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Fluid Flow in the Mouth as a Measurable Aspect of Drinkability

According to relevant definitions in literature, drinkability can be divided into a conscious part regarding measurable beer attributes and a subconscious part which contains both social and psychological factors. The fluid flow of beer in the mouth and the resulting mouthfeel can be considered as being an aspect of the conscious and therefore measurable attributes. For this reason, the current study deals with the improving our understanding of the intra-oral fluid flow, visualized by means of numerical simulations and with the resulting sensory sensations which occur during the process of drinking. The aim of the study is to develop a hybrid tool which offers the opportunity to describe and predict mouthfeel only by virtue of the rheological characteristics of beverages and liquid foods.

Descriptors: drinkability, fluid mechanics, numerical simulations, descriptive sensory evaluations, haptic perception, hybrid cognitive methods

1 Introduction

Currently, the topic of drinkability is under vigorous discussion. The common definition “suitable and safe for drinking” which can be found in some publications is meaningless compared with the manifold attempts of defining the term in the relevant literature. According to *Mattos* and *Moretti* [1], drinkability can be understood as a consumer acceptance indicator. A beer is drinkable in the case that the consumer feels throughout comfortable both with its quality and image and with the consumption environment. From this point of view, drinkability is more an affective attribute than a descriptive one.

One important question which has to be answered is whether drinkability is a real beverage characteristic with a meaningful construct behind the expression. *Thomson* and *Bailey* [2] posed the question as to whether or not drinkability might be a temporary fashion established by the beverage industry. These authors suggest the hypotheses that drinkability could manifest itself as both sessionability and repeatability. Taking into account *Mattos* and *Moretti*'s definition [1], this means that the consumer appreciates the beer including all related attributes of drinkability and feels invited to drink another glass within the same or in the next session of drinking for this reason.

The current importance of the topic was emphasised by the holding of an EBC Symposium dealing with drinkability in Edinburgh in 2006 [2, 3, 4, 5]. Delegates with completely different backgrounds (for example brewing technology, marketing, and psychology) discussed the term of drinkability considering several aspects in breakout sessions in order to come closer to a general definition. All groups highlighted the importance of beer attributes but also the more subconscious impacts on the individual drinking behaviour arising due to marketing or social aspects like brand aura, presentation, atmosphere, environment or cultural background.

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Figures see Appendix

It seems sensible to consider that the impression of drinkability could be understood as a combination of multilayered single attributes. According to *Mattos* [3], drinkability is subject of the so-called gestalt psychology for this reason. This means that the whole is greater than the sum of its parts or in other words that the collective term “drinkability” has priority over its single attributes. Actually, there is no widely accepted scientific method which enables the brewer to evaluate the drinkability of beer as there are no references for high and low drinkability at the moment. For this reason, analyzing drinkability by means of measurable parameters will be an important milestone, keeping in mind that it must be understood being aware of each single aspect. Brewing technologists are able to influence these measurable factors actively in order to improve drinkability, meaning the chemical and physical beer attributes which can also act as objective references. These attributes arise from the ingredients and the technology as well as the automation strategy of the process and yield a specific taste and odour of the beer. *Davies* [4] states that these sensory attributes are perceived consciously and that a drinkable beer must have certain desirable attributes the consumer recognizes during drinking.

Flavour perception takes place by means of the complex human sensory system including the optic, gustatory, olfactory and haptic perception. Nevertheless, most studies deal with aroma components exclusively. Texture and therewith the resulting mouthfeel were underestimated for a long time, although *Meilgaard* and *Muller* [6] included the term of mouthfeel in their flavour wheel as an aspect of taste impression in 1987.

