

The Characteristics of Vortex Spray Countercurrent Mass Exchange Device (VSCMED)

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Abstract

The article contains the results of the efficiency research of vortex dispersing countercurrent mass exchange device performance. There are recommendations given on the basis of analysis of liquid jet and liquid drops movement to assess the mass exchange surface. Processes and Equipment of Chemical and Petroleum Refineries Department of Sumy State University has carried out a great research to design new constructions of vortex mass exchanged devices with countercurrent flow of gas and drop flows.

Keywords: vortex device, mass exchange, gas velocity, drops, mass Exchange surface.

مميزات جهاز تبادل الكتلة العكسي لناثر الدوامة

الخلاصة

تحتوي المقالة على نتائج بحث كفاءة اداء جهاز تبادل الكتلة مبدد الدوامة. هناك توصيات تعطي على اساس التحليل لحركة منفث السائل وقطرات السائل لتخمين سطح تبادل الكتلة. قام قسم العمليات والمعدات الكيميائية والنفطية لبحث كبير لتصميم بناء جديد لاجهزة دوامة تبادل الكتلة المصاحب للجريان العكسي للغاز والقطرات.

Introduction

The different design of mass exchanged equipment is widely used not only in technological processes of chemical, oil-refining and food industry, but also in other branches of industry. The constructions of such design using the vortex flow of gas and liquid have been lately of great interest for scientists, constructors and users of such devices. The first who expressed the idea of organization of countercurrent flow of phases on the same level of liquid atomization was B. Kholin [1]. Chemical Engineering and Industrial Ecology Department which is now Processes and

Equipment of Chemical and Petroleum Refineries Department of Sumy State University has carried out a great research to design new constructions of vortex mass exchanged devices with countercurrent flow of gas and drop flows.

The axial swirlers were used in the design of vortex devices with cross and direct movement of phases. The usage of tangential swirlers [2, 3, 4, 5, 6] allowed creating high speed in the centre of so called swirl chamber and getting fine dispersion of liquid phase due to interaction of gas flow and spray jet, which moves to it normally [7].

The usage of such approach allowed creating devices with

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tangential swirlers functioning the following way (Fig.1) [8, 9, 10 11]. Gas flow moving through tangential swirlers acquires rotary motion. The tangential component of gas velocity in the middle of swirl chamber is around 80...100 m/s. Gas entraps drops into rotary motion and they move in the direction of periphery.

There exists a great variety of mass exchanged devices of different design based on liquid atomization and vortex movement of gas flow. Despite this fact, there are no devices in this country and abroad providing countercurrent movement of spray in vortex gas flow along the radius of swirl mass exchanged chamber. The aim of the present work is to obtain countercurrent motion of drops and gas (steam) along the radius of vortex mass exchange chamber [12, 13, 14] in the designed vortex counter-current mass exchange device (VSCMED), (Fig.1).

Fig.1 Vortex spray countercurrent mass exchange device (VSCMED) with horizontal axis: 1- tangential input of gas (steam); 2 - gas(steam) extraction; 3 – liquid input into sprayer; 4 – liquid extraction out of the device; 5 – swirler for gas input in the circumferential direction in the vortex mass exchange chamber, 5 – slots for liquid extraction out of the vortex mass exchange chamber.

Experimental and theoretical works

The gas flow is injected into the mass exchange chamber along all its height in tangential direction, there are slits on the periphery of the mass exchange chamber. The correlation of the vortex mass exchanged chamber height and its radius with gas inputs is

chosen such that there is a flat countercurrent motion of vortex currents of gas and liquid drops flow in the area restricted by cylindrical wall with tangential gas input slits and cylindrical surface with radius equal to nipple radius for gas withdrawal out of the vortex chamber. Under such condition gas moves from the periphery the center of the vortex processing chamber. The drops influenced by centrifugal force move countercurrent to gas in the radial direction from the center to the periphery of this mass exchange chamber.

The analysis of vortex spray countercurrent mass exchanged devices performance (VSCMED) gives us the possibility to distinguish main hydrodynamic processes which influence the mass exchange efficiency. Moreover the knowledge of physical essence of hydraulic processes allows creating the design procedure for devices of such type [15, 16, 17, 18].

