

***Keywords:* Pasteurization, homogenization, rheology, activation energy, shear thinning, thixotropy.**

I. INTRODUCTION

Juice production schemes can differ depending on whether the starting point is production from juice concentrate or juice fruit. Also, the scheme differs based on the required juice product, whether it is required to produce cloudy juice, juice with pulp or clear juice from concentrate or puree [1]

Juice produced could vary in fruit content and type as per the following table:

Table-I: Fruit juice types

Juice type	Description
100% Fruit Juice	Pure juice coming from fruit without any additive
Juice Nectar	Contain specific percentage of juice solid (30-50)%
Fruit Drink	The fruit content is not less than 10% and not more than 25%
Artificial Fruit Drink	Fruit content is less than 10%.

Different technologies are adopted while manufacturing juice in terms of the equipment used and the operating conditions. A common method of production of juice is by Pasteurization. First, proper selection of the fruit is necessary, followed by washing in chlorinated water.

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In particular, mango fruits are reduced to a pulp that is next pressed to extract the juice. Following is a filtration step where the clear liquid is collected as filtrate. Peptic enzymes are often added to accelerate that step. The filtered juice is thoroughly mixed to reach homogeneity. The next step is Pasteurization at about 90ºC for 20 to 40 minutes. This step serves in killing the bacteria present in juice and also assists in further homogenization. The processed homogeneous liquid is then cooled down to temperatures ranging from 10 to 18ºC in case of mango juice [2]. The need for studying the flow behavior of the treated juice in the three main parts of the process (After mixing, after Pasteurization and after cooling) is essential in predicting the pumping power requirement. In this connection, several authors have studied the rheology of different fruit juices. In this connection, Ibarz et al published a set of papers investigating the rheological properties of different fruit juices. For example, orange juice rheological behavior was studied over the temperature range 5 – 70ºC with sugar concentrations ranging from 30.7 to 60.5ºBrix [3]. A concentric disk viscometer was used for this purpose. They deduced that under all conditions, the flow was Newtonian with an activation energy ranging from 14.7 to 40 kJ.mol^{-1} according to the concentration. A similar result was obtained by Kar et al [4] on investigating orange juice as the flow was found to be Newtonian with viscosities ranging from 3 to 12 cP depending on concentration and temperature. The activation energies obtained varies, according to Brix number, from 15.5 to 19.6 kJ.mol^{-1}.

In a comprehensive paper, Diamante et al [5] reviewed the different constitutive equations governing the flow behavior of a large number of fruit juices. The general form of the constitutive equation is the Herschel – Bulkey equation (1):

$$\tau = \tau_0 + k.\dot{\gamma}^n \qquad (1)$$

Where: τ is the shear stress, Pa

τ_0 is the yield stress, Pa

$\dot{\gamma}$ is the shear rate s-1

k is a constant, known as the consistency factor

If $\tau_0 = 0$, the behavior is that of a power law fluid. It is shear thinning or thickening depending on whether $n < 1$ or $n > 1$ respectively.

If n = 1, the fluid is said to be of the Bingham type

Newtonian fluids have $\tau_0 = 0$ and $n = 1$.

They also set a table for the activation energy of most fruit juices at different sugar concentrations and temperatures. This important parameter indicates the extent to which viscosity depends on temperature.

It is calculated from an Arrhenius type equation (2):

$$\mu = K.e^{-\frac{E}{RT}} \qquad (2)$$

Where: K is a constant and R the general gas constant ($J.K^{-1}.mol^{-1}$)

The behavior of Mango juice reported in this paper referred to the work of Bhattacharya et al [6] who reported a flow behavior consistent with equation (1) at Brix 16° and temperatures in the range 25 to 60°C. They used a central composite design to follow the variation of shear stress with shear rate, temperature and percent pectinase enzyme added. In their work involving investigating the rheological behavior of mango juice, Singh et al [7] found out that flow data were better fitted by a Newtonian model rather than a power law. Their study involved a Brix range from 15 to 66° and temperatures in the range 15 to 85°C. They also reported an activation energy ranging from 6.35 to 35.3 $kJ.mol^{-1}$. On the other hand, Dak et al [8] used a torsion viscometer to follow up the flow behavior of "Kesar" mango juice at temperatures ranging from 20 to 70°C and at different solid concentrations. They reported a shear thinning behavior and activation energies in the range 3.8–13.7 $kJmol^{-1}$. More recently, Zhou et al [9] presented the first study that related the viscosity of mango juice to change in pressure during homogenization. They reported that this step has for effect to increase the apparent viscosity of the juice and affect its rheological properties, in particular its thixotropy.