As early as 1944, *Scott Blair* [7] discussed the psychological effects of rheological properties. *Szczesniak* [8] was the first scientist who emphasized the impact of texture on the overall perception in the early 1960s. After characterising texture-related terms for food in general she also focussed on beverages and developed a list of typical terms which can be used to describe the mouthfeel of beverages. The viscosity-related terms dominate the list [9]. Afterwards, *Langstaff* et al. [10] suggested refining *Meilgaard* and *Muller*'s flavour wheel using nine different attributes belonging to three groups: carbonation, fullness and afterfeel. Recent contributions of *Strassburg* et al. [11] and *Strassburg* [12] have not only proven the high significance of texture, but also show results completely unexpected as there is a range in which disc geometries distinguished in their thickness cannot be kept apart

although the difference lies above the known threshold of 25 μm . This interval includes the thicknesses from 125 to 190 μm whereas the elastic modulus of the discs is 480 MPa.

Anyway, texture is considered not to be the first characteristic of beverages and food consumers pay attention to. But consumers are likely to recognize texture if it deviates from their expectance [13]. Consequently, they may not accept the beverage at all, totally independent from all the other flavour attributes. This means that the complete flavour, but particularly the mouthfeel has to fulfil the expectations of the consumer. Otherwise the consumer will not be encouraged to keep on drinking – the beverage has limited or no drinkability. This is not affective any longer but possible to define concretely in terms of physics. For this reason, it is valuable to analyze the fluid flow in the mouth during drinking and its impact on mouthfeel. Thus, the current study aims at the development of an expert system which offers the opportunity to predict mouthfeel on the basis of the physics of fluid flow by means of cognitive approaches which facilitate describing and modelling mechanically induced sensations of human beings.

2 Materials and methods

Different flavour-neutral model solutions made of various food thickeners were used for the current study. They were varied in terms of their viscosity and density as a consequence of their concentration and their rheological behaviour due to the type of employed food thickener.

These solutions were characterized by descriptive sensory analyses regarding in terms of their mouthfeel and their rheological measurements. The flow curves resulting from the rheological measurements act as input values for numerical simulations. These simulations were used to clarify the fluid flow of beverages and liquid food in the mouth.

A hybrid system consisting of artificial neural networks and fuzzy logic provides the possibility to combine the data sets resulting from both the descriptive sensory analyses and the numerical simulations. It is used to correlate the physical parameters of fluid flow and the resulting stimuli with the perceived mouthfeel. Therewith, the current study belongs to the field of psychorheology which is widely established in the food industry and still not understood completely so far.

The aim of the investigation is to develop a hybrid tool using cognitive methods to predict mouthfeel only by means of the rheological characteristic of beverages and food capable of flowing. Figure 1 shows the concept of the whole study at a glance.

2.1 Model Solutions

Several food thickeners are supposed to be applied during the study in order to represent the different rheological behaviours that occur when dealing with beverages and food. These are the Newtonian behaviour as well as the pseudoplastic behaviour without and with yield stress. Similar modifications are known in literature in order to clarify the mouthfeel of wine [14].

The first part of the study deals with solutions of xanthan gum in different concentrations including solutions of 0.25 to 2.0 % (w/w). Xanthan gum is used as a food thickening agent in ketchup and soups, for example.

2.2 Rheological Measurements

Rheology deals with the deformation and flow of matter in response to applied stress or strain. The reaction of matter evoked by the

applied stress or strain is used to characterise rheological behaviour [15]. This behaviour can be measured by means of a rotational rheometer. In the current study, both the above mentioned model solutions and food which is associated with the mouthfeel of these solutions were measured. Thereby, the rheological behaviour of the fluids was observed in a shear rate range of 0.1 to 100 s^{-1} .

2.3 Modelling and Numerical Simulations

Numerical studies were employed to mimic and visualize the fluid flow in the mouth. They are able to clarify resulting flow patterns as well as shear and elongation loads according to the implemented material properties of the model food solutions resulting from the rheological measurements and the characteristic of the model tongue movement. Numerical simulations have become a powerful method for describing widespread cases of fluid flows, but in particular in such cases which cannot be described analytically any longer [16, 17]. This is especially relevant for complex geometries resulting in challenging flow situations. Numerical simulations require a mathematical abstraction in terms of a model. Here, the latter consists of the basic equations of fluid flow, namely the equation of continuity

$$\nabla^+ \cdot \vec{v}^+ = 0$$

and the conservation equation of momentum.

$$\frac{\partial \vec{v}^+}{\partial t^+} + \vec{v}^+ (\nabla^+ \cdot \vec{v}^+) = -\nabla^+ p^+ + \frac{1}{Re} \Delta^+ \vec{v}^+$$

These equations are applied in their dimensionless forms. Here, \vec{v}^+ is the dimensionless velocity, t^+ is the dimensionless time, p^+ is the dimensionless pressure, and Re is the Reynolds number. The equations are valid for a Newtonian, nonpolar, isotherm and inert beverage and they do not take into account the action of gravity [18].

