

RHEODYNAMIC MODELING OF THE PROCESS OF PERIODIC COMPRESSION OF MINCED MEAT

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The article considers the possibility of using rheology methods for mathematical modeling of the mechanical impact of the working bodies of technological equipment on minced meat as a complex viscoelastic dispersed system. The feasibility of using a mechanical model consisting of parallel-connected elastic and viscous elements for an adequate description of the process of periodic compression of minced meat by a cam mechanism is substantiated. This approach makes it possible to take into account the simultaneous manifestation of elastic and viscous properties of the product during its mechanical deformation. A mathematical apparatus is proposed for determining the main kinematic and power parameters of the process, in particular the movement of the working body, the speed of its movement, the deformation stress, work and energy costs for processing minced meat. Special attention is paid to establishing the relationship between the geometric parameters of the cam mechanism, the angular velocity of its rotation and the rheological characteristics of minced meat, in particular its viscosity and elasticity. Taking into account these parameters makes it possible to predict the nature of product deformation and determine rational operating modes of technological equipment. It is shown that matching the frequency and intensity of periodic compression with the rheological properties of minced meat contributes to a more efficient use of mechanical energy, reducing unproductive energy consumption and preventing excessive destruction of the structural bonds of the product. The proposed approach can be used when designing and improving machines for forming, mixing and mechanical processing of minced meat masses, as well as for selecting the optimal design and operating parameters of their working bodies. The obtained provisions create the basis for further experimental research of the rheological properties of minced meat and the development of energy-efficient technological equipment for the production of meat products.

Keywords: minced meat, rheology, viscoelastic system, cam mechanism, modeling, deformation, stress, energy consumption, forming.

Eq. 6. Fig. 5. Ref. 12.

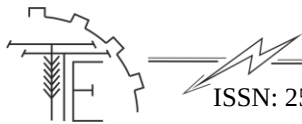
1. Problem formulation

Modern production of meat products requires the improvement of technological equipment that ensures stable product quality, dosing accuracy, uniform formation and reduction of energy costs. One of the important objects of mechanical processing in the meat processing industry is minced meat. By its structure, it is a complex dispersed system that contains crushed muscle fibers, fatty tissue, moisture, protein components, salt, spices and other recipe ingredients.

During mixing, massaging, transportation, dosing and forming, minced meat is subjected to compression, shear, friction and relaxation. Its behavior cannot be described only as the behavior of a perfectly elastic or perfectly viscous body. Minced meat exhibits viscoelastic properties: part of the deformation disappears after the load is removed, and part remains in the form of residual deformation. That is why it is advisable to use rheology and rheodynamics methods for designing working parts of machines.

Of particular importance is the study of periodic compression of minced meat by cam, pusher or piston mechanisms. Such mechanisms can be used in forming, dosing, packaging and pressing machines. The correct





choice of the amplitude of movement, compression frequency and speed of movement of the working body allows to ensure the required density of the product without excessive destruction of its structure.

When designing equipment for processing minced meat, it is necessary to determine the forces, stresses, displacements and power of the machine drive. In practice, these parameters are often taken approximately, without sufficient consideration of the rheological properties of the minced meat. This can lead to excessive energy consumption, unstable product formation, uneven density, disruption of the structure of the protein-fat system and deterioration of the quality of the finished product.

Minced meat is a material whose properties change depending on the degree of grinding, temperature, fat content, moisture, salt, protein additives and the duration of mechanical processing. Therefore, the working elements of the equipment should act on the product not randomly, but in accordance with its structural and mechanical characteristics.

The problem is to create a mathematical model that allows you to describe the process of periodic compression of minced meat by a cam mechanism and determine the optimal deformation modes taking into account viscosity, elasticity, speed of movement of the working element and the duration of product relaxation.

2. Analysis of recent research and publications

The rheological properties of food materials are of considerable importance in the development and improvement of technological equipment, since they determine the relationship between mechanical loading, deformation, structural changes, and energy consumption. The theoretical foundations of rheological modeling of food systems are presented in the works of Rao (2014) [9] and Steffe (1996) [10], which describe the mechanical behavior of viscoelastic materials and methods for determining their structural and mechanical characteristics. The technological aspects of meat processing, including the influence of mechanical treatment on the structure and quality of meat products, are considered by Toldrá (2010) [11].