In the present paper, the rheological properties of mango juice are determined at the end of three steps in the production line: First, after the mixing step, second after homogenization and finally after cooling.

II. MATERIALS AND METHODS

Samples of juice were collected after each of the three aforementioned steps from the production line of a juice factory located in a Cairo suburb and the following properties determined:

Brix concentration: This was determined in the factory's lab through determination of the refractive index of the juice [10].

Acidity of solution: A digital Mettler-Toledo pH meter with two decimals accuracy.

Rheological properties: A RST-CPS Brookfield cone and plate Rheometer was used having a digital display of the following parameters: Viscosity, rpm, shear rate, percent torque and shear stress.

III. RESULTS AND DISCUSSION

This journal uses double-blind review process, which means that both the reviewer (s) and author (s) identities concealed from the reviewers, and vice versa, throughout the review process. All submitted manuscripts are reviewed by three reviewer one from India and rest two from overseas. There should be proper comments of the reviewers for the purpose of acceptance/ rejection. There should be minimum 01 to 02 week time window for it.

A.Results following the mixing step

The analyses of the mango juice following the mixing step are presented in Table-II.

The effect of varying shear rate on shear stress was studied at two temperatures which represent the lower and higher commonly used limits. Figure (1) illustrates these relations. It can be seen that at both temperatures the behavior follows a Bingham fluid described by the following equations relating shear stress τ (Pa) to shear rate $\dot{\gamma}$ (s^{-1}).

At 10°C: $$\tau = 0.0185\,\dot{\gamma} + 0.468 \qquad (3)$$

At 18°C: $$\tau = 0.0156\,\dot{\gamma} + 0.298 \qquad (4)$$

Table-II: Analyses of mango juice following mixing at 18°C

Parameter	Value	Test Methods
Brix (°Bx)	14.776	Refractometer
pH	3.714	pH meter
Specific Gravity	1.0581	Pycnometer

As expected the increase in temperature from 10 to 18°C has had for effect to decrease the yield stress from 0.468 to 0.298 Pa and the (consistency index from 0.0185 Pa.s to 0.0156 Pa.s.

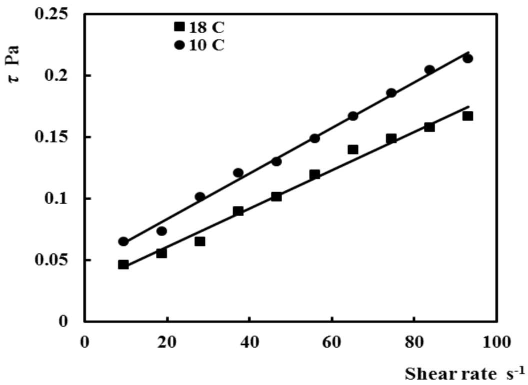

Fig. 1 Shear stress – shear rate diagram of mango juice after mixing

The corresponding curves for apparent viscosity (Pa.s) against shear rate are illustrated in Figure (2). Both curves clearly display asymptotic character approaching limiting values of viscosity at high shear rate. This is typically of Bingham fluids where the apparent viscosity approaches the value of consistency index at infinite shear rate.
Although two temperatures only were involved in studying the effect of temperature on viscosity, it was possible to calculate the value of E at different shear rates. The values were close enough to obtain an average activation energy of 24 $kJ.mol^{-1}$.

