

The Research of the Agglomeration Process During the Formation of an Abrasive-Polymer Compound for Waterjet Cutting in a Fluidized bed Installation

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The research of the agglomeration process during the formation of an abrasive-polymer compound for waterjet cutting in a fluidized bed installation

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Abstract The article deals with the issues that allow creating conditions that exclude the formation of abrasive agglomerations in the process of applying a polymer coating in installations with a fluidized bed. The authors pay attention to the stages of agglomeration of the abrasive in the fluidized bed, as well as possible situations that arise when one particle collides with another. The problem of agglomeration development in the installation chamber is relevant, as it directly affects the quality of the coating, its uniformity. In addition, the critical size of the agglomerations will stop the coating process and lead to large material losses. The research carried out in the article on the process of obtaining a new effective abrasive material for waterjet cutting makes it possible to increase the cutting capabilities of a water jet.

Keywords Waterjet cutting, Abrasive particle, polymer, Fluidized bed, Agglomeration.

1 Introduction

Waterjet cutting is one of the most advanced and popular technologies in the world [1-14]. It has found successful applications not only for cutting any materials in the industry, but also for deep-sea

repair, defragmentation, cleaning of sea laying pipeline systems, including in the Arctic.

As a working material in this technology the garnet is typically used, as it is a strong abrasive (over 7.5 on the Mohs scale) with rounded edges that allows us to slow down the wear of the nozzle focusing tube of the water jet installation. The garnet is mined in Australia, South Africa, the USA, India and China, companies around the world, including Russian ones, use it despite the high price. The use of more affordable superhard abrasives (elbor, boron carbide, silicon carbide, electro corundum) was impossible due to the critical wear of the focusing tube of the nozzle (several minutes).

The authors propose to create a new composite material obtained by coating the abrasive grain with a protective polymer shell to prevent the negative impact of the contact of the abrasive with the surface of the nozzle tube, and this will significantly increase the efficiency and expand the possibilities of waterjet cutting.

2 Main part

During the abrasive processing in the fluidized bed, the particles repeatedly collide with each other, which is accompanied in some cases in the presence of a liquid by their union or agglomeration. Of course, two, three or more particles can be combined in the collision process. We can ignore this and consider only the paired agglomeration [15].

Consider the stages of agglomeration of abrasive in a fluidized bed:

1. Primary agglomeration. At this stage, the strength of the stuck agglomerates together is low, so when it is exposed to other particles colliding during processing, such a bond is quickly

destroyed. This stage does not affect the quality of the polymer coating on the abrasive, the layer will be uniform.

2. Sustainable agglomeration. This stage is accompanied by the formation of agglomerates with sufficiently strong bonds that are not destroyed during movement in the fluidized bed. Maintaining the bond between the particles leads to even more abrasive sticking and an increase in the size of the agglomerates. In addition, since there may be several stuck particles in the layer, it is possible to combine them into one agglomerate. Further development of this process leads to the transition to the third stage of agglomeration.

3. Deposition. The size of agglomerates reaches such a value when it is impossible to hold them in a suspended state in a fluidized bed. This development will lead to the deposition of agglomerates on the structural elements of the coating plant. In the zone where the agglomerate settles, the air flow will flow around the obstacle, which will create conditions for additional deposition of particles on the settled agglomerate. In this zone, the drying process will be difficult, heat exchange with the environment will slow down, which will lead to an increase in temperature and melting of the polymer coating and increase the strength of the agglomerate. Further operation of the fluidized bed coating unit is not possible and requires a cleaning of the treatment area to continue.

4. Adhesion. Agglomerates that have grown to a critical size can no longer be supported in a suspended state by a fluidizing agent having a certain speed, they are deposited on the gas distribution grid. From this point on, the adhesion begins. Above the settled agglomerate, a stagnant zone is formed, where other agglomerates and particles rush. Both in the stationary and in the boiling layer, due to the deterioration of heat exchange, the mass of particles and agglomerates is strongly overheated, its melting begins. At this stage, the process stops. Such an emergency state of the system can be eliminated only by disassembling the device (machine), and its cleaning is often carried out manually. This leads to extremely large material losses.

