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## ELASTIC DEFORMATIONS AND ANOMALOUSLY HIGH CUTTING ABILITY OF A POLYMER SOLUTION JET

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**Summary.** 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. 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 PEO 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. 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.

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

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**Introduction.** The problem of developing innovative cutting equipment remains one of the important problems in the development food enterprises. The works [1 – 3] deals with the regularities of the frozen foodstuff hydrocutting to increase its efficiency and to improve the quality of cut surface by working liquid modification. The influence of polyethylene oxide (PEO) concentration on cutting depth and rate for food frozen at  $-25^{\circ}\text{C}$  by pressure water-polymer jet of 100 MPa flow pressure and  $0.35 \cdot 10^{-3}\text{m}$  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/s – 4 times, and the quality of the cut surfaces is also improved.

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].

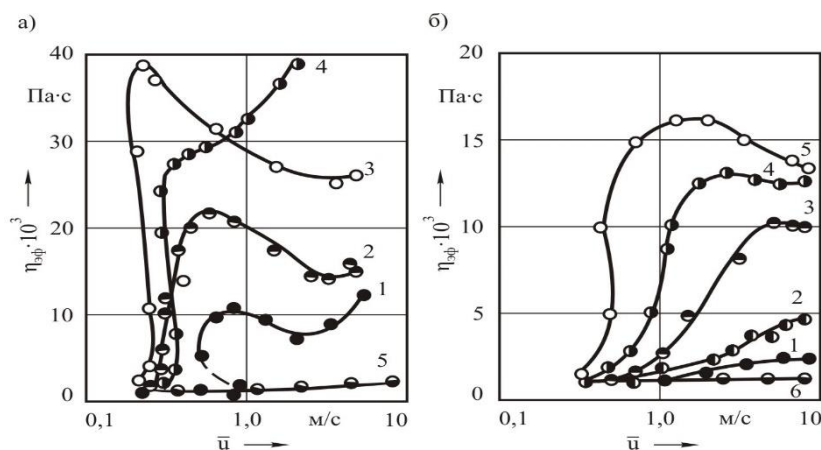
**Objective** – to determine peculiarities of macromolecule deformation behavior under conditions of a jet-shaping head that would allow to solve the issue related to the mechanism of increasing water-jet cutting power with polymer additions.

**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  $180^{\circ}$  was used. The instrument contained a cell having a rectangular cross-section  $(10 \times 17) \cdot 10^{-3}\text{m}$  and height of  $8 \cdot 10^{-2}\text{m}$  and two short removable capillaries having the following diameter and length,

respectively:  $0.5 \cdot 10^{-3}$  and  $0.21 \cdot 10^{-3} m$  (capillary I) and  $0.37 \cdot 10^{-3} m$  and  $1.1 \cdot 10^{-3} m$  (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  $\bar{u}$  was measured volumetrically using a photo-electronic system; the flow downstream the capillary inlet was submerged. PEO having the viscosity-average molecular weight of  $M_\eta = 3 \cdot 10^6$ ,  $4 \cdot 10^6$  and  $6 \cdot 10^6$  was used as a polymeric additive.

The methods of  $\Delta n_\infty$ , calculations and experimental procedure of  $\Delta n$  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.** Data describing the influence of discharge velocity on effective viscosity of water PEO solutions with different concentrations for molecular weights of  $4 \cdot 10^6$  and  $6 \cdot 10^6$  at  $25^\circ C$  are given on fig.1.



**Figure 1.** Dependence of effective viscosity of water PEO solutions on average discharge velocity

a)  $d_k = 0.34 \cdot 10^{-3} m$ ,  $l_k = 10^{-3} m$ ,  $M_{PEO} = 4 \cdot 10^6$ ,  $C_{PEO}$  :

1 – 0.01%, 2 – 0.02%, 3 – 0.05%, 4 – 0.1%, 5 – water;

