UDC 641.512+541.64

# MECHANISM OF THE HIGH EFFICIENCY OF THE CUTTING FROZEN FOOD PRODUCTS USING WATER-JET WITH POLYMER ADDITIONS

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**Abstract.** The article to determine peculiarities of macromolecule deformation behavior under conditions of a jet-shaping head that would allow to solve the issue related to the mechanism of increasing water-jet cutting power with polymer additions. In converging polyethyleneoxide solution flow macromolecules are forced by a hydrodynamic field to rather strong stretching that causes the dynamic structure formation in solutions. There have been studied experimentally velocity fields and their gradients as well as the degree of macromolecule unrolling under pattern conditions of a jet-shaping head in poluyethyleneoxide solutions flow. In converging polymer solution flow macromolecules are forced by a hydrodynamic field to rather strong (~ 60 % and more) stretching that causes the field restructuring. The determined regularities of macromolecules behavior in the flow under conditions of a jet-shaping head and manifested in this case effects of elastic deformations have paramount importance in understanding the mechanism of «anomalously» high cutting power of water-polymer jet. The work for the first time makes it possible to explain the nature of increased water-jet cutting power with polymer additions when cutting food products. Understanding the nature of increased cutting power of water-polymer jet will make it possible to develop recommendations on choosing regimes for water-polymer jet processing of food products by cutting.

**Keywords:** polymer solution, food products, polyethyleneoxide, velocity, hydrodynamic field, velocity gradient, deformation effects.

# МЕХАНІЗМ ВИСОКОЇ ЕФЕКТИВНОСТІ РІЗАННЯ ЗАМОРОЖЕНИХ ХАРЧОВИХ ПРОДУКТІВ ВОДЯНИМ СТРУМЕНЕМ З ПОЛІМЕРНИМИ ДОМІШКАМИ

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**Анотація.** Вивчено особливості деформаційної поведінки макромолекул в умовах струменеформувальної голівки, які дозволили вирішити проблему, пов'язану з механізмом аномально високої ріжучої здатності водополімерного струменя. Доведено, що при течії розчинів полімеру в умовах ріжучої голівки макромолекули піддаються сильному деформаційному впливу гідродинамічного поля, що призводить до динамічного структуроутворення в розчинах. Експериментально вивчено поля швидкостей і їхніх градієнтів, а також ступінь розгорнутості макромолекул у модельних умовах струменеформувальної голівки під час течії водного розчину поліетиленоксиду. У збіжному потоці розчину полімеру макромолекули під дією гідродинамічного поля піддаються досить сильному (~ 60 % і більше) розгортанню, що викликає перебудову структури поля. Встановлено закономірності поведінки макромолекул при течії в умовах струменеформувальної голівки і ефекти пружних деформацій, що проявляються в цьому випадку мають першорядне значення в розумінні механізму аномально високої ріжучої здатності водополімерного струменя. Робота вперше дозволяє пояснити природу збільшення ріжучої здатності гідро струменя з полімерними домішками при обробці харчових продуктів різанням. Розуміння природи підвищеної ріжучої здатності водополімерного струменя дозволить розробити рекомендації щодо вибору режимів струменевої водополімерної обробки харчових продуктів різанням.

**Ключові слова:** полімерний розчин, харчові продукти, поліетиленоксид, швидкість, гідродинамічне поле, градієнт швидкості, деформаційні ефекти.



DOI: http://dx.doi.org/10.15673/fst.v11i2.517

## Introduction

The works [1-3] complex studying of the process of hydro-cutting frozen food products is carried out. It has given the chance to offer the most expedient ways of intensification of the process of hydro-cutting frozen food products. It has been experimentally proven that using polyethyleneoxide (PEO) water solutions as a working liquid while cutting frozen food products substantially increases efficiency of hydro-cutting process and quality of the cut surface.

The works [3-6] deals with the regularities of the frozen food products hydrocutting to increase its efficiency and to improve the quality of cut surface by working liquid modification. The influence of PEO concentration on cutting depth and rate for food frozen at –25 °C by pressure water-polymer jet of 100 MPa flow pressure and $0.37\cdot10^{-3}$ m nozzle diameter is investigated. It is experimentally proved that when PEO water solutions as a working liquid are used the optimum distance between nozzle edge and food surface increases 15 times, cutting depth at cutting speed of $0.100$ m$\cdot$s$^{-1}$ – of 4 times, and the quality of the cut surfaces is also improved. In connection with this, it is important to know physical mechanism of the observed effect.