The occurrence of agglomerations can be observed both at the first and at the second stage in any area of the installation chamber. When creating a fluidized bed, when the speed of the air flow raises part of the abrasive particles, the other

is already at this point prone to the formation of agglomerates of the chamber. At this time, the air flow flows around a part of the particles lying on the grid of the chamber. Further increase in air flow rate and velocity destroys these stagnant zones. However, if the particles are wet and conditions are created for them to stick together, an increase in the flow rate will not have any effect on their destruction and involvement in the fluidized bed. The process can only be accompanied by further consolidation of agglomerates.

The paper considers the conditions of adhesion in a developed fluidized bed. At the same time, it is shown that particles, whose protective shell has not hardened yet and is liquid, prone to sticking together. Adhesion occurs during the impact of two particles (triple collisions are neglected). Before the impact, the particles moved relative to each other, had certain absolute velocities \vec{v}_1 and \vec{v}_2 , and the relative velocity $\vec{v}_{12} = -\vec{v}_{21} = \vec{v}_1 - \vec{v}_2$ of the first particle with the mass m_1 relative to the second particle with the mass m_2 . It is assumed that before and after the collision, the total mass of the particles, as well as the mass of each of them, with the exception of the negligible mass of possible lost droplets of the liquid shell, is preserved

$$m_1 + m_2 = \text{const} . \quad (1)$$

In addition, it is believed that the impact of particles against each other is absolutely inelastic, since the opposite case involves the separation of particles from each other after the impact. This assumption means that after the impact, the total momentum that the particles had before the impact is preserved. In this case, the condition of equality of particle velocities after impact is met. The condition of conservation of their total energy, which is characteristic of an absolutely inelastic impact, is not fulfilled. It is replaced by the condition of equality of velocities - particles, stuck together, formed a single body. Let \vec{v}'_1 , \vec{v}'_2 , $\vec{v}'_{12} = -\vec{v}'_{21}$ be the corresponding velocities of the particles m_1 and m_2 (we will denote them by denoting their masses) after the end of the impact (it is assumed that it lasts a certain time τ from the moment of contact of the particles to the moment when the relative motion ends). Then the comparison of the characteristics of the particles

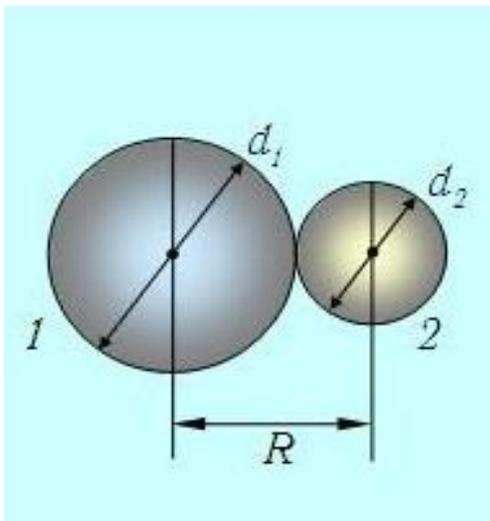
before the impact and after it ends leads to the equalities:

$$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v', v_1' = v_2' = v' \quad (2)$$

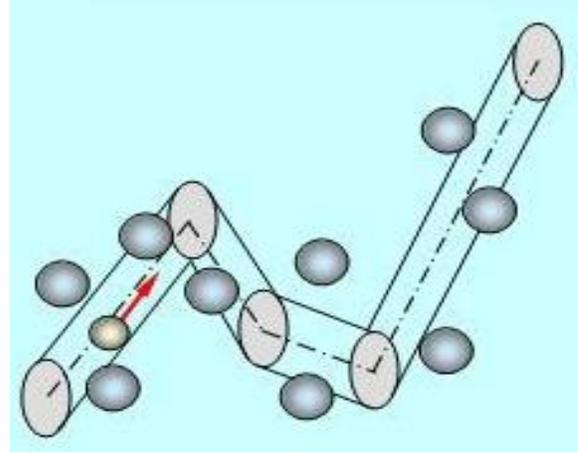
Two particles will stick together if they move at different speeds and if the energy of their relative motion after impact is equal to zero.