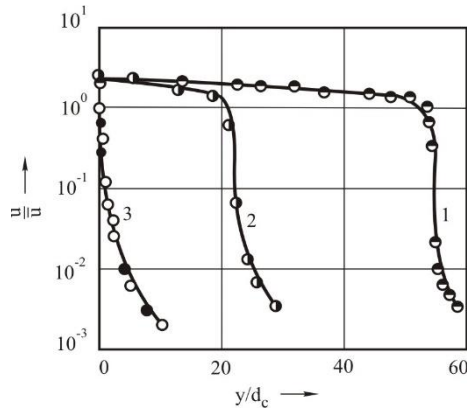
b)  $d_k = 0.12 \cdot 10^{-3} m$ ,  $l_k = 0.2 \cdot 10^{-3} m$ ,  $M_{PEO} = 6 \cdot 10^6$ ,  $C_{PEO}$  :

1 – 0.0005%, 2 – 0.001%, 3 – 0.002%, 4 – 0.003%, 5 – 0.004%, 6 – water

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  $\bar{u}$  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. 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 Figure 2. It can be seen that, before the critical flow regime is attained, the increase of the effective viscosity

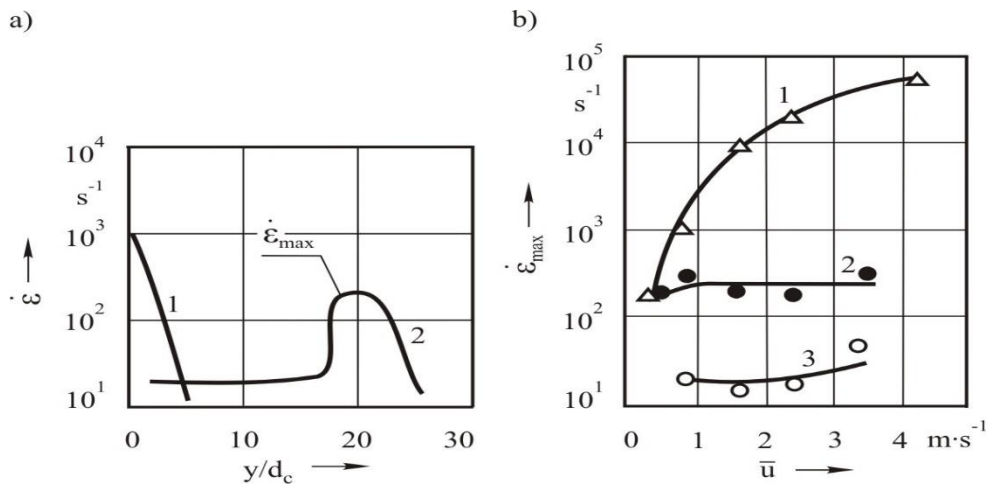
is not exhibited and the axial distributions of velocity for the polymeric solution and pure water are almost the same (curve 3) and filled circles on curve 3, respectively. After passing through the critical flow regime, the curves exhibit a considerable deformation and development of the axial velocity profile (curves 1 and 2 in Figure 2).



**Figure 2.** Velocity distribution for the polymer solution along the flow axis. Flow through the capillary I at the average flow rate  $\bar{u} = 2.5 \text{ m} \cdot \text{s}^{-1}$  (1), flow through the capillary II at  $\bar{u} = 0.8 \text{ m} \cdot \text{s}^{-1}$  (2) and through the capillary II at  $\bar{u} = 0.5 \text{ m} \cdot \text{s}^{-1}$  (3). Filled circles represent the data for water when  $\bar{u} = 0.8 \text{ m} \cdot \text{s}^{-1}$

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 (Figure 3).

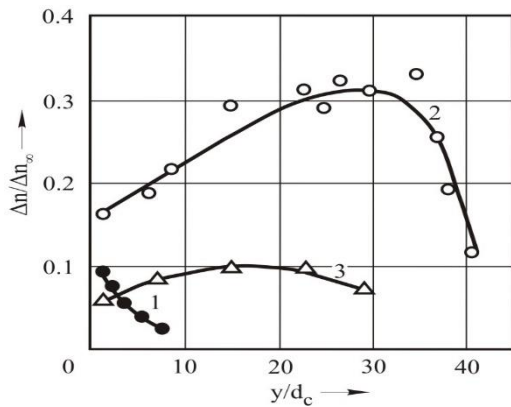
It can be seen that the maximal rate gradient  $\dot{\epsilon}_{\text{max}}$ , occurs not at the entrance of the capillary, but at some distance from that (Figure 3 a, curve 2). The  $\dot{\epsilon}_{\text{max}}$  at the entrance of the capillary for polymeric solution is considerably lower that for 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.