Firstly, it is the movement of gas swirling flow in the swirl chamber. Here of great importance is the law of variation of gas velocity flow along the radius of swirl mass exchanged chamber of VSCMED. to assess the hydraulic resistance of the device , the pressure distribution in the swirl mass of the exchanged chamber and hydraulic losses correlation of energy between mass exchanged chamber and different designed elements of the device should be known, for example, tangential slots for gas supply, radial diffuser, etc.

Secondly, the influence of liquid phase on the hydrodynamics of the gas

swirling flow should be taken into account. The liquid jet dispersion injected into gas flow takes place due to the gas energy. The gas flow involves the drops of liquid into rotary motion. All these factors should cause the redistribution of energy datum between gas and drops of liquid. In its turn the decrease of gas flow velocity should result in increase of the dimension of drops of atomized liquid. The knowledge of interference of the flows is necessary for assessment of their hydrodynamic parameters [19, 20, 21, 22, 23, 24]. Moreover the liquid jet dispersion takes place under the condition of high relative velocity phases the zone of the highest gas flow velocity and parameters of atomization should be estimated, because dispersion, i.e. the size of liquid drops, depends on velocity difference of liquid and gas phases in the atomization area.

It is necessary to provide the liquid drops movement from center to periphery under the influence of centrifugal force in the countercurrent device, to achieve this, the right correlation between mass and aerodynamic forces influencing the drops should be taken [25]. The intensification of inner circulating current in drops increases the renewal of inter-phase surface and influences positively the mass exchanged processes [26].

The analysis of VSCMED performance under the condition of rectification [27], the experience of commercial operation [28, 29] showed that the devices of such type are high-performance mass exchanged devices of low materials consumption. But

wide application of VSCMED in different branches in industry of CIS needs further research of mass exchanged characteristic to gather experimental material to improve design procedure.

To achieve this aim a special test stand was designed on the basis of Processes and Equipment of Chemical and Petroleum Refineries Department of Sumy State University. It was described in this article [12]. During the research the technique of assessment of mass exchange coefficient was used. The assessment of mass exchange coefficient is complicated as there are no reliable techniques allowing estimating the concentration on inter-phase boundary. So the indirect method was used to assess the mass exchange coefficient on the basis of experimental data. The fact that diffusion coefficient in liquid is significantly lower than in gas was taken into consideration.

The complicated hydrodynamic conditions in the processing chamber of VSCMED, the lack of information on research of hydrodynamic and the mass exchanged characteristic of such device restrain wide manufacturing application of VSCMED. That is why the working out of design procedure of parameters influencing the intensity of mass exchange in the processing chamber of VSCMED is an urgent task. It gives a possibility to assess the volume mass-transfer coefficient K_{xv} which is connected with the mass-transfer coefficient K_x

$$K_{Cv} = K_C a . \quad \dots(1)$$

An essential role in efficient performance of VSCMED is played by the value of phase contact specific surface "a" connected with the inter-phase surface by means of the following equation

$$a = \frac{V_{AP}}{F} \dots(2)$$

The inter-phase surface in VSCMED is the surface of liquid drops, the quantity of which is

$$n_K = \frac{V_g}{V_K} = \frac{6V_g}{\rho d_K^3}, \dots(3)$$

where V_g - the quantity of liquid in the vortex mass exchange chamber between sprayer and cylindrical wall at radius R_1 (Fig.1) from which liquid is extracted out of device; V_K - the volume of a liquid drop; d_K - the characteristic diameter of a drop.

If we know the quantity of liquid drops, their diameter or value of liquid drop surface S_K , we can estimate inter-phase surface taking into consideration the equation (3)

$$F = S_K n_K = 6V_g / d_K \dots(4)$$

If the vortex motion is absent in the processing chamber of VSCMED, the liquid jet coming from the inlet of the sprayer has cylindrical shape close by the size to the diameter d_f of nozzle sprayer (fig. 1). Taking into consideration the quantity of nozzles on the sprayer n_f and the position of sprayer near the radius of

gas withdrawal out from the mass exchange chamber, the jet length is $l=R_1-R_2$, the quantity of liquid in the mass exchange chamber is

$$V_g = \frac{\rho d_f^2}{4} (R_1 - R_2) n_f \dots(5)$$

The rotary gas motion in the vortex chamber does not influence the liquid outflow rate through sprayer W_{BX} , but it causes the fact that the jet bends and splits into drops, the size of which can be estimated with the help of the expression

$$d_K = \frac{We\sigma}{rV_{OTH}^2}, \dots(6)$$

Where We – Weber criterion ranging 12...14 at jet disintegration; r - gas density; σ - surface tension of liquid; V_{OTH} – relative velocity of phase motion