Among the attempts to explain the nature of the effect of water-polymer jet anomalously high cutting power a special place is held by an approach based on deformation impact of hydrodynamic field on macromolecules. To substantiate this approach it is necessary to prove experimentally the presence of strong deformation impact of hydrodynamic field under conditions of a jet-shaping head. The research of converging currents has shown that it is possible to generate flow with predominantly longitudinal velocity gradient, i.e. to simulate conditions that appear in a jet-shaping head, with the help of a short capillary tube [4,5].

**Objective** – to determine peculiarities of macromolecule deformation behavior under conditions of a jet-shaping head that would allow to solve the issue related to the mechanism of increasing water-jet cutting power with polymer additions, and the quality of the frozen food products cut surfaces.

## Methods and materials

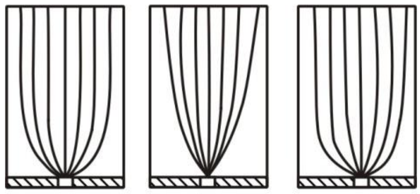
In this study, velocity and velocity gradient fields as well as the degree of the coil-stretch transition at the entrance of the capillary were investigated for various flow regimes. A flow viscometer with an entrance angle of 180° was used. The instrument contained a cell having a rectangular cross-section $(10\times17)\cdot10^{-3}$ m and height of $8\cdot10^{-2}$ m and two short removable capillaries having the following diameter and length, respectively: $0.5\cdot10^{-3}$ and $0.21\cdot10^{-3}$ m (capillary I) and $0.37\cdot10^{-3}$ m and
$1.1\cdot10^{-3}$ m (capillary II). The velocity field at the entrance of the capillaries was measured using a laser Doppler anemometer according to the method [5]. The average flow rate **ū** was measured volumetrically using a photo-electronic system; the flow downstream the capillary inlet was submerged. PEO having the viscosity-average molecular weight of $M_{PEO}$ = $3\cdot10^6$, $4\cdot10^6$, $6\cdot10^6$ and hydrolyzed polyacrylamide (HPAA) with molecular mass $4.5\cdot10^6$ were used as a polymeric additive. The degree of PAA hydrolysis was 5 percent.

The methods of $\mathbf{\Delta n_\infty}$, calculations and experimental procedure of Δn measurements are given elsewhere [6,7]. The solutions were prepared in the following manner. A previously (one week before) prepared 0.1 % solution of PEO was diluted with distilled water. Additives of 0.05 % potassium iodide were introduced to exclude degradation of the polymer solutions upon storing.

## Results and their discussion

*3.1. Dynamic structure formation in solutions polymers*. Let's examine the tests allowing to reveal the ability of solutions polymers to dynamic structure formation effected by hydrodynamic field with stretching. To create hydrodynamic field with stretching there has been used a flow of Newtonian liquid converging to a small outlet $0.3\cdot10^{-3}$ m in diameter. At quite a distance from the outlet there have been injected in this flow some jets of PEO solutions or HPAA.

Polymer solution velocity in points of injection agreed with velocity of the main liquid flow. Visualization of the flow in the inlet area was done with the help of dye additives injected into polymer solution. Under small outflow velocities dyed jets of polymer solution visualize stream-lines of the main flow (fig. 1).



a) b) c)

$M_{PEO} = 6\cdot10^6$, $C_{PEO}$=0.025 %; $M_{HPAA} = 4.5\cdot10^6$, $C_{PEO}$=0.05 %;

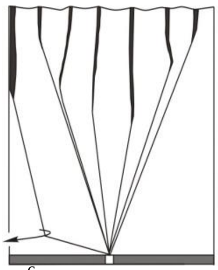
a) water into water at $\acute{\varepsilon} > \acute{\varepsilon}_{cr}$; b) HPAA into water at $\acute{\varepsilon} > \acute{\varepsilon}_{cr}$; c) PEO into water at $\acute{\varepsilon} < \acute{\varepsilon}_{cr}$

**Fig. 1. Picture of flow in the inlet area of a capillary when injecting polymer solution into water during precritical mode of outflow**

In his case behaviour of PEO and HPAA solution jets doesn't differ at all from the behaviour of water jets injected into converging liquid flow. Reaching some critical flow rate of liquid through the orifice the character of jet flow of polymer solution drastically changes. Rather thick polymer jets transform into thin threads that change their length with time flow (fig. 2).