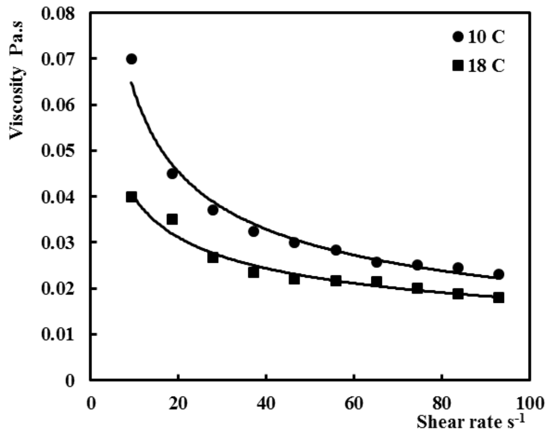

Fig. 2 Apparent viscosity – shear rate diagram of mango juice after mixing

Finally, it is worth mentioning that when the shear rate was decreased, the values of shear stress decreased and were almost identical at each shear rate to those obtained on increasing the shear rate. This reveals an absence of any thixotropic behavior during the mixing step.

B. Results following the homogenization step

Figure (3) reveals that a change in the pattern of rheological behavior of mango juice following the homogenizing step. Shear stress – shear rate curves were drawn over the industrially used temperature range (50 – 103°C). At all temperatures a shear thinning behavior was observed following the general expression:

$$\tau = k.\dot{\gamma}^{n} \ (n < 1) \qquad (5)$$

The values of k and n obtained at the minimum temperature in that range (50°C) were 27.23 Pa and 0.39 respectively. Otherwise, the value of the flow index n was practically constant at all temperatures with a mean value n = 0.525 and a maximum error = 1.8%.

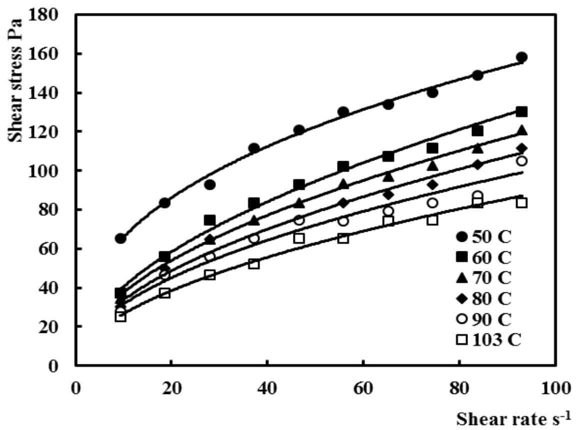

Fig. 3 Shear stress – shear rate diagram of mango juice after homogenization

As for the constant k, it steadily decreased with temperature in an almost linear way. Figure (4) shows that it decreases from about 12 Pa at 60°C down to about 7.9 Pa at 103°C.

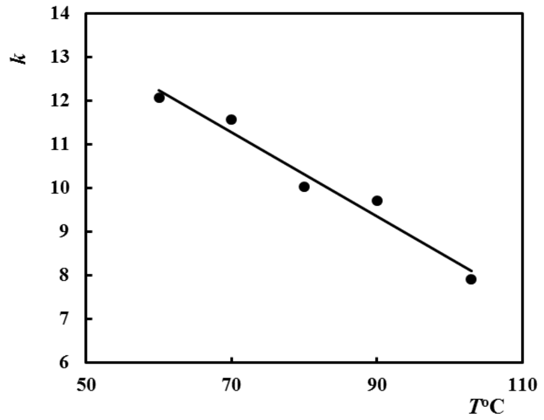

Fig. 4 Variation of constant k in equation (5) with temperature

The values of viscosities at different shear rates and temperatures are plotted in Figure (5) and display the pattern proper to shear thinning fluids. As expected, there was a decrease in viscosity following a rise in temperature.

To investigate the effect of temperature on apparent viscosity, five shear rates were chosen and the Arrhenius plot of ln μ against 1/T performed.

