Rotational Viscometry as Key to Customised Taste: How Flow Behaviour Affects Food Products

Judith Hartmann, Anton Paar GmbH

Modern food production is highly industrialised and aims for constant quality. A product's flow behaviour is relevant not only for quality control, both of incoming raw materials and the final product, but also for formulating the product to customise it for the intended target group. This article provides an overview of the basic parameters describing flow behaviour and explains why viscosity is a relevant physical quantity for food. Application examples illustrate why rotational viscometry is the tool of choice when analysing flow behaviour.

Flow behaviour and viscosity

The flow behaviour describes how the viscosity (colloquially, 'thickness') of a substance changes under stress, where 'stress' means any force acting on the material. Viscosity is the physical quantity that defines a substance's internal flow resistance, or, simply put, how easily a substance flows. Water is a typical example for low viscosity, while mayonnaise or peanut butter are at the high end of the scale. To add further to the complexity, external stress is not the only cause of viscosity changes. Viscosity strongly depends on temperature and also on pressure. By assuming that temperature and pressure remain constant, three different types of flow behaviour can be discerned:

- Curve 1: Newtonian (named after Sir Isaac Newton) - in this case, the viscosity is independent of an external force. Water and oil are typical examples.
- Curve 2: Shear-thinning - the viscosity decreases with increasing stress. Yogurt, most creams, and sauces show this behaviour.
- Curve 3: Shear-thickening - the viscosity increases with increasing stress. This behaviour is rare, but can be observed in highly concentrated starch solutions or dough.

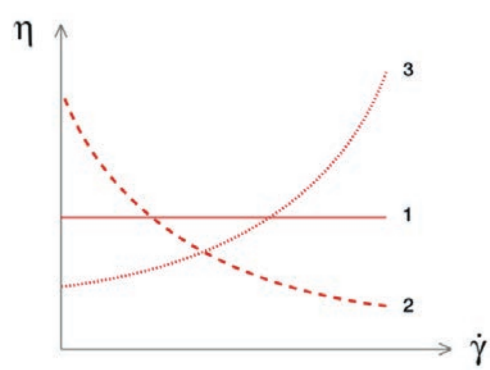


Figure 1: Viscosity curves. Newtonian flow behaviour (1), shear-thinning (2), shear thickening (3).

In correct physical terms, viscosity is defined as shear stress tau divided by shear rate gamma-dot.

Equation: $$\eta = \frac{\tau}{\dot{\gamma}}$$

This mathematical definition is best explained by the two-plates model [1], which consists of two solid plates containing the viscous substance between them. The lower plate stands still, while the force F moves the upper plate slowly sideways as shown in *Figure 2*.

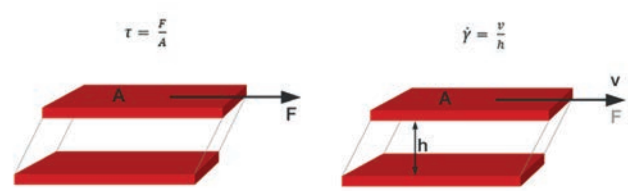


Figure 2: The two-plates model as tool to define shear rate, shear stress, and viscosity.

The force F moving the upper plate divided by the area A of this plate is the shear stress. The movement is accounted for by the shear rate, which is the result of the upper plate's velocity v divided by the distance h between the two plates.

Reasons to analyse flow behaviour in food production

During production processes, most steps involve some kind of force influencing the flow behaviour and consequently the viscosity of the food material: This involves stirring, pumping, pouring, or extruding the food material.

Furthermore, flow behaviour is equally important from the consumer point of view.

- The product should be easy to pour or squeeze out of its container without unnecessary force or undesirable splashing and staining.
- Some products require the right viscosity for spooning or spreading on e.g., bread.
- Texture and taste are closely connected: If consumers do not enjoy the expected mouthfeel, they perceive the product to be inferior compared to one that has the right structure.

Notably, the expected mouth feeling and food texture vary in relation to regional preferences as well as over age cohorts [2].

- More critical than mouthfeel is swallowing as another shear force. Due to certain clinical conditions, older or sick people sometimes cannot swallow nourishment if it is too liquid [3], while highly viscous food is difficult to swallow for small infants.

The following table gives a short overview of the shear rates occurring during food production and consumption:

Table 1 [4]: Typical Shear Rates in Food-Related Processes

Process	Shear Rates [s^{-1}]	Example
Sedimentation of particles	≤0.001 to 0.01	Fruit juices
Sagging of coatings, flow under gravity	0.01 to 0.1	Chocolate coatings (couvertures)
Dip coating	1 to 100	Dip coatings, candy masses
Chewing, swallowing	10 to 100	Baby food, yogurt, cheese
Spreading	10 to 1,000	Peanut butter, butter, jam
Extrusion	10 to 1,000	Dough

The yield point as parameter for mouthfeel

To make mouthfeel measurable, another parameter needs to be introduced: the yield point or yield stress. Simply put, some substances subjected to shear stress behave like a solid up to a certain value. Once this critical value - the yield point - has been exceeded, they start to flow [5].