When observing the dynamics of forming and destructing separate threads (here lies the moving pulsation character of the flooded polymer jets) the following regularity comes to life. At the beginning when polymer jets approach the orifice there can be traced their gradual bend towards the orifice. Here their velocity growth along these curve trajectories becomes more noticeable as the jet thickness gets reduced. Near the orifice discontinuous (for PEO solutions) reduction of jets thickness takes place as they are transformed into thin threads. Transformation area of a thick jet into a thin thread starts to shift up along the jets resulting in the increase of the thread length. HPAA water solutions reveal more gradual change of jet thickness than PEO solutions. As jets approach the orifice not concurrently the length of threads spun by the flow from separate polymer jets is different at each given moment. Birefringence is observed in the area of thread emergence.

When reaching some critical length a thread cuts off in close proximity to the orifice. After that the remaining at the top thread loses its elasticity and sags marking one of the stream lines of the main flow. When a polymer jet approaches the orifice again the whole thing is repeated anew. This process is resumed with time interval from fractions of a second to several seconds depending upon the outflow mode of the main flow, polymer molecular mass, polymer type, solvent quality and temperature, as well as polymer concentration in solution.



$M_{PEO} = 6\cdot10^6$, $C_{PEO}$=0.03 %, $\bar{u}$ = 2.5 m·s$^{-1}$

**Fig.2. Photo of flow at the point of wire probe effecting a polymer thread spun by hydrodynamic field**

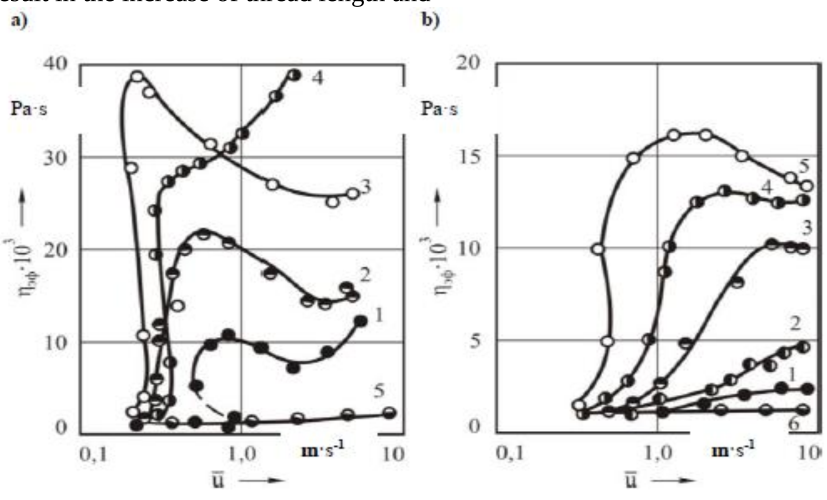
Outflow velocity growth of converging water flow as well as increase of molecular mass and polymer concentration result in the increase of thread length and reduction of their length-changing rate. Temperature growth leads to the opposite effect. Tests with acetone and dioxan (solvents with poorer thermodynamic qualities than water) showed that under the same velocities as in tests with water pulsation rate of thread length is bigger, but the amplitude of these changes is less than in case of injecting polymer solution into water. It should be also stressed that there are such ejection modes for concentrated (to Debay $[\eta]_0\cdot C > 1$) polymer solutions, when the emerged polymer threads don't cut off during the whole period of observation.

So, the results obtained by us show that dynamic structure formation and periodic processes subjected to Prigozhin's principles of self-organization may occur in polymer solutions in flow with stretching, i.e. unde jet-shaping head in model conditions.

*3.2. Distortions of the Molecular Shape of Polymers unde jet-shaping head conditions*

Data describing the influence of discharge velocity on effective viscosity of water PEO solutions with different concentrations for molecular weights of $4\cdot10^6$ and $6\cdot10^6$ at 25 °C are given on fig. 3.