The drops acquire rotary motion and they move to the periphery of the processing chamber on the plain spiral trajectory. The quantity of liquid between the cylindrical sections with radii R_1 and R_2 does not change. The increase of the length of flight track of liquid drops and the time of phase contact in the mass exchange chamber takes place due to the transition to spiral motion. The increase can be estimated with the help of equation for liquid drop motion taking into consideration the influence of gas flow. Then to estimate the value of inter-phase surface we can write down

the following equation F, taking into account the drop diameter d_K which is characteristic and spraying is mono-disperse enough.

$$F = \frac{3}{2} \frac{d_f^2}{d_K} p(R_1 - R_2)n_f . \dots\dots(7)$$

Therefore the equation (7) allows having the connection between the main geometric dimensions of the chamber R_1 and R_2 and the parameters of the sprayer unit. This allows us to take into account the obtained data while designing new high performance VSCMED and forecast its mass exchange characteristics.

While carrying out the research, the methodology of the mass exchange coefficient evaluation suggested in the works was used. The experimental evaluation of the mass exchange coefficient is complicated because there are no modern reliable enough methods to measure concentration on the interphase boundary. That is why to evaluate the mass exchange coefficient on the basis of experimental data the indirect method was used. While choosing the method, the fact that the diffusion coefficient in liquids is sufficiently lower than in gases was taken into account.

In the framework of this research, to assess the mass-transfer coefficient of the liquid phase, the experiments were carried out aiming at desorption of CO_2 . In this case we can neglect the gas phase resistance and consider the mass exchange

coefficient of liquid phase equal to mass-transfer coefficient [1].

Water saturation with carbon-dioxide gas took place in absorption chamber at upward direct flow phase motion. The quantity of CO_2 in water supplied to the VSCMED sprayer was estimated with the help of titration.

Because of the low concentration of CO_2 in gas and the high constant of phase equilibrium in the mixture of CO_2 – water ($\tau_{yx} = 1440$), the influence of gas phase on desorption driving force may be neglected ($K_{xv} = f(\beta_{xv}, \beta_{yv})$, if $\beta_{yv} \sim 0$, to $K_{xv} = \beta_{xv}$) and the efficiency can be estimated according to the equation[12]

$$E_{Mx} = \frac{x_1 - x_2}{x_1} , \dots\dots(8)$$

Where E_{Mx} – efficiency according to Murphy, x_1 and x_2 – CO_2 concentration in liquid and at entry and exit of VSCMED

The quantity of transfer units at low concentration of the component is equal to

$$N_x = \ln \frac{x_1}{x_2} , \dots\dots(9)$$

Or using volume mass - transfer coefficient is equal to

$$N_x = \frac{b_{xv} \times V_{an}}{Q_g} , \dots\dots(10)$$

Where V_{an} - the volume of the processing chamber of VSCMED, m^3 ; Q_g - the liquid phase load, m^3/s ; β_{xv}

- the volume mass - transfer coefficient in liquid phase, $1/s$.

According to the equation (10) the volume mass - transfer coefficient in liquid phase is equal to [12]

$$b_{X_V} = \frac{N_x Q_g}{V_{an}} \dots(11)$$

The quantity of transfer units is estimated according the equation (9). During the experiment the liquid temperature changed, that is why β_{X_V} value was reduced to $20^{\circ}C$. The CO_2 desorption out of water takes place at the temperature of $5...40^{\circ}C$ $\beta_{X_V} \approx e^{0.023t_g}$, where t_g - the liquid temperature. So the volume mass - transfer coefficient in liquid phase for VSCMED with temperature correction is

$$b_{X_V} = \frac{N_x Q_g}{pR_l^2 H} e^{0.023(20-t_g^o)} \dots(12)$$

Three VSCMED were studied. Two devices had the radius and the height of mass exchanged chamber 380 mm and 80 mm . The sprayer of both devices was a nipple with 6 inlets which diameter is 1 mm used for irrigation of the mass exchanged chamber in radial direction. The difference was in the construction arrangement of the devices.