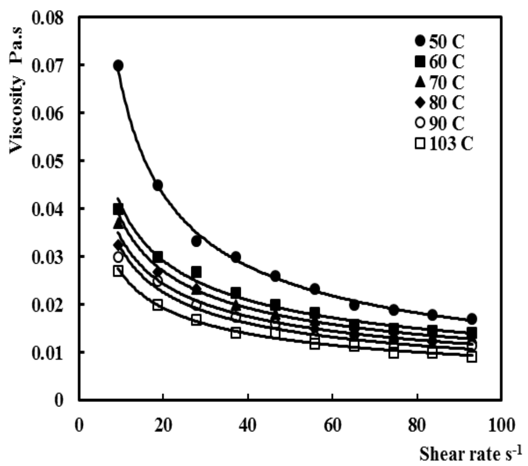

Fig. 5 Apparent viscosity – shear rate diagram of mango juice after homogenization

As revealed in Figure (6), the lines were almost parallel indicating that the activation energy for apparent viscosity does not depend on shear rate. The average value of activation energy = 10.93 $kJ.mol^{-1}$ revealing that homogenization has resulted in a decrease in activation energy to less than half its value before that step (24 $kJ.mol^{-1}$).

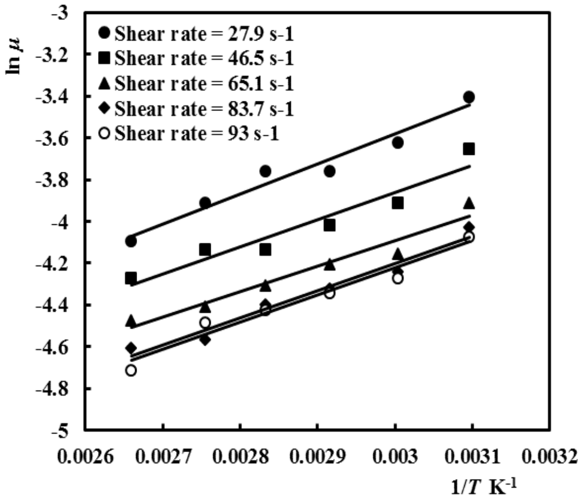

Fig. 6 Arrhenius plots for mango juice following homogenizing

While the shear stress – shear rate curves of mango juice after mixing didn't display any thixotropic behavior, the situation after homogenizing was different. In Figure (7), a thixotropic behavior can be observed as evidenced by the presence of a hysteresis loop. Thixotropic behavior is not widespread in fruit juice and has been reported to occur in mandarin juice at low temperatures (– 12 to 6°C) by Falguera et al [11]. These authors indicated that at high shear rate (400 s^{-1}) necessary to fix the shear rate for 180 seconds to ensure breaking down the thixotropic behavior.

C. Results following the cooling step

Homogenized juice was then cooled down from temperatures in the range 50 to 103°C to the range 20 to 50°C. The shear stress – shear rate plots show that a Bingham behavior is followed. The slope of the straight lines increased with decreasing temperature (Figure 8).

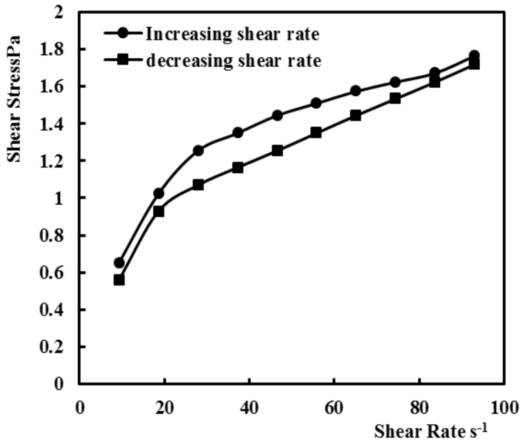

Fig. 7 Thixotropic character of mango juice following homogenization

This is since the slope represents the consistency factor k which is equivalent to infinite shear rate viscosity.