It can be seen, that the phenomena, unusual for purely viscous mediums are characteristic of such currents. At certain critical (threshold) values of average exhaust velocity $\bar{\mathbf{u}}$ the relative pressure differential begins sharply to increase, and it is the sharper the more is the concentration of polymer in a solution. The marked character of dependence $\xi = f(\bar{u})$ testifies about high dissipation (sometimes, than is on 2 orders of magnitude more) of energy during the course of solutions of polymers through an slot i.e. the increased hydrodynamic resistance on supercritical flow rates is observed

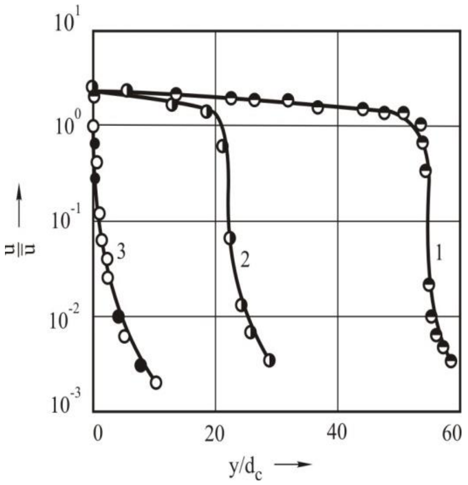



a) $d_k$= $0.34\cdot10^{-3}$ m, $l_k$=$10^{-3}$ m, $M_\eta = 4\cdot10^6$, $C_{PEO}$: 1 – 0,01 %, 2 – 0.02 %, 3 – 0.05 %, 4 – 0.1 %, 5 – water; b) $d_k$ = $0.12\cdot10^{-3}$ m, $l_k$ =$0.2\cdot10^{-3}$ m, $M_\eta = 3\cdot10^6$, $C_{PEO}$: 1 – 0.0005 %, 2 – 0.001 %, 3 – 0.002 %, 4 – 0.003 %, 5 – 0.004 %, 5 – water

**Fig. 3. Dependence of effective viscosity of water PEO solutions on average discharge velocity**

Transition to a mode of current with an increased dissipation of energy is accompanied by formation of the source flooded jet as «cord» enclosed by secondary currents in the shape of a ring-shaped vortex. In case of supercritical mode of current for area of the concentration lying between very diluted and moderately concentrated solutions of polymers, there happens rather strong deformation effect of a hydrodynamic field on molecular chains.

To interpret the data, the structure of the hydrodynamic field and degree of the molecular shape distortions induced by the field should be evaluated. Distribution of the flow rate along the flow axis for 0.05 % PEO solution in dimensionless coordinates is depicted in fig. 4. It can be seen that, before the critical flow regime is attained, the increase of the effective viscosity is not exhibited and the axial distributions of velocity for the polymeric solution and pure water are almost the same (curve 3) and filled circles on curve 3, respectively. After passing through the critical flow regime, the curves exhibit a considerable deformation and development of the axial velocity profile (curves 1 and 2 in fig. 4).




Flow through the capillary I at the average flow rate $\bar{u}$ = 2.5 m·s$^{-1}$ (1), flow through the capillary II at $\bar{u}$ = 0.8 m·s$^{-1}$ (2), and through the capillary II at $\bar{u}$ = 0.5 m·s$^{-1}$ (3). Filled circles represent the data for water when $\bar{u}$ = 0.8 m·s$^{-1}$

**Fig. 4. Velocity distribution for the polymer solution along the flow axis.**

The latter curves have at least two linear regions. Using the experimental velocity distributions along the flow axis, the respective rate gradient distributions were calculated (fig. 5). It can be seen that the maximal rate gradient $\varepsilon_{max}$, occurs not at the entrance of the capillary, but at some distance from that (fig. 5,a, curve 2). The $\varepsilon_{max}$ at the entrance of the capillary for polymeric solution is considerably lower that for water. Hence, the hydrodynamic field results in perturbation of the macromolecules, which, in turn, affects the velocity field in such a way that the longitudinal velocity gradients are decreased.

Thus, the longitudinal velocity gradient at the flow axis does not exceed 30 s$^{-1}$. An increase in molecular weight of the polymer and its concentration also results in decrease of the longitudinal gradient at the flow axis. Thus, the respective value for 0.2 % PEO solution and capillary I at the average flow rate 2 m·s$^{-1}$ is equal to 10 m·s$^{-1}$. Fig. 5,b illustrates that the longitudinal rate gradient at the axis of the flooded jet as «cord» (curve 3) and maximal value of the rate gradient at the entrance of capillary (curve 2) are only slightly dependent on the average flow rate through the capillary.