One of them was installed in such a way that the axis was vertical. The gas withdrawal took place in the upper part of the device, the liquid extraction was fulfilled from the cylindrical walls and then through

outlets in the lower end cover. The second device had the horizontal axis. The gas withdrawal took place through outlets in the end cover placed vertically. The liquid extraction was carried out through the tangential slots in the lower part of cylindrical frame of the mass exchange chamber.

The axis of the third device was vertical. The diameter and the height of the mass exchanged chamber were 1000 mm and 250 mm correspondently. The carried out research revealed the dependence between splash carrying away and efficiency reduction of VSCMED. Almost in all operating conditions the reduction of the mass-transfer coefficient coincides with the increase of relative value of splash carrying away. The charts are shown on Fig. 2, where V_{Bx} - gas velocity at entrance tangential slits; N_x - the quantity of theoretical stages of concentration change on one stage of spraying; L/G - the load correlation in liquid and gas phases. Such increase of liquid quantity carrying away by gas is explained by the device design and its hydrodynamics. As the sprayer is in the centre of mass transfer chamber, where we have axial gas motion around $20-40\text{ m/s}$, at relatively low outflow velocity (low L/G), we observe fine dispersion of liquid due to high relative velocity of phases. Heavy centrifugal force influences the drops due to which liquid "skips" the dangerous zone of axial gas velocity. Then with the increase of liquid pressure the gas velocity decreases which influence the force action on the drops and results in some increase of splash carrying away. The next increase of

liquid pressure and jet outflow velocity out of sprayer slits changes the picture of liquid phase motion in the central zone. The jet dispersion takes place at the radius near to radius R_2 (the radius of gas withdrawal out of the vortex chamber), i.e. near the boundary of dangerous zone of axial velocity and high peripheral gas velocity.

Fig.2 The quantity of theoretical stages of concentration change (N_x) depending on phases load (L/G) at different entry gas(steam)velocity in entry tangential slits of the vortex chamber (V, m/s): 1 – 9,0; 2 – 12,7; 3 – 15,6; 4 – 20,1; 5 – 23,8[20].

Results

The theoretical calculations of the mass transfer coefficient of other parameters characterizing the efficiency of VSCMED is complicated, that is why according to the experimental data we need to obtain the following dependence [12]

$$Nu = f(Re, Pe, \Gamma_1, \Gamma_2) \quad (13)$$

Where Re , Pe , Γ_1 , Γ_2 - Criteria of hydrodynamic, mass and geometric similarity.

Taking into account that the majority of the experiments took place under the condition of CO_2 desorption while working out the next dependences we can consider that $\beta_{xv} \approx K_{xv}$. In its turn, the connection between the volume mass transfer coefficient β_{xv} and the mass transfer coefficient is expressed by the correlation.

$$\beta_x = \beta_{xv} a, \quad \dots(14)$$

So the connection between the mass transfer coefficients is presented by the following dependence

$$b = \frac{b_v}{a} = \frac{b_v V_{an}}{F} = \frac{2 b_v V_{an} d_K}{3 d_f^2 n_f p (R_1 - R_2)} \quad \dots(15)$$

Moreover, taking into account that the drop diameter is influenced by gas velocity in the spray zone which depends on the correlation of radii R_1 (tangential inlets are placed here) and R_2 and entry gas velocity V_{BX} . The entry gas velocity depends on the square of tangential slits and the height of the mass transfer chamber. In the equation (13) we can simplify the functional dependence N_u from defining criteria.

$$Nu = f\left(Re, Pe, \frac{l}{R_1}\right), \quad (16)$$

where

$$Nu = \frac{b_g d_K}{D_g}; l = R_1 - R_2; Pe = \frac{W_{BX} d_K}{D_g}$$

, W_{BX} - entry liquid velocity.