The inequality of initial velocities means, if their values are equal, the absence of parallelism or crossing of the directions of their vectors, and if they are unequal, the directivity along one straight line or parallel lines located in a tube with a diameter equal to the sum of the diameters of colliding particles (fig. 1). In this case, the initial kinetic energy $W_{k(12)}$ of the relative motion of the particles m_1 and m_2 must be lost completely or partially to viscous friction in the liquid shells during the time τ . This energy can be calculated. Regardless of the developing impact of particles – direct (frontal), tangential or intermediate between these types, the magnitude W_f of the work of viscous friction forces is largely determined by the viscosity coefficient of the liquid shells.

Particles that are brought closer together by impact fall under the action of long-range adhesive forces [16]. These particles will stick together if their total energy W_a is greater than their kinetic energy when they collide, minus the work of the viscosity forces of their liquid layers $W_{k(12)} - W_f \leq W_a$. (3)



a)



b)

Fig. 1 Collision of two particles and the trajectory of one of the particles after the collision. a – collision of two particles. b - trajectory of one of the particles after the collision

From the formula (3) it can be seen that the process of adhesion of pairs of particles, their agglomerations will be the more intense for the pair of particles for which the magnitude of the kinetic energy of relative motion will be less, and the work of viscous forces is greater. The greater the work W_f , the greater the viscosity of the shells of abrasive particles, provided that their liquid state is preserved. Agglomeration of sticking pairs of particles will take place faster where there is a greater probability of their collision, that is, where their concentration is greater. Maintaining the liquid state, the viscosity of the polymer liquid significantly depends on the local temperature of the process, the length and shape of the macromolecules. Further, the impact of each of the reasons is considered separately.

The stability and reliability of the fluidized bed is influenced by the nature of heat and mass transfer. A.V. Lykov [17] showed that the transfer of heat and substance cannot be considered separately independently of each other, but only in their relationship. The worst heat transfer occurs in those environments where aggregation is most pronounced. The temperature in the clot can reach the melting point of the material. The resulting local overheating zones are the main cause of the development of agglomeration, due to the appearance of the liquid phase in these zones. A decrease in the porosity of the system leads to fluctuations in the thermal equilibrium.

An increase in temperature changes the ratio of solid and liquid phases in favor of the latter, and this, in turn, stimulates the aggregation of particles. For the solid part, the addendum W_f in inequality (3) is missing. When the particles overheat, their shell can go into a liquid state, so that the addendum W_f will be non-zero, and the inequality will be satisfied for a larger number of particles W_f than in the absence. The speed of aggregation will increase.

In this paper, a new, but already quite common water – soluble polymer, polyoxyethylene, is considered as a coating of abrasive particles. It is obtained by polymerization of oxyethylene. Polyoxyethylene is known abroad as Polyox (polyox) and is a high-molecular polymers of ethylene oxide with a molecular weight of several hundred thousand to five million. Polyox is produced under various brands that differ in molecular weight. Polyoxyethylene is thermoplastic, its melting point is 66-67 °C. At a temperature of 150 °C, the polymer forms a viscous melt without noticeable degradation.

To answer the question of whether the coated abrasive particles will stick together or not, based on the solution of the Langmuir equation, we conclude that the shell will harden or not by the time one particle collides with another. To do this, three possible situations are considered.

1) A drop of polyethylene oxide dissolved in water, formed at a height of h , fell to the bottom (after the formation of the fluidized bed, the thickness h_0 of the abrasive embankment equals to zero or tends to it $h_0 \rightarrow 0$). At the same time, in the oncoming air flow, the water from the solution evaporates, and the polyethylene oxide hardens. The question is whether these processes will be completed by the time of the fall or not. At this point, the remaining drop material may collide with the bottom or a new h particle of abrasive.

2) At the height of h , the drop immediately hit the abrasive particle and falls with it, spreading over its surface. The question is how soon the water will evaporate from the coating and the polyethylene oxide will solidify, whether the end time of the process is commensurate with the average time between collisions of particles in the layer.

3) In the previous case, the protected particle reaches the bottom and collides with it. The question is whether the protective shell is in a liquid or solid state at this moment.

