Research consistency of disperse systems by gravitational penetration method

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Keywords:

Penetration
Viscosity
Consistency

Article history:

Received 03.10.2013
Received in revised form 15.12.2013
Accepted 23.12.2013

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ABSTRACT

Introduction. Methods for determining the consistency of food need to be improved, simplified experimental equipment, the development of a single indicator measurements.

Materials and methods. Experimental researches performed on a gravitational penetrometer. Mathematical modeling is made from the analysis of motion of the gravitational force penetrometer.

Results and discussion. On the basis of a theoretical research relating to the instrument design a simple method of determining the consistency of concentrated fluid food disperse systems has been developed. The mathematical model of calculating the resistance of a free-fall penetrometer immersion as the product consistency characteristics has been drawn and explained on a theoretical basis. The model of a free-fall penetrometer motion through a layer of the product, which is based on a second-order differential equation, has been set. The solution has been obtained by the boundary conditions. To simplify the research its differentiation has been completed and the penetrometer immersion speed has been determined.

Conclusions. The results of the research are recommended to be used for various consistency properties of food dispersed systems.

Introduction

The assessment of the consistency is conducted according to organoleptic and physical methods that need improvement. The technological term "consistency" means structural and mechanical properties of the product with the exception of its surface properties: surface rubbing and adhesion.

To control the consistency of food viscometers, consistometers, penetrometers and other devices are commonly used. They are different in design and form the basis of test systems. Efficient functioning of the latter is achieved by the use of modern sensors and measuring devices, mathematical models that describe the process of deformation, piercing, cutting of a product and modern computer technology for processing results. This allows to process the results quickly and efficiently and to determine their authenticity.

In the process of conducting the research the measured parameters are usually reduced to a common characteristic, which can be a marginal shear pressure (static and dynamic), efficient, plastic, dynamic viscosity, elastic modulus, relaxation time and in some cases other parameters. Determining the consistency of food disperse systems empiric dependences are the most common. They have limited possibilities of practical use.

Food products form mostly liquid (coagulation) structures, which have the ability to flow with the destruction of links between the parts creating the frame, and their subsequent restoration, and solid (condensation and crystallization) structures characterized by a relatively strong and resilient frame, which has inherent visco-elastic-plastic properties. It limits the system's ability to flow and renew the form in the event of destruction of the structure. Between liquid and solid products a food group can be identified that form the poorly flowing concentrated disperse systems the deformation. flow and destruction of which begins only after reaching the marginal shear pressure. In this case there is a nonlinear dependency between shear pressure and velocity gradient, and the system usually goes to the flow of destruction and partial structure upgrades. By increasing the speed of deformation zones are formed where the structure is almost completely destroyed and has no time to be updated. These products primarily include disperse systems with weak cohesive links.

The study of deformation and flow of food products based on their structural features is carried primarily on three types of devices. Properties of liquid products are studied by exploring of their ability to flow in the capillary and rotational viscometers, concentrated weak flowing products – in rotational viscometer and penetrometer and solid products – on the load devices by studying the behavior of the product under its tension and compression and needle free-fall penetrometers.

Analytical research shows that a large amount of conflicting data on the structural and mechanical properties of the same product can be found in the literature. They vary greatly especially if during the measurements different instruments and methods are used. It is not connected only with a large variety of materials and a wide range of products, but also with the following reasons.

Firstly, the properties of food raw materials and finished products change over time and depend on technological factors, first of all - temperature, humidity, shelf life, a way of receiving, transportation conditions, duration and type of mechanical stress, etc.

Second, the inadequacies of existing research methods, especially taking into account the complexity of factors related to the nature of the interaction product of work by instrumentation, as well as the environment.

Third, the different behavior of the product, due to the uneven level of destruction of its structure in different ways deformation: three-dimensional, linear, radial, and others, as well as different modes of application of voltage: pulse, fast, slow, etc.

Therefore, in case of the same disperse systems studying applying different methods on different instruments by design, we have to deal with the variety of research results.

So, if in the course of experimental studies the same or similar conditions of deformation can’t be created, it is necessary to specify the method, mode and devices the results were received.

The description of fluid food products’ consistency includes shear properties. They appear under the influence of external forces on the processed product and characterize the behavior of the sample under the action of tangential pressure if it is between two plates that are moving at different speeds. To study the shear properties of fluid food products capillary and rotational viscometers are used. The typical feature of the first one is the movement of the product within the capillary along its walls, and the typical feature of the latter – in coaxial gap between the cylinder and the working part, which is usually also the cylinder but corrugated. At the same time, especially by a small gap between the cylinders, the fluidity of the material close to the shear can be traced.