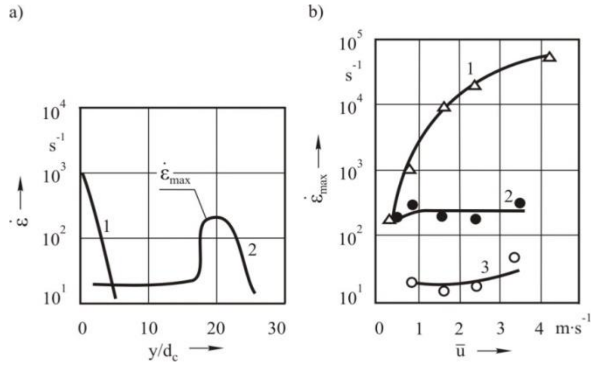
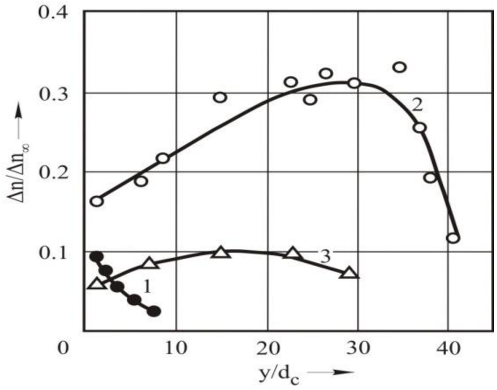



**Fig. 5. (a) – Velocity gradient distribution along the flow axis at $\bar{u}$ = 0.8 m·s$^{-1}$ for water (1) and 0.05% PEO solution (2).** Measurements were performed with the capillary I; (b) – Dependence of the maximal longitudinal velocity gradient on the average flow rate for water (1) and 0.05 % PEO solution (2) and $\dot{\varepsilon}$ in the vortex for 0.05 % PEO solution (3).

The observed changes in the structure of the hydrodynamic field can be associated with large distortions of the macromolecular coils induced by hydrodynamic field, leading to non-linear elasticity effects. The degree of the coil-stretch transition may be estimated from the value of the deformational factor $(\Delta n/\Delta n_\infty)_{max}$, where **Δn** is the experimental flow birefringence value, while the $\Delta n_\infty$, is the limiting value of the flow birefringence calculated at the given concentration of polymer [8].

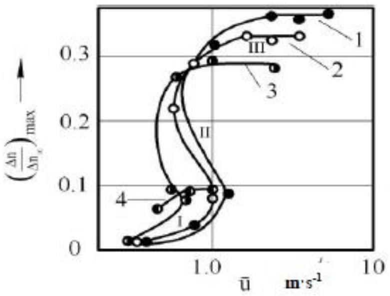
Results of the studies of the influence of hydrodynamic field on the polymeric solution are depicted in fig. 6. The value of deformational factor increases when approaching the entrance of the capillary for the average flow rate equal to the critical value (curve 1) and reaches its maximum at rather high $\bar{u}$ values (curve 2). The maximum position of the deformational factor $(\Delta n/\Delta n_\infty)_{max}$, at the entrance of the capillary corresponds to the domain with maximal longitudinal velocity gradient (fig. 5,a, curve 2).

The obtained distribution of the deformational factor over the flow axis at the entrance of the capillary (fig. 4) envisages the possibility of a high degree of coil-stretch transition under the free-converging flow conditions. The flow birefringence ratio attains the value of 0.29 – 0.37, which corresponds to ~60 % and more coil-stretch transition degree. Increasing the polymer concentration results in a decrease of the deformational factor (curve 3).