The review is carried out under the condition that the initial T_0 and final T_1 temperatures in the working chamber are known. The origin $y = 0$ of the vertical coordinate y is placed at the bottom of the chamber. The temperature distribution $T(y)$ over height is assumed to be linear for ease of calculation

$$T(y) = T_1 + \frac{T_0 - T_1}{h}(h - y). \quad (4)$$

The air speed v_a in the upstream flow is known and is considered constant over the entire segment $y \in [0, h]$. The thermodynamic parameters of air and water vapor from the drop, as well as the size of the drop, and the concentration of water in it are also considered known. The speed of the droplet v_d and abrasive particle v_p are determined by the conditions of vertical motion in the upward flow and the field of gravity. The initial characteristics of the movement are agreed when specifying these conditions. When moving up $v_d > 0$, $v_p > 0$, when moving down $v_d < 0$, $v_p < 0$.

First, we consider the vertical motion of a ball of radius R in the air flow in a gravitational field with the acceleration of free fall g . The mass of the ball is equal to $m = \frac{4}{3}\pi R^3 \rho$, the speed of

movement $v = \frac{dy}{dt}$. The speed of the ball is considered small. So, as the law of interaction between air and a ball, we can use Stokes law with force $f = -c(v - v_a)$, where $c = 6\pi R \mu$; μ is the dynamic viscosity of the liquid. Depending on the situation of resistance, this force can be both a resistance force and a force that pushes the ball. In different situations, the ball simulates an evaporating droplet or a protected or unprotected abrasive particle. In all cases, the mass of the ball is considered constant. In cases where the movement is accompanied by evaporation, the particle mass is taken as a value equal to the half-sum of the masses at the beginning and end of the

way.

The differential equation of ball motion has the following form.

$$v = \frac{dy}{dt}, m \frac{dv}{dt} = -mg - c(v - v_a). \quad (5)$$

General solution of this equation:

$$v = C_1 e^{-(c/m)t} + v_a - \left(\frac{m}{c}\right)g, \quad (6)$$

$$y = -C_1 \left(\frac{m}{c}\right) e^{-(c/m)t} + \left[v_a - \left(\frac{m}{c}\right)g \right] t + C_2. \quad (7)$$

The integration constants C_1 and C_2 are determined based on the initial and final conditions. In each task, they are different.

For a falling liquid drop, we assume that its final mass is zero – in this case, it falls more slowly. This means that the humidity in the air and the possibility of abrasive particles to stick together is more evident. This is the worst option for the workflow. In this case

$$m = \frac{m_0}{2}, y(0) = h, v(0) = 0. \quad (8)$$

The solution gets the following form:

$$C_1 = \left(\frac{m}{c}\right)g - v_a, \quad (9)$$

$$v(t) = \left[v_a - \left(\frac{m}{c}\right)g \right] \left(1 - e^{-(c/m)t} \right),$$

$$C_2 = C_1 \left(\frac{m}{c}\right) + h = \left(\frac{m}{c}\right) \times \left[\left(\frac{m}{c}\right)g - v_a \right] + h. \quad (10)$$

$$y(t) = h + \left[\left(\frac{m}{c}\right)g - v_a \right] \times \left[1 - \left(\frac{c}{m}\right)t - e^{-(c/m)t} \right]. \quad (11)$$

Falling from a height h , the liquid particle evaporates. In the aerosol method of coating abrasive particles, the evaporation process can be described by the Langmuir equation for the speed

w_m of evaporation by mass [18, 19]:

$$w_m = M \frac{dN}{Sdt} = p_{s.v.} \sqrt{\frac{M}{2\pi kT}} = 5,834 \cdot 10^{-2} p_{s.v.} \sqrt{\frac{M_{mol}}{T}} \frac{g}{cm^2 s}, \quad (12)$$

where $p_{s.v.}$ is the temperature-dependent (reference data) value of the saturated vapor pressure of the evaporating substance in mmHg, which increases with the temperature rise faster than \sqrt{T} ;

T is the absolute temperature;

k is the Boltzmann's constant;

S is the area from which evaporation occurs;

t is the time;

N is the number of evaporated molecules;

M is the mass of one molecule;

M_{mol} is its molar mass.