The yield point is determined by measuring the viscosity while increasing the shear rate. From the resulting curve, the yield point is calculated using empirically developed mathematical model functions. This approach has resulted in several different models, which all return the yield point as an approximated value. For this reason, the yield point depends on the measuring and calculation method used. It is no material constant. The most commonly used models are Bingham, Casson, Herschel-Bulkley, or Windhab.

While a higher yield point results in a creamier mouthfeel, the pressure required to squeeze a substance out of its tube (e.g., mayonnaise) also increases with the yield point.

Using rotational viscometry to determine flow behaviour

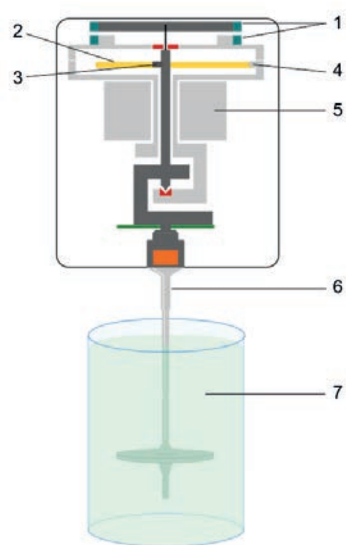
A suitable instrument is required to determine viscosity at defined shear rates as well as to model the various processes food is submitted to. Such a device needs to be sufficiently versatile to cover the wide viscosity range (e.g., from fruit juices to chocolate cream). Ideally, the instrument should be able to provide the mathematical tools for analysing the registered data, for example, for yield point calculation.

Rotational viscometers come with various measuring systems designed to suit specific applications. Instrument software allows the programming of several steps to simulate a complex process and includes mathematical model functions.

Figure 3: Rotational viscometer ViscoQC 100 and ViscoQC 300 with standard spindles.

A majority of rotational viscometers on the market have a motor and a spiral spring. The motor turns a measuring bob immersed into the sample under test. The rotational speed is user-defined. To actually turn, the measuring bob has to overcome the viscous forces of the sample, which winds up the spring. The sample's resistance is registered via the spring as torque (usually in %) and as dynamic viscosity.

In order to cover the vast viscosity range, springs of different mechanical strength and sensitivity are in use for low (L), medium or regular (R), and high (H) viscosity. This means it is important to choose a viscometer model with the correct spring for the intended application.



1- Magnets registering the deflection of the spring (difference between motor and spindle torque)

2 - Spring

3 - Spring connection to measuring bob shaft

4 - Spring connection to motor shaft

5 - Motor

6 - Measuring bob

7 - Sample

Figure 4: Spring-type rotational viscometer.

Examples for flow behaviour analysis

Example 1: Fruit juice

Fruit juices can either be clear or opaque liquids when containing fruit particles and pulp. In any case, juices are a low-viscosity application (viscosity approx. 2 mPa·s) that require a viscometer model with a highly sensitive spring. A concentric cylinder system with double-gap provides sufficient surface for shearing in order to obtain a viscosity value. A comparatively high value (greater than 100 rpm) has to be set for the rotational speed for the same reason.

Concentric cylinder systems have standardised geometries of measuring bob and cup, which allow the calculation of the shear rate. Measuring systems with defined geometry are absolute systems: Viscosity values obtained with such a system are comparable to viscosity values from a different system - provided the other system also has a defined geometry and, in case of non-Newtonian samples, the test was performed at the same shear rate.

As long as the fruit content is not too high (i.e., the sample does not resemble a smoothie), the flow behaviour is Newtonian. This can be shown by presetting a speed ramp from 120 rpm to 180 rpm and evaluating the resulting data with the mathematical model ‘Shear thinning index’. If the resulting index is greater than 1, the sample is shear thinning, while an index of approximately 1 stands for Newtonian flow behaviour. To eliminate temperature influences from variables such as unstable room temperature, a Peltier temperature device, which kept the sample at a stable 25°C, was used for a test that is reported below.

Figure 5: Rotational viscometer with Peltier temperature device with inserted double-gap measuring system.

Table 2: ‘Shear thinning index’ analysis and report table of orange juice using a rotational viscometer and double-gap measuring system.

Speed rpm	Dynamic Viscosity mPa·s	Torque %	Runtime hh:mm:ss	Temperature °C
120	2.093	33.5	00:01:00	25.0
130	2.093	36.3	00:01:00	25.0
140	2.067	38.6	00:01:00	25.0
150	2.074	41.5	00:01:00	25.0
160	2.066	44.1	00:01:00	25.0
170	2.051	46.5	00:01:00	25.0
180	2.046	49.1	00:01:00	25.0
Shear Thinning Index	1.0228			

Example 2: Chocolate

Chocolate – especially when it comes to coatings – demands more complex testing to ensure the desired quality. The main goal is to achieve a perfect surface where the coating is evenly distributed, without holes or lumps. The IOCCC (International Organization of Chocolate, Cocoa, and Confectionery) has developed its own method to analyse the chocolate’s flow behaviour at varying shear rates followed by calculation of the yield stress. The yield stress is a key parameter for successful conching and perfect coating.