First of all, the geometrical domain is discretised into small control volumes by a structured or unstructured grid. Afterwards, the basic equations of fluid flow are solved for each control volume. For these purposes, the partial differential equations of fluid flow are transferred to an algebraic system which is solved iteratively. The results consist of the pressure and the velocity components arising in the fluid for each control volume and for each time step. These single values are integrated to an entire solution which covers the whole geometrical domain [19].

As the fluid flow in the mouth is strongly affected by the movement of the tongue during deglutition, the simulation domain can be restricted to a tongue-palate model system. The movement of the model tongue as well as the flow curves resulting from the rheological measurements are incorporated as boundary and initial conditions, respectively. Thereby, the initial fluid flow velocity in the computational domain is zero.

The first investigation was based on two parallel plates representing tongue and palate [20], a model that is well established in literature [21, 22]. The process of deglutition is mimicked by moving the lower plate upwards resulting in a squeezing flow.

In order to adapt the system to better reflect real human anatomy the two parallel plates are replaced by ellipsoids (Figure 2). The average curvature is based on measurements of several individual oral cavities from the side and head on [5].

At first, the moving characteristics of the lower ellipsoid was comparable with the one implemented in the model system consisting of two parallel plates. Afterwards, the movement was adapted as

the tongue presses the fluid from the front teeth to the rear part of the oral cavity during the process of deglutition. This means that one narrow side of the geometry representing the rear part of the oral cavity is fixed while the other side representing the tip of the tongue is movable. The assumed velocity of the tongue is 1 cm/s. Therewith, the squeezing flow is replaced by a flow in a wedge [23].

2.4 Descriptive Sensory Evaluation

A trained sensory panel consisting of 30 members evaluated the above mentioned differently concentrated model solutions of xanthan gum according to their mouthfeel. The panel members were asked to describe their sensory sensations and to associate food which owns this mouthfeel afterwards.

These foodstuffs were evaluated and compared to the model solutions within a second session in order to find out the ability of the subjects to disregard those flavour attributes of samples which do not belong to the mechanically induced ones.

2.5 Hybrid System

The hybrid system has the task to merge the two arising data pools, namely the results of the numerical simulations and the results of the descriptive sensory analyses. This is possible by means of cognitive methods. The relevant methods which will be employed are artificial neural networks and fuzzy logic [24, 25, 26].

Artificial neural networks have the feature to learn adaptively as they imitate the functionality of the human nervous system. Hence, they are trained to extract information out of complex data pools efficiently. In the current study, they will be used to generate dimensionless characteristic numbers of normal and tangential stresses on the surface of the model tongue out of specific rheological input and boundary conditions and therewith replace the time consuming numerical simulations in the final hybrid model system.

In contrary to the classical set theory, fuzzy logic is able to specify characteristics gradually. Thus, linguistic descriptions can be mimicked. Membership functions of the input values are generated using the characteristic numbers resulting from the numerical simulations and the artificial neural networks, respectively. The rules which are implemented in the system emanate from expert knowledge. A simplified example reads as follows: "IF the characteristic number at the tip of the tongue = low AND the characteristic number in the rear part of the tongue = middle THEN mouthfeel = watery".

This is the way how the characteristic number of fluid mechanical stresses and the linguistic variables resulting from the descriptive sensory analyses can be interlinked. The resulting hybrid is an expert system which is able to evaluate mechanically induced sensory sensations objectively by taking into account the rheological characteristics of beverages and liquid food only.