Particular attention has been paid to the viscoelastic behavior of minced meat and meat emulsions under different processing conditions. Bruno and Moresi (2004) [1] investigated the dynamic viscoelastic properties of Bologna sausages, while Cevik and Icier (2020) [2] examined the influence of thawing methods on the rheological characteristics of minced beef. Karaman et al. (2011) [7] established the influence of temperature and oil concentration on the formation of the protein network and the dynamic mechanical properties of model meat emulsions. Yilmaz et al. (2012) [12] investigated the creep and recovery behavior of meat emulsions using mechanical simulation models, confirming the importance of considering time-dependent deformation processes.

Research by Ukrainian scientists has also contributed to the development of rheological approaches to food processing. Goots et al. (2024) [5] investigated mathematical modeling of meat salting in horizontal drums, while Goots et al. (2025) [6] considered the application of rheological principles to standardized food-forming processes. Kryzhova et al. (2020) [8] examined the influence of formulation components on the structural and mechanical properties of meat systems. The technological requirements for the production of cooked sausage products and chopped meat semi-finished products are regulated by DSTU 4436:2005 [3] and DSTU 4437:2005 [4], respectively.

Despite the available theoretical and experimental studies, insufficient attention has been paid to the integrated mathematical description of periodic compression of minced meat by mechanical working bodies, particularly cam-driven mechanisms. Existing research mainly focuses on determining rheological characteristics, evaluating product structure, and analyzing individual technological operations, whereas analytical relationships between the kinematics of working bodies, viscoelastic resistance, deformation forces, and energy consumption remain insufficiently developed. Therefore, the development of a rheodynamic model that combines the geometric and operating parameters of a cam mechanism with the elastic and viscous properties of minced meat is a relevant scientific and engineering task.

3. The purpose of the article

The aim of the article is to substantiate the mathematical model of periodic compression of minced meat by a cam mechanism based on the viscoelastic rheological model and to determine the main parameters that affect the deformation stress, processing speed, and energy consumption of the process.

4. Results and discussion

Minced meat is a complex food system consisting of crushed muscle fibers, adipose tissue, moisture, proteins, salt and other recipe components. By its properties, it is neither a solid nor a liquid, therefore it is



advisable to consider it as a viscoelastic system.

The elastic properties of minced meat are manifested in the ability to partially restore its shape after compression or other mechanical impact. This is due to the presence of a protein structure and muscle fibers. Viscous properties are manifested in the fact that minced meat resists movement, shear and shaping, and part of the energy is spent on internal friction between product particles.

During the action of the working parts of the equipment - a screw, piston, pusher or forming plate - stresses and deformations occur in minced meat. After removing the load, part of the deformation disappears, but part remains. This confirms the viscoelastic nature of minced meat.

Minced meat should be considered as a viscoelastic system, since its resistance to mechanical stress depends on both the magnitude of the deformation and the rate of its change. Taking into account these properties is important for the correct choice of mixing, molding, injection molding and equipment calculation modes. In this case, it is advisable to consider it as a viscoelastic system, which consists of elastic and viscous elements connected in parallel (Fig. 1).

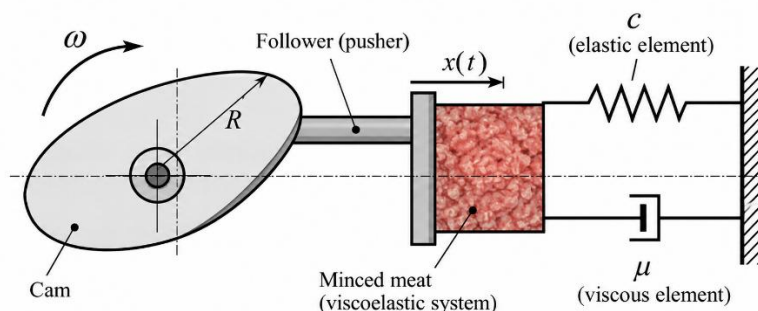


Fig. 1. Scheme of compression of minced meat as a viscoelastic system by a cam mechanism:

R – geometric parameter of the cam mechanism, m; ω – angular velocity of cam rotation, rad/s; $x(t)$ – displacement of the pusher, m; c – elastic stiffness coefficient of the viscoelastic model, N/m; μ – viscous damping coefficient of the viscoelastic model, N·s/m

The elastic element characterizes the ability of the minced meat to partially restore its shape after the load is removed, and the viscous element describes the resistance to internal particle movement, friction between structural components, and energy dissipation.