$C_{PEO}$ = 0.3 % (1), ū = 1 m·s$^{-1}$; $C_{PEO}$ = 0.03 % (2), ū = 2.5 m·s$^{-1}$; $C_{PEO}$ = 0.1 % (3), ū = 1 m·s$^{-1}$

**Fig. 6. The distribution of the coil-stretch transition degree over distance from the entrance of the capillary for aqueous PEO solution**




$d_k = 0{,}5\cdot 10^{-3}$ m, $l_k = 0{,}21\cdot 10^{-3}$ m, $M_{PEO}$: $6\cdot 10^6$ (1), $4\ 10^6$ (2), $3\cdot 10^6$ (3); $C_{PEO}$ = 0.03 %; $M_{PEO}$: $4\cdot 10^6$; $C_{PEO}$ = 0.1 % (4)

**Fig. 7. Dependence of the coil-stretch transition degree on average flow rate**

Fig. 7 envisages deformational behavior of macromolecules at the different flow rates. It can be seen that the $(\Delta n/\Delta n_\infty)_{max}$, versus average flow rate dependence may be divided onto three domains. Domains 1 and 3 are characterized by a monotonic increase of the coil size with growth of the flow rate, while in the intermediate domain 2 the transition is rather sharp. From a comparison of Figures 3 and 5, it can be concluded that an increase of the **ū** in the domain I is accompanied by growth of the longitudinal velocity gradient, which results in an increase of the size of the coils. Otherwise, the reverse stretch-coil transition occurs [9,10] and macromolecules decrease their influence on the velocity field, which, in turn, results in a steep increase of the velocity gradient. This will lead to the coil-stretch transition and all the above processes will happen once again.

Hence, the stable state is characterized by the minimal value of the velocity gradient which is sufficient for a sharp coil-stretch transition. Increase in the flow rate results in some additional growth of the deformational factor due to nonlinear effects (fig. 7, domain 3) sufficient for stability of the rate gradient field of the chosen polymeric system (fig. 5,b, curve 2).

## Conclusion

The determined regularities of macromolecules behavior in the flow with longitudinal velocity gradient and manifested in this case effects of elastic deformations have paramount importance in understanding the mechanism of anomalously high cutting power of water-polymer jet processing of foodstuffs by cutting. The nature of the anomalously high efficiency of hydro-jet water-polymer processing of food products by cutting is explained quite well from the point of view of the strong deformation effect of the hydrodynamic field on molecular coils. The outflow of water appears to be armed macromolecules and dynamic structures stretching to a large extent. Part of its energy goes into a structural reorganization of the flow, which leads to an increase in the compactness of the jet with polymer additives. The latter circumstance is favorable for increasing the threshold distance from which the material is still cut, and the quality of the cut frozen food products surfaces is also improved (fig. 8).

**a** **b**

**Fig. 8. Photos of the cut surfaces by jets in a frozen pork meat: a) – the hydro-jet water-polymer; b – the water jet**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# МЕХАНИЗМ ВЫСОКОЙ ЭФФЕКТИВНОСТИ РЕЗАНИЯ ЗАМОРОЖЕННЫХ ПИЩЕВЫХ ПРОДУКТОВ ВОДНОЙ СТРУЕЙ С ПОЛИМЕРНЫМИ ДОБАВКАМИ

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**Анотація.** Изучены особенности деформационного поведения макромолекул в условиях струеформирующей головки, которые позволили решить проблему, связанную с механизмом аномально высокой режущей способности водополимерной струи. Доказано, что при течении растворов полимера в условиях режущей головки макромолекулы подвергаются сильному деформационному воздействию гидродинамического поля, что приводит к динамичному структурообразованию в растворах. Экспериментально изучены поля скоростей и их градиентов, а также степень развернутости макромолекул в модельных условиях струеформирующей головки при течении водного раствора полиэтиленоксида. При сходящемся течении раствора полимера макромолекулы подвергаются весьма сильному (~ 60 % и более) разворачиванию под действием гидродинамического поля, что приводит к перестройке структуры этого поля. Установленные закономерности поведения макромолекул при течении в условиях струеформирующей головки и проявляющиеся при этом эффекты упругих деформаций имеют определяющее значение в понимании механизма аномально высокой режущей способности водополимерной струи. Работа впервые позволяет объяснить природу увеличения режущей способности гидроструи с полимерными добавками при обработке пищевых продуктов резанием. Понимание природы повышенной режущей способности водополимерной струи позволит разработать рекомендации по выбору режимов струйной водополимерной обработки пищевых продуктов резанием.

**Ключевые слова:** полимерный раствор, пищевые продукты, полиэтиленоксид, скорость, гидродинамическое поле, градиент скорости, деформационные эффекты.

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Отримано в редакцію 18.03.2017 Received 18.03.2017
Прийнято до друку 24.04. 2017 Approved 24.04. 2017