Proc S Afr Sug Technol Ass (2008) 81: 227 - 233

SHORT COMMUNICATION

MASSECUITE CONSISTENCY MEASUREMENT USING A PIPELINE VISCOMETER

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Abstract

The use of traditional rotating viscometers to measure the rheological properties of massecuite in a sugar factory has not been suitable due to the presence of crystals in the massecuite, hence the suitability of a pipeline viscometer to measure massecuite consistency was investigated. The theoretical aspects of the viscometer and its ability to measure non-Newtonian fluids are reviewed, and the results of comparisons between the pipeline viscometer and a traditional rotating viscometer are given. The effects of crystal content and temperature on the consistency of a final massecuite are discussed. Preliminary results show that the pipeline viscometer is better suited to measuring the rheological properties of massecuite than traditional rotating viscometers.

Keywords: massecuite, consistency, crystal content, viscometer, pipeline, viscosity

Introduction

The measurement of massecuite viscosity or consistency is extremely difficult due to the physical properties of the material. There is no instrument that is endorsed by ICUMSA for the measurement of massecuite consistency. Not many viscometers are suitable for measuring massecuites due to the high Brix concentration and crystal content of the material. Traditional rotating viscometers have been used; however, these have not found wide application due to numerous problems, the main one being that the crystals are pushed aside while the spindle is rotating, leaving only a pool of molasses. The pipeline viscometer has been used in Australia (Ness, 1980; Broadfoot *et al.*, 1998) with some success. It appears to be more suitable than the rotating viscometers for investigating flow properties of massecuites as there are no rotating spindles. Following the construction of a pipeline viscometer at the University of KwaZulu-Natal (UKZN) with the assistance of Tongaat–Hulett Sugar Ltd, investigations were conducted on the suitability of the instrument to measure prepared C-massecuites and the effect that crystal content has on massecuite consistency. The samples were also measured on a traditional rotating viscometer (Brookfield) for comparison.

Theory

Viscosity is defined as the ratio of the shearing stress applied to the rate of shear produced. For a Newtonian fluid this ratio is constant, i.e. independent of shear rate, and the proportionality constant μ is called the viscosity. This is represented by Equation 1.

For non-Newtonian fluids the proportionality constant is dependent on shear rate. If the ratio μ falls progressively with an increasing shear rate, it is called the consistency (K) rather than the viscosity. The official method adopted by ICUMSA to calculate consistency is the power law model represented by Equation 2.

$$\tau = \mu\left(\frac{d\gamma}{dt}\right) \qquad \text{...........(1)}$$

where τ = shear stress (Pa)

μ = viscosity (Pa.s)

and $\frac{d\gamma}{dt}$ = shear rate (s^{-1})

$$\tau = K\left(\frac{d\gamma}{dt}\right)^n \qquad \text{.......... (2)}$$

where τ = shear stress (Pa.s)

K = consistency (Pa.s^n)

$\frac{d\gamma}{dt}$ = shear rate (s^{-1})

n = flow behaviour index (dimensionless)

K is a measure of the consistency of the fluid and n indicates the degree of non-Newtonian behaviour. When n = 1, the fluid is Newtonian. The value of K is obtained by plotting the natural logarithm of shear stress versus the natural logarithm of shear rate, namely ln (τ) versus ln ($d\gamma/dt$) using linear regression analysis. The exponential of the constant (intercept) obtained from the regression is equal to the consistency K.

Pipeline viscometer theory

This method is used in Australia and is described by Ness (1980). It consists of a tube of specific length and diameter. Massecuite is forced through the tube under pressure with compressed air, and the pressure difference across the pipe (ΔP) and the flow rate (Q) are measured. The shear rate and shear stress calculations that are required are shown in Equations 3 and 4.

$$\text{shear rate} = \frac{8V}{D} \qquad \text{...........(3)}$$

where V = fluid velocity (m.s^{-1})

D = pipe diameter (m)

$$\text{Shear stress} = \frac{D\Delta P_{pipe}}{4L} \qquad \text{.........(4)}$$

where D = pipe diameter (m)

L = length of pipe section (m)

ΔP = frictional pressure loss (Pa)