3 Results and discussion

In order to establish the hybrid system, it is necessary to create the complete underlying data pools of the numerical simulations and the descriptive sensory analyses both with regard to the rheological measurements at first.

3.1 Rheological Measurements

The different model solutions of xanthan gum as well as the food mentioned during the descriptive sensory analyses were measured

rheometrically. The model solutions and most food complied with the pseudoplastic behaviour of fluid flow. Figure 3 shows the flow curve of a 0.25 % (w/w) solution of xanthan gum measured at 37 °C as an example. The flow curves of the other described solutions of xanthan gum show qualitatively comparable characteristics.

3.2 Modelling and Numerical Simulations

In the first approach, the plate-plate model system works as a proof for the suitability of the applied method. As this model is established in food science, literature offers the possibility to check the validity of the results. Therefore, the dimensionless pressure distribution between the plates was analyzed at the final stage of simulation. The converging plates cause a significant increase of pressure in the system. The pressure distribution along the radius of the plate shows a parabolic form. The numerical simulation yields very similar results [20] compared with the ones of the dimensionless heuristic Stefan equation

$$p^+(r^+) = \frac{3}{Re} R^{+2} \left(1 - \frac{r^{+2}}{R^{+2}} \right)$$

which is valid for thin fluid films in a squeezing flow [27]. Here, p^+ is the dimensionless pressure, r^+ is the dimensionless radial coordinate, Re is the Reynolds number, and R^+ is the dimensionless outer radius of the plates.

Additionally, a shear rate in the order of magnitude of 50 s⁻¹ can be observed. This value is considered as being characteristic for the shear rate in the mouth during deglutition by *Wood* [28] already in 1968 and therewith confirms the validity of the numerical study.

Figure 4 shows the results of the numerical simulation of the tongue-palate model system that corresponds closely with the anatomic tongue-palate system. In order to realise a flow in a wedge the right side of the model tongue is the fixed and the left one moves with the velocity of 1 cm/s. The illustrated results represent the dimensionless velocity distributions near the surface of the tongue which occur due to Newtonian fluid flow behaviour using the implemented viscosities of 10⁻³ Pas as valid for beer [29] and 10⁻¹ Pas after 150 ms. The velocity reaches its maximum values at the front part of the model tongue which comes closest to the model palate [23]. The velocity is made dimensionless by means of the velocity of the tongue movement. The maximum velocities depend on the implemented viscosity. It reaches the dimensionless value of 2.7 in the case of a viscosity of 10⁻³ Pas and 3.6 in the case of a viscosity of 10⁻¹ Pas.

3.3 Descriptive Sensory Evaluation

The most common answers of the subjects when they were asked to describe the mouthfeel of the different solutions of xanthan gum were terms of viscosity as proposed by *Szczesniak* [9]. The most frequently answers were "watery / thin" and "pasty / thick" used in different modifications like "very", "pretty" and "slightly".

Asked for connotations to real food, the answers occurring most frequently were juice, soup, yogurt and pudding. The classifications worked with smooth transitions between the different groups. Many connotations were valid for at least two different solutions.

Afterwards, the subjects classified the mentioned food in decimal ordinal numbers with reference to the solutions of xanthan gum on the basis of which the connotations arose before. By comparison with the reference solutions it was possible to convert the answers into viscosity (Figure 5). An agreement with the measured viscosity at 37 °C which is close to body temperature can be stated. Consequently, the results reveal that the influence of the mechanically induced sensory sensations called mouthfeel can be

investigated detached from other flavour attributes. This mouthfeel can be judged as being one of the single attributes contributing to the measurable factors of drinkability [23].

4 Conclusion – summary

The aim of the current study is to clarify sensory sensations induced by fluid mechanics in the oral cavity. For this reason, two data pools are employed which result from different methods, namely from numerical simulations as well as descriptive sensory analyses, both regarding to the rheological characteristics of the beverages and food. The suitability of the numerical simulation in order to clarify the physical process of deglutition is confirmed by the validation with the help of data published in literature. According to the descriptive sensory analyses, it is important to know that subjects are able to separate mouthfeel from the overall taste impression.