During the action of the cam mechanism, the pusher or plate periodically compresses the minced meat layer. The movement of the working body can be described by the equation:

$$x(t) = R(1 - \cos \omega t), \quad (1)$$

where $x(t)$ is the pusher displacement; R is the geometric parameter of the cam; ω is the angular velocity of rotation; t is time.

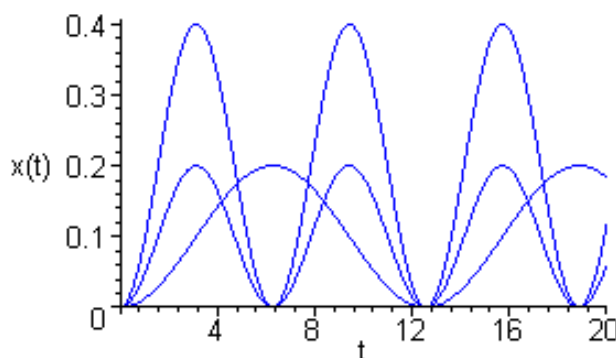


Fig. 2. Dependence of the movement of the cam mechanism pusher on time at different values of R and ω (Fig. 2. Graph $x(t)$ for $(R=0,2\text{m} - \omega=0,5\text{c}^{-1})$; $(R_1=0,1\text{m} - \omega_1=0,5\text{c}^{-1})$; $(R_1=0,1\text{m} - \omega=1\text{c}^{-1})$)

This equation allows us to determine the nature of periodic compression of minced meat. As the parameter R increases, the amplitude of deformation increases, and as the angular velocity ω increases, the frequency of mechanical action increases. For minced meat, this is important, since excessive compression amplitude can cause the product to become denser than the technologically permissible level, and excessive frequency can disrupt the relaxation process.

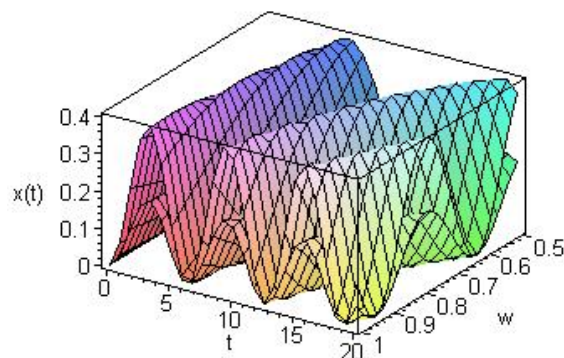


Fig. 3. Spatial dependence of the pusher movement on time and angular velocity of rotation of the cam
(Fig. 3. Dependence $x(t) = \varphi(t, w)$ in the form of a 3D graphic.

The speed of movement of the pusher is determined by differentiating the equation of motion:

$$v(t) = dx(t)/dt = R\omega \sin \omega t. \quad (2)$$

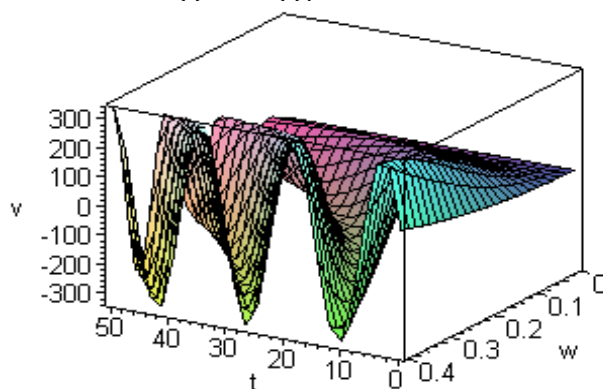


Fig. 4. Dependence of the rate of deformation of minced meat on time and angular velocity of the cam
(Fig. 4. Dependence $v(t) = \varphi(t, w)$ in the form of a 3D graphic.

The deformation rate is one of the key parameters, since minced meat reacts differently to slow and fast compression. With slow compression, the system has time to partially relax, i.e., internal stresses decrease. With fast compression, the stress increases more intensively, which increases the load on the working parts of the equipment and the machine drive.