In expression (12), the right-hand side is constant at a constant temperature over time. Therefore, on its basis, it is easy to obtain a formula for calculating the evaporation time of a known mass of liquid from a known area S . In its construction, it is assumed that the mass of a liquid spherical drop of diameter d with a density

of ρ : $m_{ev} = \rho V = \frac{\pi d^3}{6} \rho$. The evaporation surface area is considered constant, equal to $S = \pi d^2$. The desired formula takes the following form.

$$t = \frac{100m_{ev}}{5,834 S p_{s.v.} \sqrt{M_{mol}/T}} = \frac{2,86 \rho d}{p_{s.v.} \sqrt{M_{mol}/T}}. \quad (13)$$

Here, to get the correct result, we need to use the following dimensions:

$$[p_{s.v.}] = mmHg, [\rho] = cm^3, [d] = cm.$$

The coating polymer for further spraying comes in the form of an aqueous solution. To analyze the situation, we will estimate the evaporation time of a single drop of sprayed solution under conditions close to those used in the working process. We assume (with brute force) that a drop consists only of water. For calculations, the following values included in the

formula (13) are accepted.

$$\rho = 1 \text{ g/cm}^3, d = 50 \cdot 10^{-4} \text{ cm},$$

$$T = 343 \text{ }^\circ\text{K} (= 65 \text{ }^\circ\text{C}),$$

$$p_{s.v.} = 234 \text{ mmHg}, M_{mol} = 18 \text{ u.} \quad (14)$$

As a result, it is obtained that a drop of water with such characteristics at the selected temperature will completely evaporate within $t = 0,26 \cdot 10^{-3} \text{ s}$.

That is, the water from the drop evaporates very quickly.

Figure 7.5 shows the dependence of saturated water vapor pressure on temperature. Obviously, this pressure increases with increasing temperature. Moreover, (we can check) this pressure increases faster than the growth of the root \sqrt{T} included in the formula (12). That is, the function $\hat{p}(T) = p_{s.v.} / \sqrt{T}$ is increasing. So, with increasing temperature, evaporation occurs faster – an obvious fact, quantitatively described by the above dependencies. This circumstance is convenient for the manufacture of a coating of abrasive particles because it indicates the way of release of the polymer from the aqueous solution before it meets the abrasive particles. The graph shown in figure 7.5 also indicates that a decrease in temperature to room value does not significantly affect the rate of evaporation of water from the polymer solution. This conclusion allows us to reduce the temperature of the coating process in order to get on the abrasive particles of the polymer crystallized as quickly as possible. In this case, the agglomeration of particles with a freshly made coating will be less due to the fact that at low temperatures the coating is more elastic and the energy loss of colliding particles to dissipation is reduced. So, the potential compression energy of the coating is able to overcome the adhesion forces (see the analysis of equations (2) and (3)).

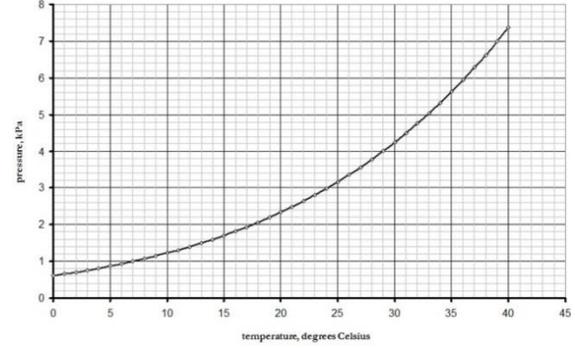


Fig. 2 Dependence of saturated water vapor pressure on temperature.

There is a question about whether the polymer particles in the non-solid state will settle to the bottom of the fluidized bed, sticking together to form an agglomerate. The answer to this question is based on the equations (9) and (11). Considering the high rate of evaporation of the solvent – water, we can say that after injecting the solution at a height h above the bottom of the chamber, the solution particle instantly turns into a polymer particle. Its size corresponds to its concentration in the solution. Instantaneous formation means that the initial velocity of the polymer particle is zero.

From the formula (9) it follows that the polymer particle will start moving down if

$$v_a < \left(\frac{m_{pol.}}{c_{pol.}} \right) g. \quad (15)$$

In this formula, the value of the velocity of the upward air flow v_a forming the fluidized bed is determined from the condition of its stability. A rough condition for this is equality

$$v_g = \left(\frac{M_{abr}}{c_{abr}} \right) g. \quad (16)$$

This value has an order $v_a = 1 \text{ m/s}$.