Both data pools are planned to be merged by a hybrid system consisting of artificial neural networks and fuzzy logic. This hybrid is working as an expert system in order to describe and predict mouthfeel objectively by means of rheological characteristics exclusively.

In the case that the intra-oral fluid flow is considered as being an aspect of drinkability, this study offers an option to measure drinkability in a physical manner. Hence, the hybrid tool comprises an interesting potential for the brewing and beverage industry as well as related industries. Knowing how to evoke specific sensations it is possible to adapt the desired mouthfeel best as well as to create drinks that cause a mouthfeel which is completely accepted by the consumer. Additionally, the glass industry can optimize drinkability by knowing the required fluid flow in the mouth to underline the characteristics of a beer or another beverage optimally by designing the adequate glass shape.

5 References

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Appendix

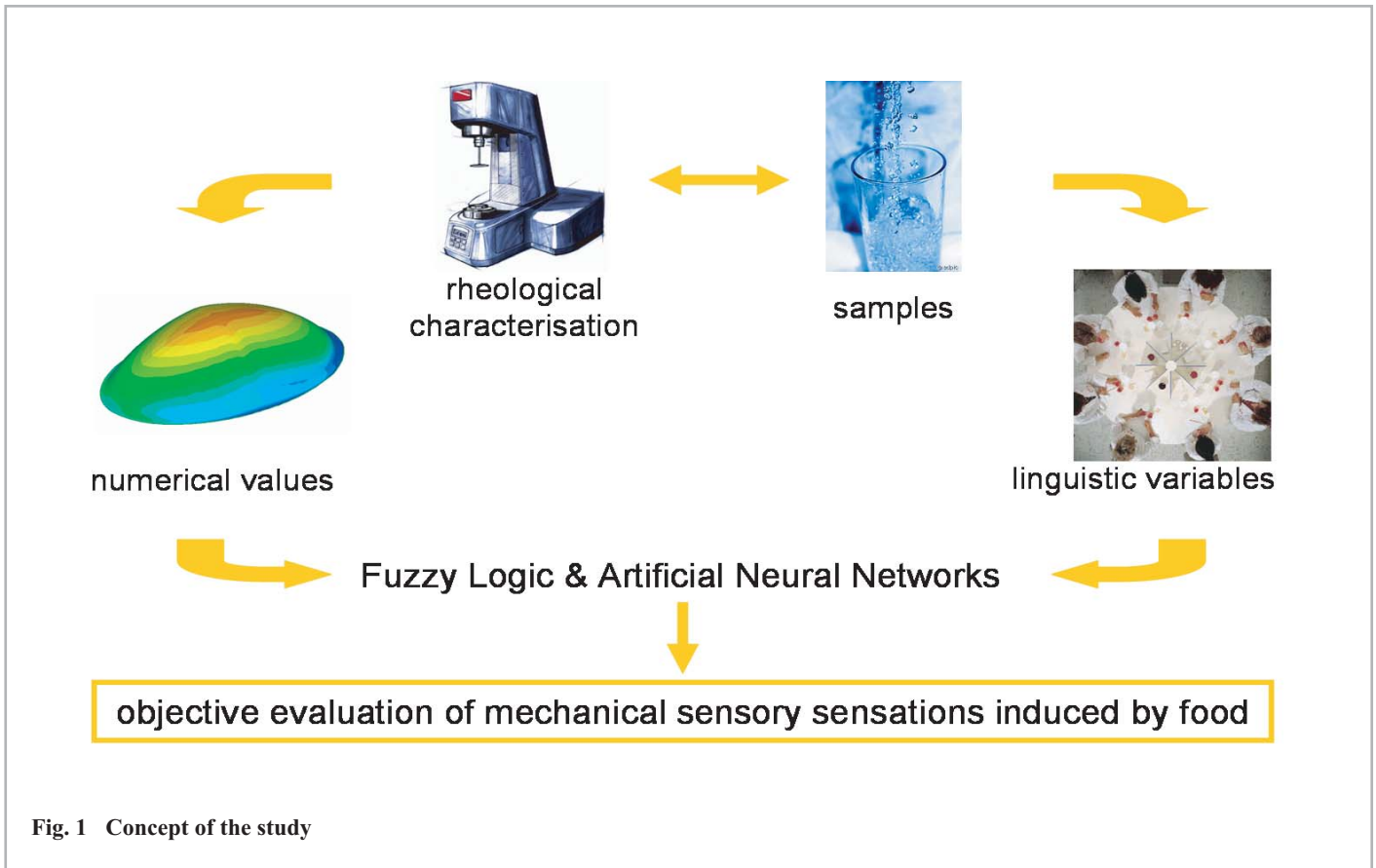


Fig. 1 Concept of the study

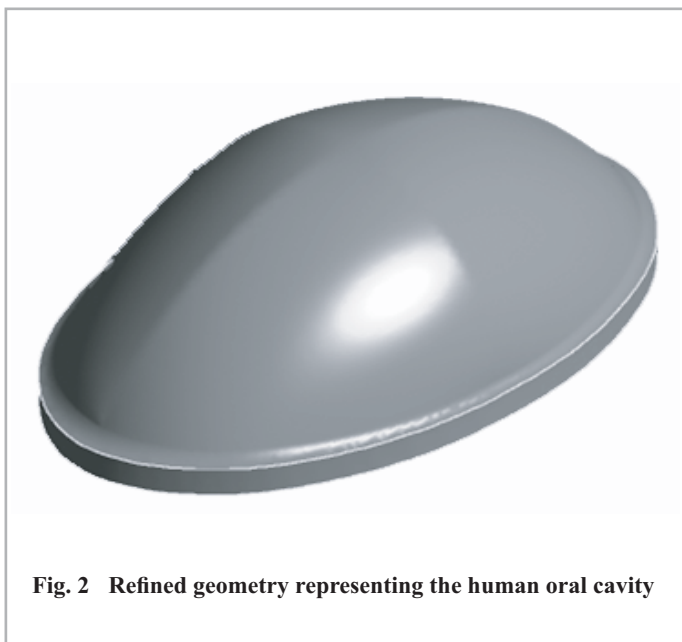


Fig. 2 Refined geometry representing the human oral cavity

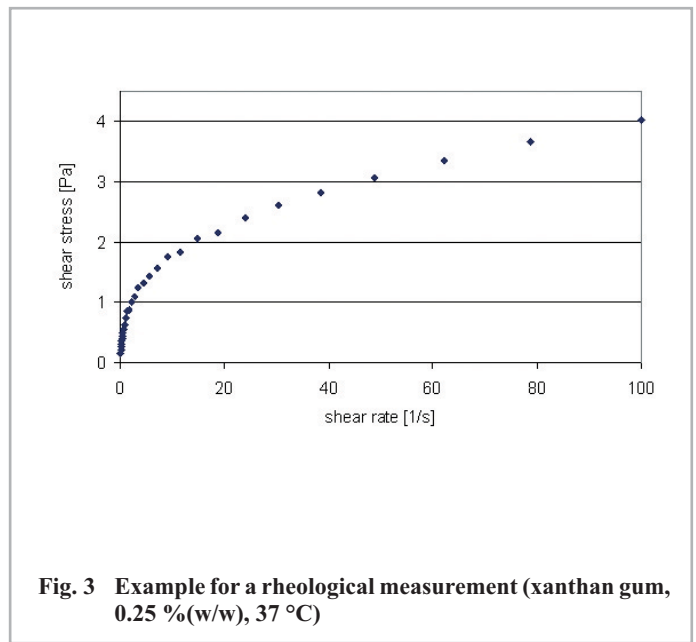


Fig. 3 Example for a rheological measurement (xanthan gum, 0.25 % (w/w), 37 °C)