The flow behaviour index n is calculated by plotting shear stress versus shear rate, and K can then be calculated (Equation 5).

$$\mathbf{K} = \frac{\dfrac{\mathbf{D\Delta P_{pipe}}}{\mathbf{4L}}}{\left[\left(\dfrac{\mathbf{3n+1}}{\mathbf{4n}}\right)\left(\dfrac{\mathbf{8V}}{\mathbf{D}}\right)\right]^{\mathbf{n}}} \qquad \mathbf{..........(5)}$$

Rotating cylinder viscometer theory

One of the most common brands of viscometer that uses rotating spindles is the Brookfield Viscometer. It makes use of cylinders, disc spindles and T-spindles to calculate the viscosity of fluid, and uses the 'rotating cylinder in an infinite medium' theory (Skelland, 1967) to calculate shear rate and shear stress. The calculations are shown in Equations 6 and 7.

$$\begin{aligned} \textbf{shear stress} &= \frac{\mathbf{t}}{\mathbf{2\Pi r^2}\ell} \qquad \mathbf{........(6)} \\ \textbf{where t} &= \textbf{torque reading from viscometer (N.m)} \\ \mathbf{r} &= \textbf{radius of cylinder (m)} \\ \ell &= \textbf{length of cylinder (m)} \end{aligned}$$

$$\begin{aligned} \textbf{shear rate} &= \frac{\mathbf{4\Pi N}}{\mathbf{n}} \qquad \mathbf{.........(7)} \\ \textbf{where N} &= \textbf{rotational speed (rps)} \\ \mathbf{n} &= \textbf{flow behaviour index (dimensionless)} \end{aligned}$$

The flow behaviour index is obtained by plotting torque (t) versus N.

Equations 6 and 7 are applicable only to cylinders and not to the T-spindles that are used with this viscometer unless some modifications are done. Based on the work by Lionnet and Barker (1995) the T-spindles needed to be treated as cylinders in order to use the infinite medium theory method described. To do this an effective length was calculated for each T-spindle. Where the viscosity of a sample is known and the infinite fluid method is applied, a new or effective length for the T-spindle can be calculated. The viscosity values used were Brookfield viscosity standards.

Effective lengths were calculated for all the T-spindles and, since shear rate and shear stress could now be calculated, consistency of non-Newtonian fluids could be measured using these T-spindles.

Experimental

To check whether the pipeline viscometer would be able to make accurate measurements, a sample of a 60° Bx sucrose solution and a sample of final molasses were measured using the pipeline viscometer and the rotating viscometer (Brookfield). Viscosity standards could not be used, as the amount of sample required was too large for a single test. Results were compared to literature values for the viscosity of sucrose solutions (Chen and Chou, 1993) and the molasses results from each viscometer were compared to each other.

C-molasses and C-sugar were collected from a South African sugar factory to prepare C-massecuites. Initial attempts to obtain Nutsch molasses from laboratory centrifugals were in vain, as the required temperatures could not be reached in a laboratory centrifugal and the massecuites would not cure without wash water. Obtaining Nutsch molasses from factory centrifugals also proved difficult, as wash water to the machines could not be stopped. Finally, the C-massecuites were prepared by measuring the Brix to calculate the amount of C-sugar to be added to the molasses to reach saturation, and then adding enough C-sugar to achieve the crystal content. The main aim was to investigate the effect of crystal content while the Brix of the mother liquor remained constant. Four different levels of crystal content were prepared, namely 3%, 17%, 22% and 28% crystal content. The crystal content was measured by allowing the massecuite samples to stir overnight in a jacketed vessel at 55°C, after which a Nutsch sample was obtained and sent for analysis.

The consistencies of the massecuites were measured at 55 and 65°C respectively, using both viscometers. In all measurements involving the pipeline viscometer, the flow through the pipe was proven to be laminar. The effects of different length to diameter ratios (L/D) were not investigated and only the results using tube 2 are shown (L/D=40). End effects were not measured and were ignored in the calculations. Ness (1980), however, does mention that at low flow rates and high L/D ratios (>10-20) the end effects are small. To minimise air entrainment, each sample was left overnight in a water bath to degas. The amount of air entrainment was not measured and calculations have assumed that there was no air entrainment in the samples.

