An examination of the use of rotational viscometers for the quality control of non-Newtonian liquid products in factories

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Abstract:
A frequent task undertaken by quality-control personnel in typical consumer-goods factories is the measurement of the viscosity of liquid products. The problem often faced in this task is how to strike the correct balance between the complete rheological characterisation of the non-Newtonian properties of the liquid of interest – which requires expensive, sophisticated equipment and can be quite time-consuming – and the dictates of production pressures that demand, as near as possible, an instant decision, and one usually based on a single number. Here we consider the rheological issues that arise in such a debate, which is aimed at finding what adequate characterisation would require.

We will investigate the implications of liquids products being non-Newtonian for two of the most commonly encountered viscometers in factory quality laboratories, i.e. the simple 'dip-in' rotating spindle viscometer of the Brookfield type (with its different forms and many imitations) and the more sophisticated concentric-cylinder-type device typified by the Haake Rotovisco VT 550 range. Each is capable of giving a single-number answer for viscosity, but the implications of understanding this single number are different in each case, with the dip-in viscometer being in an infinite sea of liquid and the concentric-cylinder situation being narrow gap. We also investigate when the infinite sea of the 'dip-in' viscometer is effectively 'infinite' and when is a concentric-cylinder geometry really 'narrow gap'? We will use the power-law model throughout our discussions.

Zusammenfassung:
Bei der Herstellung von Konsumgütern ist es eine wiederkehrende Aufgabenstellung an das Qualitätskontrollpersonal, die Viskosität von flüssigen Produkten zu messen. Dabei ist es häufig schwierig, die Balance zwischen der kompletten rheologischen Charakterisierung der nicht-newtonschen Eigenschaften der betrachteten Flüssigkeit - was eine teuere und hochentwickelte Ausrüstung verlangt und sehr zeitraubend sein kann - und dem Diktat des Produktionsdrucks, der eine möglichst unmittelbare Entscheidung verlangt, die normalerweise auf einem einzelnen Wert beruht, zu finden.

In diesem Beitrag werden die in einer solchen Debatte um die adäquate Charakterisierung auftretenden rheologischen Streitpunkte vorgestellt und diskutiert. Die Rheometrie von nicht-newtonschen Flüssigprodukten wird an zwei in den Laboratorien der Qualitätskontrolle am meisten benutzten Viskosimetern, dem einfachen "dip-in" Spindel-Viskosimeter vom Brookfield Typ (mit seinen verschiedenen Formen und Bauarten) und das anspruchsvollere Gerät vom Haake Rotovisco VT 550 Typ mit konzentrischen Zylindern untersucht. Beide Geräte geben durch einen einzigen Wert die Viskosität an, jedoch ist die Bedeutung dieser einen Zahl in beiden Fällen verschieden, da das "dip-in" Viskosimeter in einem "unendlichen See" von Flüssigkeit ist, während das Gerät mit konzentrischen Zylindern Flüssigkeit in einem schmalen Spalt misst. Zur Untersuchung, unter welchen Umständen der "unendliche See" des "'Dip-in" Viskosimeters unendlich ist, und wann in der konzentrischen Zylinder-Geometrie wirklich eine schmaler Spalt vorliegt, wird das Potenzgesetz-Modell verwendet.

Résumé:
Une tâche fréquente, entreprise par les personnels du contrôle qualité des fabriques de biens de consommation typiques, est la mesure de la viscosité de produits liquides. Le problème auquel on doit souvent faire face dans cette tâche, est de savoir comment découvrir l'équilibre convenable entre la caractérisation rhéologique complète des propriétés non Newtoniennes du liquide à étudier – qui requiert un appareillage sophistiqué et cher et peut coûter du temps - et les dictats des contraintes de la production, qui demandent autant que possible, une décision instantanée et habituellement basée sur la détermination d'un simple nombre. Ici nous nous intéressons aux questions rhéologiques qui émergent lors d'un tel débat, qui a pour objet de trouver quelle caractérisation adéquate serait requise. Nous allons rechercher quelles sont les implications pour des produits liquides non Newtoniens lorsqu'ils sont étudiés au moyen de 2 viscosimètres qui sont le plus souvent utilisés dans les laboratoires qualité des fabriques, i.e., le simple viscosimètre rotatif 'dip-in' de type Brookfield (avec ses différentes formes et ses diverses imitations) et l'appareil plus sophistiqué de type cylindres concentriques comme le Haake Rotovisco VT 550. Chacun des 2 appareils est capable de fournir un simple nombre pour caractériser la viscosité, mais la signification de ce simple nombre est différente pour chacun des cas, où le viscosimètre 'dip-in' baigne dans une mer infinie de liquide, alors que pour les cylindres concentriques, l'entrefer est dans la limite des petites valeurs. Nous cherchons également à savoir quand la mer infinie de liquide, dans le cas du viscosimètre 'dip-in', est réellement infinie, et quand la limite des petites valeurs d'entrefer est atteinte pour le viscosimètre de type cylindres concentriques. Nous utiliserons le modèle en loi de puissance tout au long de nos discussions.