To describe the deformation force of minced meat, the equation of the viscoelastic model can be used:

$$F(t) = \mu \, dx(t)/dt + c \, x(t), \quad (3)$$

where $F(t)$ is the strain stress; μ is the viscous characteristic of the system; c is the elastic characteristic of the system.

After substituting displacement and velocity, we get:

$$F(t) = \mu R\omega \sin \omega t + cR(1 - \cos \omega t). \quad (4)$$

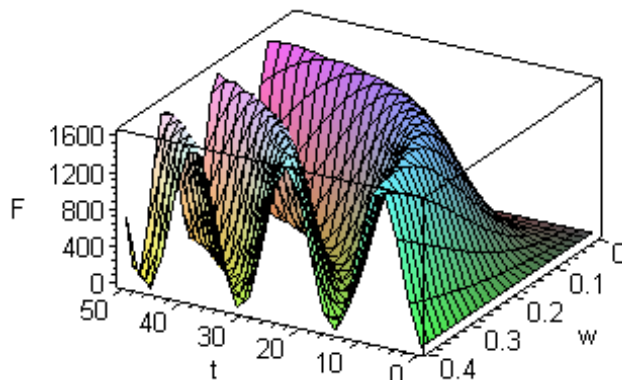


Fig. 5. Dependence of the deformation stress of minced meat on time and angular velocity of rotation of the cam
(Fig. 5. Dependence of the deformation stress of the viscoelastic system on the duration t and angular velocity w of rotation of the cam)



The first component of the equation characterizes the viscous resistance of the minced meat, which depends on the deformation rate. The second component characterizes the elastic resistance, which depends on the magnitude of the displacement of the working body. Therefore, the deformation stress is determined simultaneously by the kinematics of the mechanism and the structural and mechanical properties of the product.

For minced meat, the elastic characteristic depends on the protein structure, the degree of meat grinding, the content of connective tissue and the ability of the system to retain moisture. The viscous characteristic is related to humidity, fat content, temperature, the amount of salt and the degree of dispersion. Increasing the temperature usually reduces the viscosity of the minced meat, but excessive heating during mechanical processing can deteriorate the structure of the product.

It is important that the compression frequency corresponds to the relaxation time of the minced meat. If the next compression cycle begins before the relaxation is complete, residual deformations accumulate in the product. This can be useful when compacting or forming products, but undesirable when producing products where it is necessary to maintain a loose or juicy structure.

The specific work of deformation can be determined by integrating the stress over the displacement:

$$A = \int F(t) dx(t). \quad (5)$$

This indicator characterizes the amount of energy spent on compressing a unit of area or volume of minced meat. For equipment of meat processing enterprises it is important when choosing the drive power, calculating the strength of parts, assessing productivity and optimizing operating modes.

The deformation power is defined as the derivative of work with respect to time:

$$N = dA/dt. \quad (6)$$

The power depends on the amplitude of compression, the angular velocity of the cam, the viscosity and elasticity of the minced meat. An increase in the speed of rotation of the cam leads to an increase in power, but does not always improve the quality of molding. Therefore, optimization should be performed not only according to the criterion of productivity, but also according to the criterion of preserving the structure of the product.

For practical use, the model can be used in the design of molding machines for cutlets, meatballs, sausage loaves, semi-finished products and meat products of a given geometric shape. It allows you to determine the permissible compression modes, at which the compaction of the minced meat is ensured without excessive destruction of the protein-fat structure.

The optimal operating mode of the cam mechanism should provide:

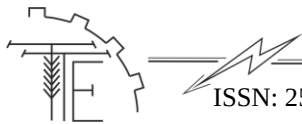
- uniform compression of the minced meat;
- sufficient time for relaxation after loading;
- minimal energy consumption;
- absence of excessive residual deformation;
- stable shape of the finished product;
- preservation of moisture-binding capacity and texture of the product.

Thus, rheological modeling makes it possible to move from the empirical selection of equipment operating modes to the scientifically based design of machines for processing minced meat.

5. Conclusion

The theoretical analysis substantiated the feasibility of considering minced meat as a complex viscoelastic dispersed system, whose mechanical behavior is determined by the combined influence of viscous and elastic properties, temperature, recipe composition, and degree of grinding. The application of a rheological model consisting of parallel-connected elastic and viscous elements makes it possible to describe the deformation behavior of minced meat under periodic mechanical loading and establish relationships between its structural and mechanical characteristics and the operating parameters of technological equipment.