All work on the pipeline viscometer was done by UKZN students at the UKZN Chemical Engineering Laboratory. Measurements using the Brookfield viscometer were done at the Sugar Milling Research Institute.

Results and Discussion

Comparative tests

The results of comparative tests done with the 60° Bx pure sucrose solution and final molasses are given in Table 1.

Table 1. Comparisons between the pipeline and Brookfield viscometer and literature values.

Sample	Temp (°C)	Pipeline viscometer		Brookfield viscometer		Literature*	
		Consistency ($Pa.s^n$)	n	Consistency ($Pa.s^n$)	n	Consistency ($Pa.s^n$)	n
Sucrose solution	17	0.24	1.1	0.10	1.3	0.08	1.0
Final molasses	65	1.3	0.9	2.4	0.8	–	–

*(Chen and Chou, 1993)

The results show that the pipeline viscometer was less accurate than the Brookfield viscometer when measuring the pure sucrose solution. The pipeline viscometer was able to measure the flow behaviour index more accurately than the Brookfield viscometer for the sucrose solution.

There was better agreement when the molasses was measured. It is expected that the errors involved when using the pipeline viscometer will be much larger than when using the Brookfield, due to the nature of the equipment, and that these errors will decrease as the consistency of the sample being measured increases.

Effect of crystal content and temperature on massecuite consistency

The differences between the consistency of massecuite and molasses (mother liquor) can only be ascribed to the presence of crystals, both the content and the size. The effects of crystal content on massecuite consistency (with regression lines) are shown in Figures 1 and 2. The consistency of the massecuite was measured with both the Brookfield viscometer and the pipeline viscometer at 55 and 65°C. Unfortunately, the consistency of the massecuite with a crystal content of 22% was not included in the investigation as the container in which it was kept was cracked. This allowed water to enter while heating, and the consistency value calculated was therefore incorrect.

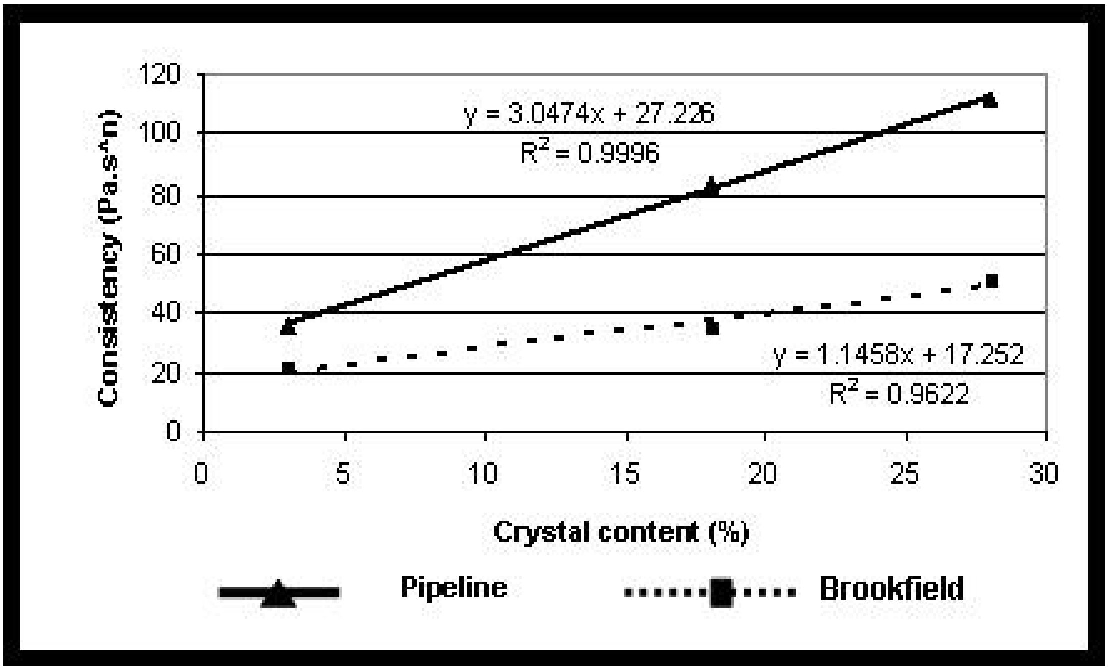

Figure 1. Effect of crystal content on massecuite consistency at 55°C.