On capillary and rotational viscometers a fundamentally different types of flows are experimentally implemented. In capillary viscometers measurements are carried out in a non-uniform field of shear and pressure velocity, and the period of the material staying in the capillary is limited. In rotary devices, however, the flow is in the pressure field of a high degree of homogeneity. The significant difference is the fact that a product that got into the capillary is continuously exposed to shear, and thus generates heat that is removed from the material, while in the rotational viscometer's functioning zone the same material is tested throughout the experiment. It heats up which affects the measurement results.

The theory of rotational and capillary rheometry is based on the same assumptions and constraints:

- hypothesis of entirety and continuity of the investigated mass;
- non-slip motion at the wall of the capillary or immovable cylinder;
- the assumption that the investigational product is isotropic;
- the assumption that the movement of the product is stable and the shear regime in coaxial gap is laminar.

The effective viscosity for the temperature regime under examination is given by the formula:

$$\eta_{ef} = \frac{\tau}{w}, \ Pa{\cdot}s$$

where w – average shear strain rate, s^{-1}; τ – shear stress in the capillary or rotational zone, *Pa*.

Materials and methods

Conducting the research on the experimental setup (Figure 1), the sequence of investigations is the following.

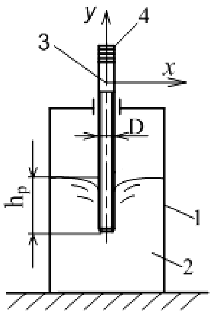

Figure 1. The experimental setup scheme of researching the consistency of concentrated fluid disperse systems

The sample 2 is placed into the cylinder 1. The penetrometer 3 is placed through a hole in the lid so that it touched the surface of the sample. Then the penetrometer is set free and the length t and depth y(t) of immersion can be recorded. There are two ways to conduct the research. According to the first – the penetrometer immerses without stopping, according to the second –it stops after a while.

Depending on this for calculation different computational mathematical models are used. By varying the cargo 4 (the penetrometer's weight) it is possible to change the speed of its immersion into the sample and reach the first or the second method of investigation.

The depth of penetrometer's immersion should not exceed the length of the zone of deposition a special coating on the surface of the penetrometer required for the adhesion of the product to the surface and not slipping. Otherwise, the penetrometer surface can slip through the layer of the material and, consequently, false results of the research will be obtained.

By the slow motion of the penetrometer its velocity determination does not require the use of special devices for simultaneous fixation of depth and duration of immersion, which greatly simplifies the research.

Results and discussion

When plastic and viscous materials with intact structure are studied the method of penetration is widely used. When a conical indenter is used the marginal shear pressure is calculated:

$$\tau = K_1 K_2 K_3 K_4 \frac{m}{h^2}\ ,\ Pa$$

where K, K_1, K_2, K_3 – are coefficients that take into account the various amendments to the research conditions; m – is weight of the cone with the exception of the friction force and spring resistance, if it is provided by its design, kg; h – depth of cone immersion, m.

Research result analysis of structural and mechanical properties of the different texture of food disperse systems using penetration has shown that the calculation mathematical models represented in the literature are empirical. Almost all properties of the product consistency are given by an approximation equation or regression function, which include factors that characterize the links of marginal shear pressure to many structural and technological factors in equipment and production process. These functional dependencies can be used for specific products under given conditions of research. These results depend on a number of subjective and objective reasons that are not included in the research. They have poor reproducibility even when similar devices are used, for example, the design provides a constant or variable load on the penetrometer. The above failures occur primarily due to the lack of reasonable theory that models the process of penetration – immersion of the indenter into the product. Based on the need of theoretical explanation of the penetration mechanism, the authors proposed to build a mathematical model of the penetration of the indenter into its investigational product based on second order differential equations, further solving boundary problems.

When the indenter has the shape of a needle in the moment of contact of the sample in general terms the differential equation of its motion (immersion) into the product will be the following:

$$m\frac{d^2}{dt^2}y(t) + F_{fr} + F_{res} = P_{и} \qquad (1)$$

where *m* – mass of the indenter, *kg; y* – immersion of the indenter into the product; F_{fr}- the resistance that occurs as a result of friction and adhesion, *N;* F_{res} – the force that prevents penetration of the indenter into the product, *N,* P_H – weight of the indenter, *N.*

At work [2], [3] the analysis and solution of equations (1) with initial conditions:

$$t = 0 \rightarrow \ y(0) = 0,\ \frac{dy}{dt} = 0 \ \text{та}\ t = 0 \rightarrow y(0) = 0,\ \frac{dy}{dt} = 0:$$

$$x = f\,(t,\, m,\, y(t),\, D,\, F_{res}), \tag{2}$$

where *D* – is the diameter of the needle; *t* – dive duration; *y* – submersion.