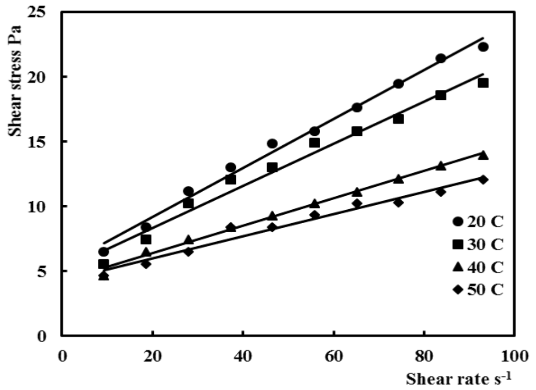

Fig. 8 Shear stress – shear rate diagram of mango juice after cooling

Also, the yield stress τ_0 obtained from the intercept with the vertical axis increased with deceasing temperature. The values of k and τ_0 at the four temperatures are listed in Table-III.

Tabl-III: Values of consistency factor and yield stress after cooling

Temp. oC	20	30	40	50
k Pa.s	0.189	0.162	0.106	0.086
τ_0 Pa	5.39	5.10	4.27	4.24

In Figure (9) are presented the apparent viscosity data obtained at different temperatures after cooling. The curves show a tendency to reach limiting values of viscosity owing to their Bingham behavior. These values show in Table (3) as the consistency factor.

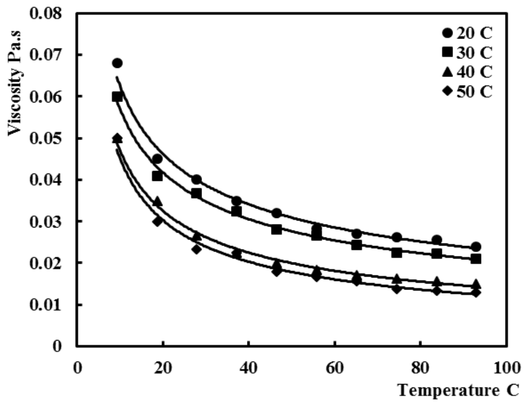

Fig. 9 Apparent viscosity – shear rate diagram of mango juice after cooling

To obtain the activation energy associated with the variation of apparent viscosity with temperature plots of ln μ against 1/T were performed at five different shear rates. In Figure (10), it appears that the straight lines obtained are fairly parallel, implying that the activation energy does not depend on the shear rate. The average value of activation energy = 11.22 $kJ.mol^{-1}$. This value compares with that obtained for the juice after homogenizing (10.93 $kJ.mol^{-1}$) proving that the value of activation energy does not depend on the physical state of the juice after the two processing steps.

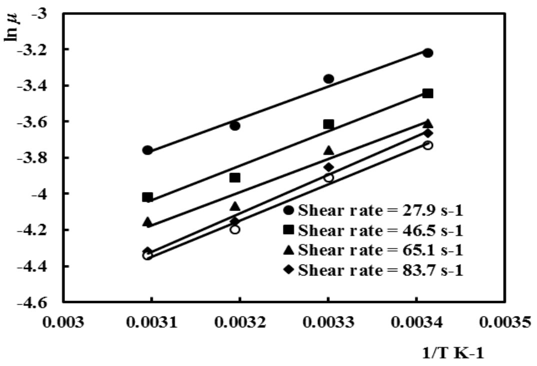

Fig. 10 Arrhenius plots for mango juice after cooling

Finally, it was found that the forward and backward shear stress – shear rate curves for mango juice after cooling were almost identical, implying a lack of thixotropic behavior for cooled juice.

IV. CONCLUSIONS

The rheological behavior of mango juice (15oBrix) was investigated following three steps in the processing line.
Mixed juice showed Bingham behavior with values of yield stress decreasing with increased temperature. The activation energy was determined to equal about 24 kJ.mol^{-1}.
Samples collected after the homogenization step exhibited shear thinning behavior with an almost constant flow index of 0.525. The activation energy was determined as 10.93 kJ.mol-1. The juice samples collected from that step exhibited a mild thixotropic behavior.
The results of the third step involving cooling of the homogenized juice revealed that the liquid reverted to Bingham behavior with values of consistency index decreasing with increased temperatures. The calculated activation energy equals 11.22 kJ.mol^{-1}.

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