Structure formation in polyethyleneoxide solution streaming through jet-shaping head while cutting foodstuffs

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Objective - to determine peculiarities of macromolecule behaviour 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. 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. The work for the first time makes it possible to explain the nature of increased water-jet cutting power with polymer additions when cutting foodstuffs. 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 foodstuffs by cutting.

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

Структорообпазование в растворах полиэтиленоксида во время протекания через струеформирующую головку при обработке пищевых продуктов резанием

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Цель - установить особенности поведения макромолекул в условиях струеформирующей головки, которые позволят подойти к решению вопроса о механизме увеличения режущей способности гидроструи с полимерными добавками. При сходящемся течении растворов полиэтиленоксида макромолекулы подвергаются весьма сильному разворачиванию под действием гидродинамического поля, что в результате приводит к динамическому структурообразованию в растворах. Установленные закономерности поведения макромолекул при течении с продольным градиентом скорости и проявляющиеся при этом эффекты упругих деформаций имеют определяющее значение в понимании механизма «аномально» высокой режущей способности водно-полимерной струи. Работа впервые позволяет объяснить природу увеличения режущей способности гидроструи с полимерными добавками при обработке пищевых продуктов резанием.Понимание природы увеличения режущей способности водно-полимерной гидроструи позволит разработать рекомендации по выбору режимов гидроструйной водно-полимерной обработки пищевых продуктов резанием.

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

It is known that small polymer additions lead to a sharp increase of water-jet cutting power when processing foodstuffs by cutting [1]. 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 dynamic structure formation in solutions by 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 [2].

Let's examine the tests allowing to reveal the ability of hydrodynamic active 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 (water, acetone, dioxan) converging to a small outlet $0.3 \cdot 10^-$ m in diameter. At quite a distance from the outlet there have been injected in this flow some jets of PEO solutions or hydrolyzed polyacrylamide (GPAA) with molecular $6 \cdot 10^6$ and $4.5 \cdot 10^6$ and characteristic viscosity 2.42 and 3.70 m^3/kg correspondingly. The degree of PAA hydrolysis was 5 percent. Interval of the studied concentrations was 0.001-0.1 percent. 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 [1,2].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 and polarization-optical method.

Under small outflow velocities dyed jets of polymer solution visualize stream-lines of the main flow (Figure 1).
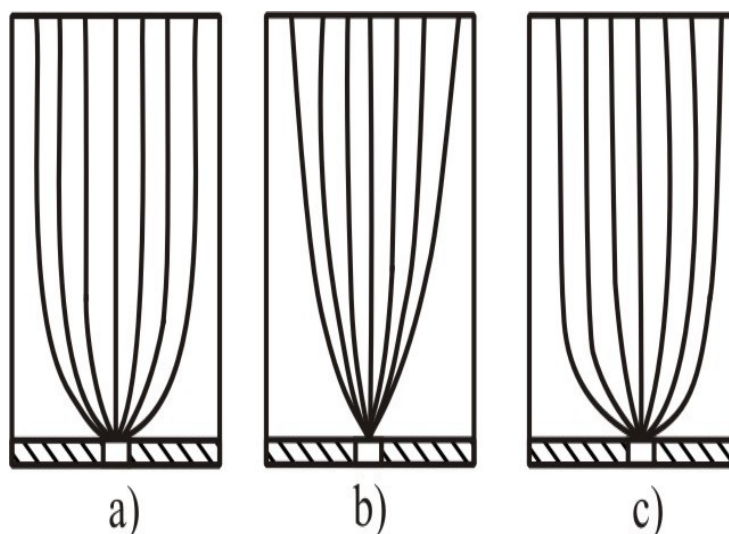
$M_{PEO} = 6 \cdot 10^6$, $C_{PEO} = 0.025\,\%$; $M_{HPAA} = 4.5 \cdot 10^6$, $C_{HPAA} = 0.05\,\%$;

a) **water into water at** $\dot{\varepsilon}$;

b) **HPAA into water at** $\dot{\varepsilon}$;

c) **PEO into water at** $\dot{\varepsilon}$

Figure 1 – Picture of flow in the inlet area of a capillary when injecting polymer solution into water during pre-critical 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 (Figure 2).