**Figure 3.** (a) – Velocity gradient distribution along the flow axis at  $\bar{u} = 0.8 \text{ m} \cdot \text{s}^{-1}$  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  $\dot{\epsilon}$  in the vortex for 0.05% PEO solution (3). Measurements were performed with the capillary I

Thus, the longitudinal velocity gradient at the flow axis does not exceed  $30 \text{ s}^{-1}$ . 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  $2 \text{ m} \cdot \text{s}^{-1}$  is equal to  $10 \text{ s}^{-1}$ . Figure 3 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.

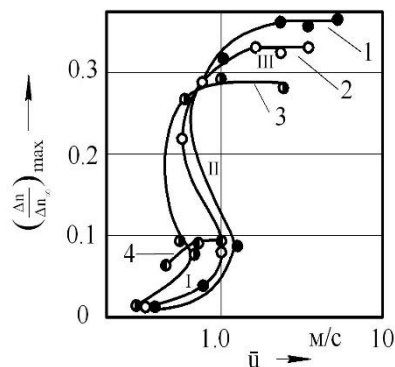
The observed changes in the structure of the hydrodynamic field can be associated with large distortions of the macromolecular coils induced by hydrodynamic field, leading to non-linear elasticity effects. The degree of the coil-stretch transition may be estimated from the value of the deformational factor  $(\Delta n / \Delta n_{\infty})_{\text{max}}$ , where  $\Delta n$  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.



**Figure 4.** The distribution of the coil-stretch transition degree over distance from the entrance of the capillary for aqueous PEO solution  
 $C_{PEO} = 0.3\%$  (1),  $\bar{u} = 1 \text{ m} \cdot \text{s}^{-1}$ ;  $C_{PEO} = 0.03\%$  (2),  
 $\bar{u} = 2.5 \text{ m} \cdot \text{s}^{-1}$ ;  $C_{PEO} = 0.1\%$  (3),  $\bar{u} = 1 \text{ m} \cdot \text{s}^{-1}$

Results of the studies of the influence of hydrodynamic field on the polymeric solution are depicted in Figure 4. 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  $(\Delta n / \Delta n_{\infty})_{\text{max}}$ , at the entrance of the capillary corresponds to the domain with maximal longitudinal velocity gradient (Figure 3 a, curve 2).

The obtained distribution of the deformational factor over the flow axis at the entrance of the capillary (Figure 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  $\sim 60\%$  and more coil-stretch transition degree. Increasing the polymer concentration results in a decrease of the deformational factor (curve 3).



**Figure 5.** Dependence of the coil-stretch transition degree on average flow rate  
 $d_k = 0,5 \cdot 10^{-3} \text{ m}$ ;  $l_k = 0,21 \cdot 10^{-3} \text{ m}$ ;  
 $M_{PEO} : 6 \cdot 10^6$  (1),  $4 \cdot 10^6$  (2),  $3 \cdot 10^6$  (3);  
 $C_{PEO} = 0,03\%$ ;  $M_{PEO} = 4 \cdot 10^6$ ;  $C_{PEO} = 0,1\%$  (4)

Figure 5 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  $\bar{u}$  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 (Figure 5, domain 3) sufficient for stability of the rate gradient field of the chosen polymeric system (Figure 3 b, curve 2).

**Conclusions.** 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 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.

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## ПРУЖНІ ДЕФОРМАЦІЇ Й АНОМАЛЬНО ВИСОКА РІЖУЧА ЗДАТНІСТЬ СТРУМЕНЯ РОЗЧИНУ ПОЛІМЕРУ

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**Резюме.** Вивчено особливості деформаційної поведінки макромолекул в умовах струменоформуючої головки, які б дозволили вирішити проблему, пов'язану з механізмом аномально високої ріжучої здатності водополімерного струменя. Експериментально вивчено поля швидкостей і їх градієнтів, а також ступінь розгорнутості макромолекул у модельних умовах струменоформуючої головки 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 струменоформуючої головки й ефекти пружних деформацій, що проявляються в цьому випадку, мають першорядне значення в розумінні механізму аномально високої ріжучої здатності водополімерного струменя. Розуміння природи підвищеної ріжучої здатності водополімерного струменя дозволить розробити рекомендації щодо вибору режимів струминної водополімерної обробки харчових продуктів різанням.

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

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