The higher viscosity of chocolate requires a viscometer R- or H-model with a more robust spring. As in Example 1, a concentric cylinder system (here: CC12) was selected because the shear rate is essential for the IOCCC test. A Peltier temperature device ensures that the sample remains liquid at 40°C. In addition to the IOCCC test, the temperature device can be used for a temperature scan to determine the perfect conching temperature.

The IOCCC test consists of four steps [6]: Step 1 serves to homogenise and control the temperature of the sample. Step 2 and 3 are an upward shearing ramp plus high shearing interval as preparation for Step 4, which is the main measuring step for analysing the yield point (*Figure 6*).

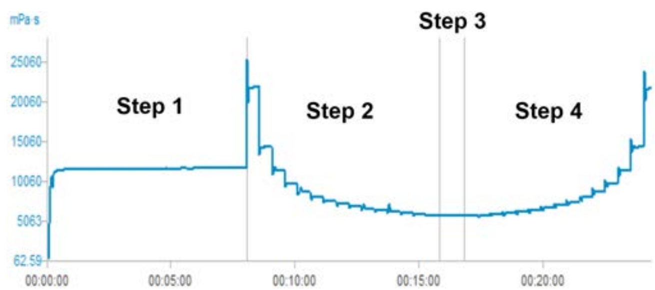


Figure 6: Real-time graph of the IOCCC step test.

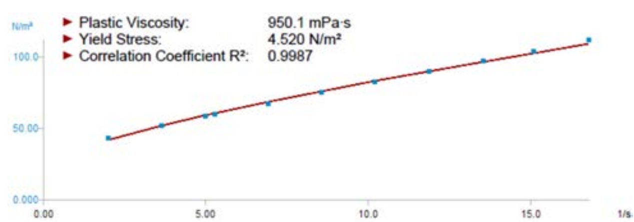


Figure 7: Flow curve and yield stress analysis of dark chocolate according to Casson using a rotational viscometer with built-in analysis software.

Table 3: Temperature-dependent test of milk chocolate from 50°C down to 30°C using a rotational viscometer (R-model) with concentric cylinder measuring system

Speed	Dynamic Viscosity	Torque	Runtime	Temperature
rpm	mPa·s	%	hh:mm:ss	°C
7.75	4805	30.7	00:00:30	50.0
7.75	5384	34.4	00:00:30	45.0
7.75	6214	39.7	00:00:30	40.0
7.75	7309	46.7	00:00:30	35.0
7.75	8734	55.8	00:00:30	30.0

Example 3: Fruit puree and vegetable sauce

Fruit puree and vegetable sauces are typical examples where the right mouthfeel is critical. The end product depends on the quality of the basic ingredients, which may frequently vary depending on their maturity or water content. By modifying the cooking process and by adding thickening agents such as pectin or starch the viscosity can be adapted. The puree and sauce under test do not flow easily, so a cylindrical measuring bob would - after a full revolution - create an air channel in the sample. The use of a motorised stand with T-bar spindles eliminates this channelling problem. While the spindle rotates, the viscometer automatically travels downwards through the sample resulting in a helical movement. This ensures that the spindle constantly is in touch with fresh sample. T-bar spindles are used in vessels of approximately 500 mL without defined geometry for shear rate calculation. Consequently, the reported viscosity values are relative.

Figure 8: Rotational viscometer ViscoQC 300 with motorised drive and T-bar spindle for measuring non-flowing substances.

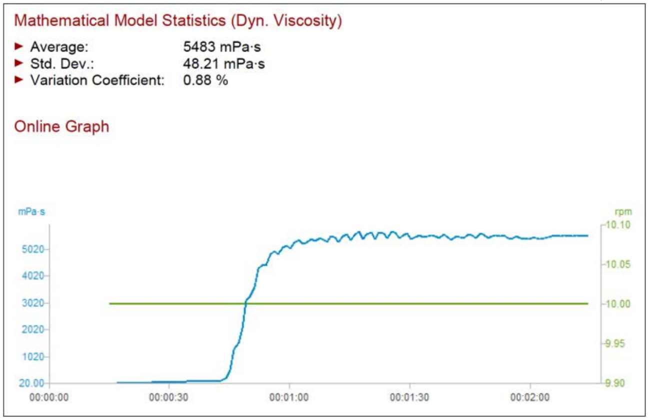


Figure 9: Live graph and statistical analysis of tomato sauce with rotational viscometer ViscoQC 300 and Heli-Plus with T-bar spindle.

The measurement was started approximately half a centimetre above the sample where the viscosity is zero. The increase in viscosity depicts the transient phase when the spindle is immersed into the sample. The plateau is where the measurement values have become stable and the viscosity can be averaged.

References

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