From the equation the resistance is given F_{res}, knowing the characteristics of the penetrometer, having measured the depth y and duration of immersion t. It will describe the product consistency.

The disadvantage of the above model for consistency measuring is the necessity of measuring the length and depth of penetrometer immersion. Taking into account the high initial velocity of its motion ($V = \sqrt{2gh}$), it requires the use of special equipment for video fixation of the process.

In order to eliminate these defects and to develop a simple universal method of investigation, which will allow determining the consistency of the fluid disperse systems of different concentrations, the following model of a free-fall penetrometer motion with a weight m through a layer of the investigated product is proposed.

$$m\left(\frac{d^2}{dt^2}y(t)\right) + \pi D\mu\left(\frac{d}{dt}y(t)\right) - mg = 0, \tag{3}$$

where *m* – is a weight of a penetrometer; *t* – is the depth and time of penetrometer's immersion; D – is the diameter of the penetrometer; μ – typical viscosity, *Pa·s;* $g = 9{,}8$ m/s^2.

Taking into account that the penetrometer is immersed partially, the pushing force (lifting force) is neglected.

The equation solution in general form:

$$y(t) = \frac{mgt}{\pi D\mu} - \frac{m e^{\left(-\frac{\pi D\mu t}{m}\right)} C_1}{\pi D\mu} + C_2 \tag{4}$$

Find constants of differentiation C_1 and C_2 by the initial conditions t = 0, y(0) = 0; $y(t_1) = h_1$ (boundary problem). Finally, we get:

$$y(t) = \frac{e^{\left(-\frac{\pi D\mu t}{m}\right)}(h_1\pi D\mu - mgt_1)}{\pi D\mu\left(-1 + e^{\left(-\frac{\pi D\mu t_1}{m}\right)}\right)} + \frac{mgt}{\pi D\mu} - \frac{h_1\pi D\mu - mgt_1}{\pi D\mu\left(-1 + e^{\left(-\frac{\pi D\mu t_1}{m}\right)}\right)} \tag{5}$$

Defining y(t) and t for a particular fluid disperse system with fixed values m, D, t we calculate μ from the equation (5).

Completing the derivation of the equation (5), we get the speed of a penetrometer immersion:

$$\frac{d}{dt}y(t) = \frac{mgt}{\pi D\mu} - \frac{e^{\left(-\frac{\pi D\mu t}{m}\right)}(h_1\pi D\mu - mgt_1)}{\pi D\mu\left(-1 + e^{\left(-\frac{\pi D\mu t_1}{m}\right)}\right)} \quad (6)$$

The equation (3) solution is obtained using the system of a computer symbolic mathematics “Maple”.

In case the penetrometer stops *dy(t)/dt=0* it is better to use the equation (6). Then measuring the duration t_1 to its stop, the feature of consistency is defined – the viscosity μ.

Given that in food technology the variety of structural and mechanical properties of the fluid disperse systems are used, the choice between equations (5) or (6) depends on each case.

Using a mathematical model (6) we define the characteristic viscosity μ Pa·s of the dispersed food systems, provided $dy(t)/dt=0$ $t = 10s$; $m = 0{,}05$ *кг*; $D = 0{,}005$ *м*; $h_p = 0{,}1$ *м.*

As an example of the practical use of the developed models we defined the viscosity of fondant sugar masses. The fondant was received by sugar syrup boiling followed by whipping and adding flavorings. The samples were studied at a temperature T 45, 55, 65°C.

Substituting in equation (6) experimental data for T = 65 °C, we get:

$$0 = \frac{31{,}21}{\mu} - \frac{20{,}00e^{(-3{,}77\mu)}(0{,}0016\mu - 4{,}9)}{e^{(-3{,}14\mu)}} \quad (7)$$

From equation (7) we find μ:

At a temperature of 45 and 55°C consequently $\mu_{45} = 6103{,}5$; $\mu_{55} = 4405{,}3$ *Pa·s.*

Conclusions

The usage of a free-fall penetration will expand opportunities and will facilitate the study of food disperse systems different by consistency.

The setup to conduct a research is simple in design. Models are based on second order differential equations, which allow you to perform calculations, taking into account the initial conditions at various intervals of experimental research.

The expediency of a mathematical model of a free-fall penetrometer motion through a layer of the product in the study of its consistency has been explained on a theoretical basis and proved by the experiments. Diagram of the device has been given. As an example the viscosity of the disperse system at different temperatures has been determined.

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