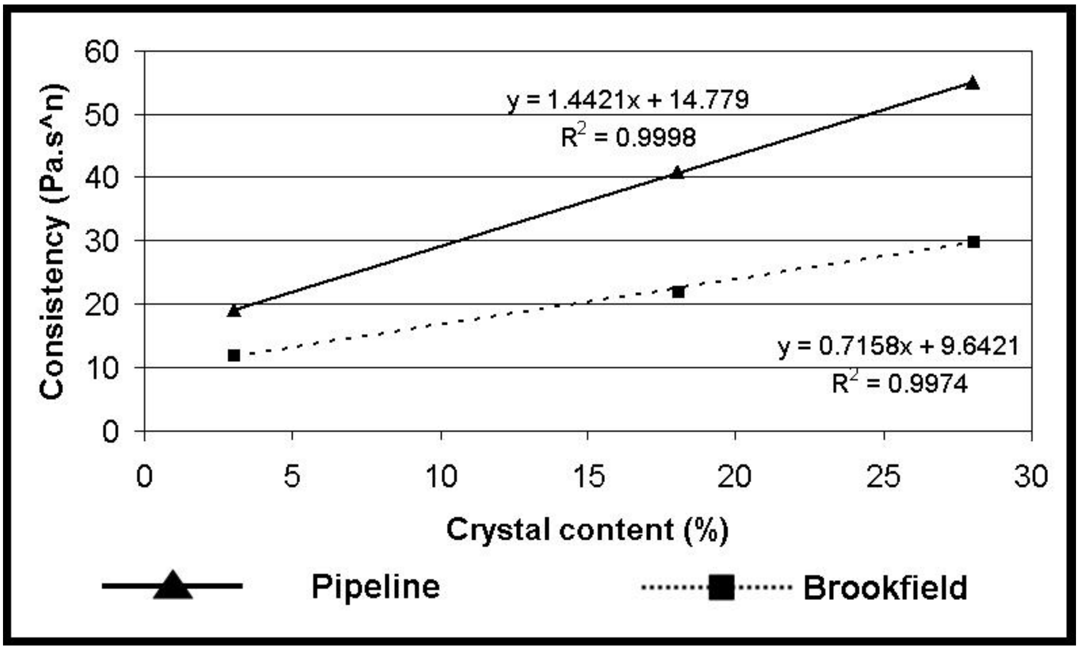

Figure 2. Effect of crystal content on massecuite consistency at 65°C.

The following was established with these investigations:

- Both the pipeline viscometer and the Brookfield viscometer show that the effect of crystal content appears to be linear at both temperatures with good correlations. Awang and White (1976) and Ness (1980) show a logarithmic relationship between crystal content and viscosity of massecuites. However, direct comparisons between their work and this work is difficult due to the different test methods used.
- The pipeline viscometer measured higher consistency values than the Brookfield viscometer. Work done by Ness (1980) showed the opposite result. However, Ness used rotating cylinders and this work used T-spindles.
- The consistency of the massecuite is approximately halved for a 10°C rise in temperature; this was evidenced with both viscometers. This result agrees with that reported by Ness (1980).

Further work

This is the first time that a pipeline viscometer has been used to measure South African massecuites, and the results presented here are preliminary. Further investigations are required in the following areas:

- Repeatability tests need to be done.
- Measurement of a suitable high viscosity standard is required.
- The effects of different sized tubes (L/D ratios) need investigation.
- Measurements of molasses and massecuites from different factories need to be done.

Acknowledgements

The author would like to thank D Padaychee, R Ishak and L Moonsamy, who conducted all consistency measurements, and Professor Starzak from the University of KwaZulu-Natal and S Peacock from Tongaat–Hulett Sugar Ltd for their valuable assistance and input. A special acknowledgement is due to Tongaat-Hulett for the use of their pipeline viscometer.

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