When observing the dynamics of forming and destructing separate threads (here lies the moving pulsation character

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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.
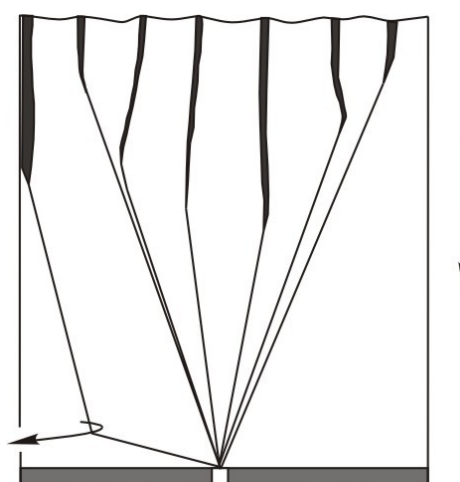
$$M_{PEO} = 5 \cdot 10^6, \ C_{PEO} = 0.03\%, \ \bar{u} = 2.5 \, m \cdot s^-$$

**Figure 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 $[\eta]_0 C > 1$) polymer solutions, when the emerged polymer threads don't cut off during the whole period of observation.

There also has been studied the effect of initial (non-turbulent by hydrodynamic field) sizes of molecular coils, that in poly-electrolytes (HPAA) depend on the hydrogen measure of the surroundings, on the ejection character of HPAA solution jets injected into water flow. The experiment has shown that in case of pH of the main flow equaling 2 the length of a polymer thread decreases sharply (3-4 times for 0.05 percent concentration) while the thread length-changing rate increases by 1.5-2 times. The increase of pH in the range between 7 and 9.5 practically doesn't influence the ejection character.

The main regularities of the polymer jets behaviour when injected into a flow with stretching, which is the main liquid flow, are similar to those in case of polymer solution outflow through short capillaries [2,3]. Hence, the observed behaviour peculiarities of the flooded polymer jets in flow with stretching are caused by rather strong polymer coils unrolling effected by hydrodynamic field (the degree of unrolling here as it was said above reaches ~60 percent). Uncoiling of macromolecule chains leads to decrease of their flexibility, which under certain conditions causes phase

separation effected by hydrodynamic field, i.e. it leads to dynamic structure formation.

The following experiment may serve as a proof of dynamic structure formation effected by hydrodynamic field with stretching. A thin wire with a device for polymer thread hold-up is introduced into the inlet area of the orifice during the pre-critical mode of the main flow ejection. This wire travel in the plane perpendicular to jets doesn't change the flow picture, i.e. during these modes the polymer jets are permeable to it. If the experiment is repeated during over-critical mode of liquid outflow, then it would be possible to hold-up one or several polymer threads during their growth and divert them as it is shown in Figure 2. This can be done only if there is a strong interaction between polymer molecules, i.e. when sub-molecular structure is formed, in this case under the effect of stretching hydrodynamic field. The minimum concentration of PEO water solutions allowing to divert a thread spun by hydrodynamic field was 0.008 percent, which corresponds to the range of diluted solutions ($[\eta]_0 C < 1$).

The given results as well as those obtained while studying converging flows of polymer solutions allow to state that hydrodynamic active polymer solutions should be divided into at least three concentration ranges. The first is the range of diluted polymer solutions when macromolecules are under strong deformation effect (unrolling) caused by hydrodynamic field, but the interaction between them is still weak. The second is the range of semi-diluted solutions (intermediate) when during pre-critical flow modes become diluted and during over-critical modes they become concentrated due to super-molecule structure formation caused by the shift of phase separation curves effected by hydrodynamic field. These dynamic structures should be classified as dynamic phase transitions that are studied by the theory of dissipation structures [4]. And the last range is the one of concentrated solutions ($[\eta]_0 C > 1$), when noticeable interaction between molecules do exist without hydrodynamic field. It should be stressed that the first two ranges refer to concentrations when the "anomalously" high cutting power of water-polymer jet processing of foodstuffs by cutting effect is manifested.

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 hydrodynamic active polymer solutions in flow with stretching. 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.

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