Key words: Brookfield viscometer, Haake VT 550 viscometer, non-Newtonian liquids, power-law model

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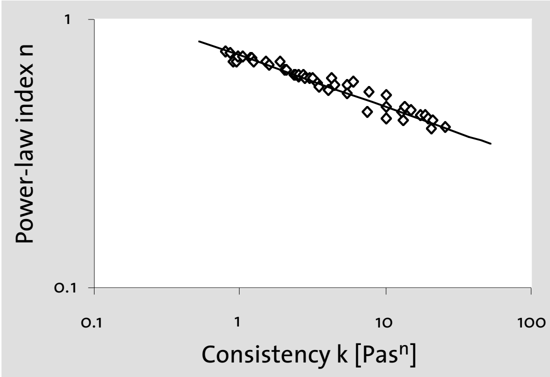
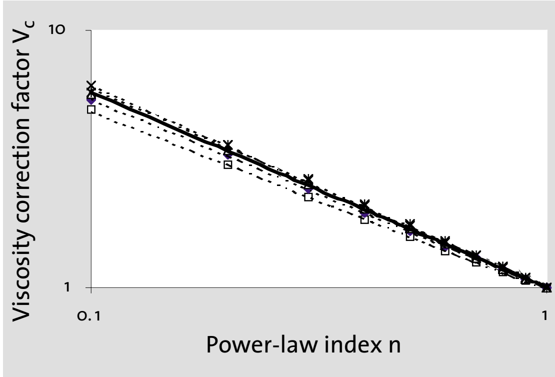
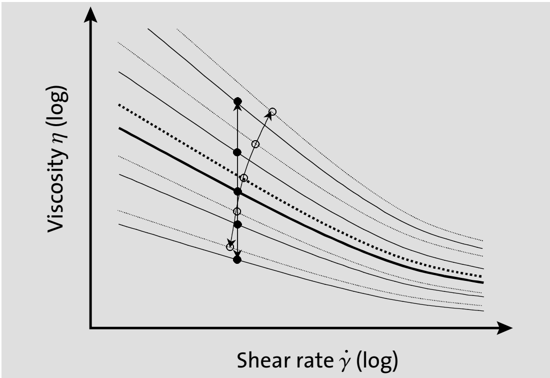
Figure 17 (left above): Consistency and power-law index relationship for 45 different European fabric conditioners [16].

Figure 18 (right above): Viscosity correction factor, V_C, as a function of power-law index, n, for Brookfield spindles RV2 – 6 respectively, (points and dotted lines), together with the simple function $V_C = n^{-0.75}$ shown as a solid, bold line. RV2 data is the lowest curve, progressing upwards to RV6, the highest.

Figure 19 (left below): A schematic representation of viscosity versus shear rate (logarithmic axes) showing typical day-to-day variations of a non-Newtonian liquid product. Solid lines slow equivalent Newtonian viscosities and shear rates, while dashed lines show the actual curves. The 'mean' product is represented by the heavy lines. The lines ending in arrows ⇓ represent the variations at one particular spindle speed for the Newtonian assumption (vertical line) or the real viscosity/shear-rate points obtained using a non-Newtonian analysis (curves line ending in arrows).







the implications of this for measuring non-Newtonian liquids? If for instance we measure a power-law liquid with an n of 0.5 using an RV3 spindle, the scale reading will indicate the correct average shear stress, but the Newtonian shear rate based on the rotation speed and the normal instrument constants (i.e. Newtonian) will actually be higher than the real average. Hence, as above for the concentric-cylinder situation, the supposed viscosity will be too high. In this case, we cite Williams' equation (Eq. 6) and knowing that for the RV3 spindle, then *a, b, c,* are given by 0.1234, 0.2576 and –0.1129 respectively, with the sum $(a+b+c)$, i.e. the Newtonian situation, being 0.2681. Then the actual average shear rate would be given by 0.448N, but the supposed shear rate would be the lower value of 0.2681N.