Assuming that the polymer particle has the shape of a ball of diameter d_{pol} with the density of the material ρ_{pol} , taking into account that the coefficient of resistance to its movement in air $c_{pol.} = 3\pi \mu d$, for the right part of the inequality (15), we can obtain:

$$\left(\frac{m_{pol.}}{c_{pol.}} \right) g = \frac{\rho_{pol.} g d_{pol.}^2}{18 \mu}. \quad (17)$$

From this it can be seen that the larger the particle, the greater the probability that the inequality (15) will be fulfilled and the particle will settle to the bottom of the chamber. Therefore, an estimated calculation was performed for a large particle under the assumption that the polymer particles remaining after evaporation, agglomerating with each other, reached the size of the solution particles, for the following data.

$$\rho_{pol.} = 1,2 \cdot 10^3 \text{ kg/m}^3, \quad d_{pol.} = 50 \cdot 10^{-6} \text{ m},$$

$$\mu = 200 \cdot 10^{-7} \text{ H} \cdot \text{c} / \text{M}^2. \quad (18)$$

It is obtained that in the considered case

$$\left(\frac{m_{pol.}}{c_{pol.}} \right) g = \frac{\rho_{pol.} \cdot g \cdot d_{pol.}^2}{18 \mu} \cong 0,5 \text{ m/s}. \quad (19)$$

This value, although less than $v_a = 1 \text{ m/s}$, which indicates that there is no settling of polymer particles to the bottom, but is commensurate with it. Considering the approximate nature of the assessment, we can say that when agglomerates of polymer particles appear, the probability of their deposition is not zero.

The obstacle to such agglomeration are the temperature rise – it increases the viscosity of air and, consequently, increases the removal of not deposited particles of polymer on the abrasive from the working area (the theoretical dependence of the Sutherland viscosity on temperature is presented in book [20]), and the reduction of the concentration of the polymer solution – during evaporation of the solvent, the concentration of polymeric particles in the air will be less than if the concentration of the solution is great.

Ensuring non-compliance with equality (15) contributes to the fact that the aerosol of the polymer solution forms a cloud in the upper part of the fluidized bed that does not settle to the bottom of the chamber. It should be noted that the high temperature in this cloud, close to the melting point of the polymer, plays a negative role, since the polymer layer deposited on the abrasive particles in a near-liquid state during the collision of particles contributes to their adhesion and the appearance of agglomerates.

3 Conclusions

On the basis of the arguments presented in this

paragraph, we can state the following. Agglomeration of sticking pairs of particles will take place faster where there is a greater probability of their collision, that is, where their concentration is greater. Maintaining the liquid state, the viscosity of the polymer liquid is significantly dependent on the local temperature of the process. For the successful operation of coating abrasive grains, the temperature in the spray zone of the polymer solution must be close to the melting point of the polymer, but below it. A high temperature value promotes rapid evaporation of the solvent-water, which reduces the probability of small drops of solution merging into large ones falling to the bottom of the chamber. At temperatures lower than the melting point of the polymer, they harden quickly without solvent, and in the solid state their agglomeration is unlikely.

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Compliance with ethical standards

Conflict of interest. The authors declare that they have no conflict of interest.

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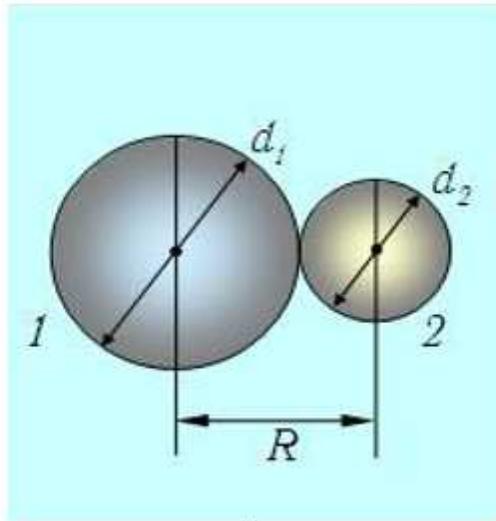
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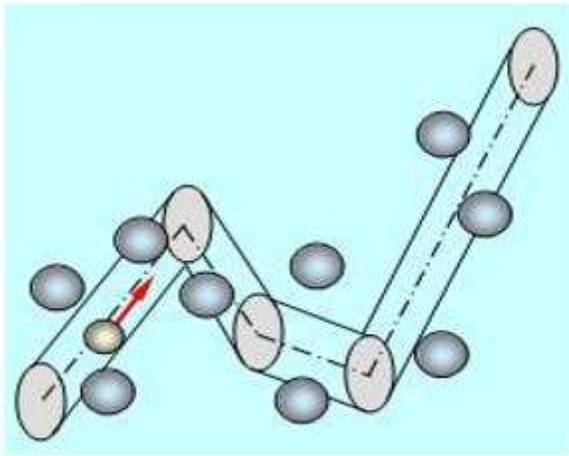
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Figures



a)



b)