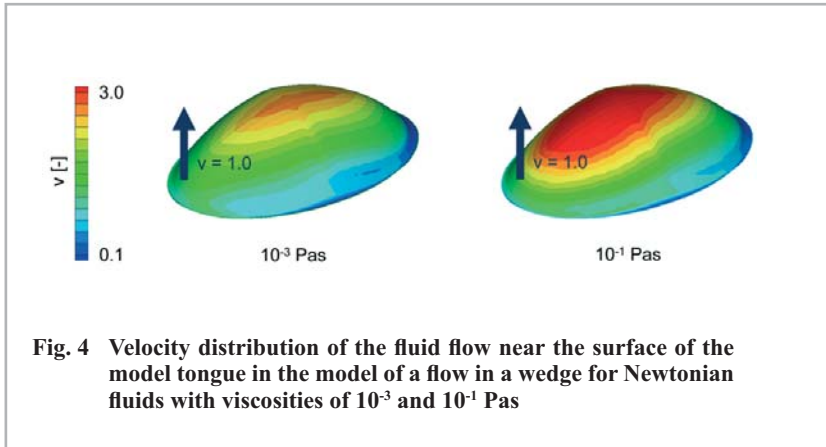


Fig. 4 Velocity distribution of the fluid flow near the surface of the model tongue in the model of a flow in a wedge for Newtonian fluids with viscosities of 10^{-3} and 10^{-1} Pas

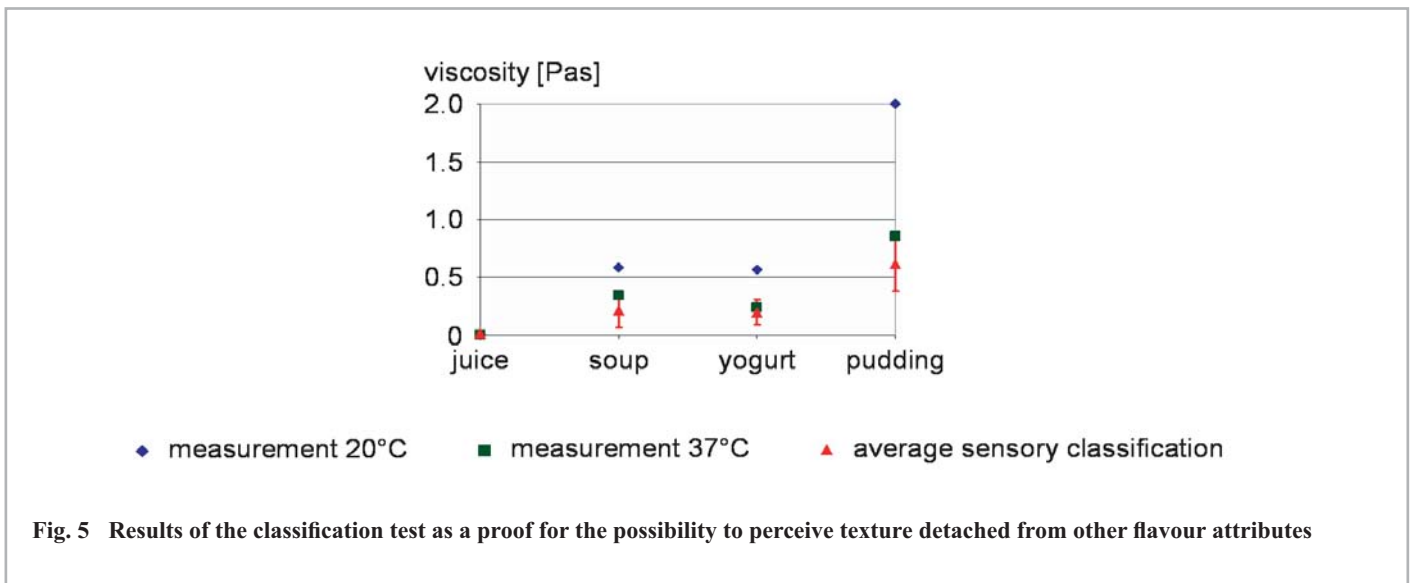


Fig. 5 Results of the classification test as a proof for the possibility to perceive texture detached from other flavour attributes

Received 29 June, 2007, accepted 26 July, 2007