The real viscosity would then be greater by a factor of 0.448/0.2681 or 1.67, or two-thirds higher. The ratio of real to supposed shear rates varies little with spindle number, the viscosity correction factor ratio, V_C, will be similar for the typical disc spindles 2 – 6. Fig. 18 shows this function, which is very close to the simple function $V_C = n^{-0.75}$, cp. Briggs and Steffe's [15] approximation cited above. Similar corrections for other spindles and values of power-law index can be worked out from the Williams formula. As stated above, the implications of this are not always that dramatic, since the viscosity is itself a function of n for most liquids in day to day production variations.

CONCLUSIONS

We have discussed the implications of test liquids being non-Newtonian in the case of the dip-in and concentric-cylinder viscometers often used in factories. We can conclude that if no corrections are made, then either with rotating discs of the Brookfield RV type or the Haake wide-gap concentric-cylinder geometries (b < 0.8), then gross errors will be made if the equivalent Newtonian liquid viscosity is taken as the viscosity. The implications of these errors can be considerable if comparisons are made between different systems, but if comparisons are only made with typical day-to-day variations of the same product, then because of the nature of typical variations, no real problems are encountered in a quality-control situation.

In terms of the constraints on the narrow-gap or infinite-sea criteria, the more non-Newtonian the liquid, the narrower the gap needs to be (see Fig. 8), but similarly, the container does not need to be so big to ensure an infinite-sea situation (see Fig. 10).

As far as measuring the ENV and specifying at a given rotation speed is concerned, we have seen that for normal day-to-day product variation, there is no real problem. Effectively, we can visualise the result in Fig. 19, where we show schematically that although there will be two different sets of curves arising from the real and supposed viscosity/shear-rate curves, there is still a one-to-one relationship between them. Hence no problem arises in quality control situations using a single spindle speed. Obviously, greater discrimination between products of this kind is achieved by using as low a speed as possible, where the viscosity diverge more.

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APPENDIX: CALCULATING AN APPROXIMATE VALUE OF N USING BROOKFIELD DATA

Typical Brookfield users would not be familiar with ways the logarithmic manipulations necessary to find the value of *n*. A simple way of obtaining an approximate value of *n* just using simple arithmetic is now shown.

$$n = \frac{d \log \sigma}{d \log \dot{\gamma}} = \frac{\dot{\gamma}}{\sigma} \frac{d\sigma}{d\dot{\gamma}} \tag{A1}$$

Expressed in terms of speeds, *N*, and scale readings *T*, this be written as

$$n = \frac{N}{T} \frac{dT}{dN} \tag{A2}$$

For any three rotational speeds, N_1, N_2 and N_3, which give % torque scale readings of T_1, T_2 and T_3, we can calculate an approximate value of *n* as

$$n \approx \frac{N_2}{T_2} \frac{(T_3 - T_1)}{(N_3 - N_1)} \tag{A3}$$

For instance, for a power-law of 0.5, and consecutive values of *N* (say N_1, N_2 and N_3, are 5, 10 and 20 rpm respectively), then if say T_1 was 10, then T_2 and T_3 would be 14.1421, and 20 respectively. Then our approximate value of *n* is 0.4714 instead of 0.5. In the same way, the approximate values of $n = 0.25$ and 0.75 are 0.2322 and 0.7248. These are not dissimilar to the kind of variations in the values of *n* one would obtain when drawing a line through experimental points. Thus, for the purposes of a first correction, this approximation suffices. It is not difficult to show that if the ENVs have already been calculated, then

$$n = \frac{1}{V_2} \frac{(V_3 N_3 - V_1 N_1)}{(N_3 - N_1)} \tag{A4}$$

where V_m is the ENV at N_m rpm.

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