Figure 1

Collision of two particles and the trajectory of one of the particles after the collision. a – collision of two particles. b - trajectory of one of the particles after the collision

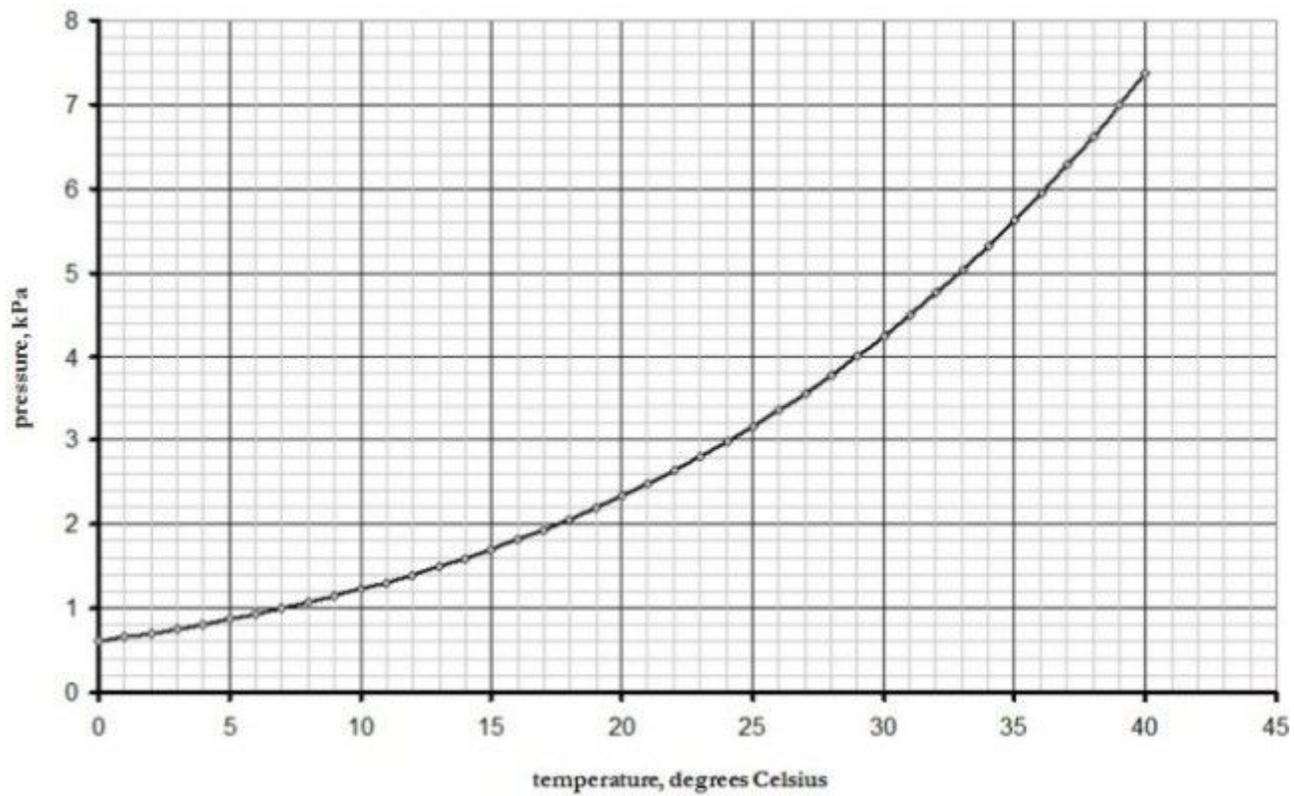


Figure 2

Dependence of saturated water vapor pressure on temperature.