The process of periodic compression of minced meat by a cam mechanism was mathematically described using the displacement equation $x(t)=R(1-\cos\omega t)$. Based on this relationship, analytical dependencies were obtained for determining the displacement and velocity of the working body, deformation force, mechanical work, and power consumption. It was established that the geometric parameter of the cam determines the compression amplitude, while the angular velocity of its rotation affects the frequency and rate of deformation, thereby influencing the mechanical loading conditions of the processed material.



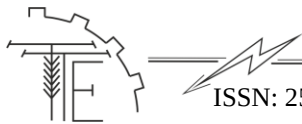
The deformation resistance of minced meat was shown to consist of two interrelated components: viscous and elastic. The viscous component depends on the velocity of the working body and the viscous characteristics of the product, whereas the elastic component is determined by the magnitude of deformation and the elastic properties of the material. The proposed mathematical relationships make it possible to evaluate the influence of these components on the total deformation force and provide a theoretical basis for calculating the energy parameters of the compression process.

The importance of coordinating the frequency and intensity of periodic compression with the time-dependent rheological characteristics of minced meat was substantiated. Taking into account the relationship between loading frequency and the characteristic deformation and recovery time of the material is necessary when selecting rational operating modes of technological equipment. Such an approach creates prerequisites for limiting excessive mechanical loading, reducing unnecessary energy consumption, and maintaining the required structural and textural characteristics of meat products.

The proposed rheodynamic modeling approach can be used in the design and improvement of cam, piston, and forming mechanisms intended for the production of chopped meat semi-finished products, sausages, and other formed meat products. The obtained analytical dependencies provide a theoretical basis for substantiating the design and operating parameters of working bodies, evaluating mechanical loads, and estimating energy requirements during minced meat processing. Further research should focus on experimentally determining the rheological coefficients of minced meat, verifying the adequacy of the developed mathematical model, and establishing rational compression parameters that ensure the required product quality with reduced energy consumption.

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**РЕОДИНАМІЧНЕ МОДЕЛЮВАННЯ ПРОЦЕСУ ПЕРІОДИЧНОГО СТИСКАННЯ
М'ЯСНОГО ФАРШУ**

У статті розглянуто можливість застосування методів реології для математичного моделювання механічного впливу робочих органів технологічного обладнання на м'ясний фарш як складну в'язко-пружну дисперсну систему. Обґрунтовано доцільність використання механічної моделі, що складається з паралельно з'єднаних пружного та в'язкого елементів, для адекватного опису процесу періодичного стискання фаршу кулачковим механізмом. Такий підхід дає змогу врахувати одночасний прояв пружних і в'язких властивостей продукту під час його механічного деформування. Запропоновано математичний апарат для визначення основних кінематичних і силових параметрів процесу, зокрема переміщення робочого органу, швидкості його руху, напруги деформування, роботи та енергетичних витрат на оброблення фаршевої маси. Особливу увагу приділено встановленню взаємозв'язку між геометричними параметрами кулачкового механізму, кутовою швидкістю його обертання та реологічними характеристиками м'ясного фаршу, зокрема його в'язкістю і пружністю. Врахування зазначених параметрів дає можливість прогнозувати характер деформації продукту та визначати раціональні режими роботи технологічного обладнання. Показано, що узгодження частоти та інтенсивності періодичного стискання з реологічними властивостями фаршу сприяє ефективнішому використанню механічної енергії, зменшенню непродуктивних енерговитрат і запобіганню надмірному руйнуванню структурних зв'язків продукту. Запропонований підхід може бути використаний під час проєктування та вдосконалення машин для формування, перемішування й механічного оброблення м'ясних фаршевих мас, а також для вибору оптимальних конструктивних і режимних параметрів їх робочих органів. Отримані положення створюють основу для подальшого експериментального дослідження реологічних властивостей фаршу та розроблення енергоефективного технологічного обладнання для виробництва м'ясних виробів.

Ключові слова: фарш, реологія, в'язко-пружна система, кулачковий механізм, моделювання, деформація, напруга, енерговитрати, формування.

Ф. 6. Рис. 5. Літ. 12.

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