Mathematical treatment of experimental data revealed the following functional dependence

$$Nu = A \exp(B Re) Pe^n, \quad \dots(17)$$

Where $A = 1.124 - 1.24 \left(\frac{l}{R_1}\right)$;

$$B = 2.47 \times 10^{-4} \left(\frac{l}{R_1}\right) - 2.4 \times 10^{-4};$$

$$n = 0.78 \dots 0.84$$

So we can estimate the volume device taking the amount of matter M from the equation of material balance

transferring from gas into liquid and the mass transfer coefficient from equation (17). We should take into account that equation (17) is derived from the condition $\beta_x \approx K_x$. The further calculations of its geometry and hydrodynamics of mass transfer characteristics are needed [20].

$$V_{an} = \frac{M}{K_{XV} DX_{CP}} \dots(18)$$

The received numerical data prove the high-performance of such devices and theoretical data about the influence of transverse gradient of gas flow velocity on the quantity of change stages of concentration on one stage of atomization.

Even under the most unfavorable conditions, from the point of view of hydrodynamics, the quantity of theoretical stages in one atomization stage was more than 1,2. Under the conditions close to optimal (fine dispersion, low splash carrying away) the quantity of theoretical stages of concentration change was over 4.

Fig.2 shows graphic dependence (on the basis of the experiment) of extraction ratio on gas velocity in input tangential slots at different liquid velocity in the sprayer slots for VSCMED with the diameter of 380 mm, horizontal and vertical axes.

The information received during experimental research of mass exchanged characteristics was used for proving of theoretical analysis allowing theoretical grounding of mass exchange in countercurrent vortex gas and drop flow; identifying the dependence of circulation flow in drops of liquid moving in

countercurrent direction to gas flow on hydrodynamic data of this flow and degree of their influence on mass exchange efficiency. The interaction of vortex gas and liquid drop flow when gas moves from the periphery to the center and drops vice versa is studied. The mathematical dependence of velocity field and pressure on parameters of VSCMED is theoretically grounded and improved [15, 19, 22, 32]. The dependence of local velocity fields and pressure in the processing chamber of VSCMED is experimentally studied. The received data prove the validity of worked out theoretical equations.

The research of mass exchanged data of VSCMED on the processes of absorption (desorption) is the testing basis of new improved VSCMED design. The new principles of efficiency and performance increase were worked out. The design of VSCMED sprayer unit was worked out [30, 31] reaching the most effective liquid dispersion. The physical and mathematical motion models of gas and liquid drops in the processing chamber were grounded from the point of view of the influence on circulation flows in drops. The most favorable conditions of motion and interaction were chosen. The comparison of VSCMED efficiency with other design devices for mass exchanged processes was carried out. The theoretically and experimentally grounded methodology of design procedure of mass exchanged and hydraulic characteristics of VSCMED was worked out. The main development and improvement guidelines are suggested. The stated

conditions of VSCMED performance are the most reasonable.

All above mentioned tasks are the part of research of new high performance mass exchanged devices. The practical significance consists in the fact that theoretical grounds, experimental data and theoretical equations allowed working out and implementation of a new way of mass exchange and a new design of mass exchanged device. That is vortex spray countercurrent mass exchange devices (VSCMED). The created design procedure of VSCMED allows efficient design of VSCMED and forecast hydraulic and mass exchanged characteristics. The created design procedure of VSCMED was used while working out new devices implemented in different technologies of chemical industry.

These are the processes of methanol production, rich absorbent dividing, dividing of acetone-water mixture in Moscow Chief Institute for Nitrogen Industry (Russia). Projects and their implementation: the technological process of synthesis product distribution in Sorsk Molybdenum Plant (Russia), the technological abrading process of gas emission in Shostka production association "SVEMA" (Ukraine), the technological abrading process of gas emission from fluorine and ammonia in Sumy production association "Khimprom" (Ukraine), the technological process of natural gas dehydration worked out by the research institute "Kompresormash" (Ukraine).

Conclusions

1. The received results prove the possibility to change the concentration on one stage of spraying, which corresponds to some theoretical stages of concentration changing.
2. One has also got the mathematical dependences, which make it possible to calculate the surface of mass transfer in vortex spraying counter-flowing mass changing device.
3. We have also got the equations using which one can calculate mass transfer volume coefficients for the vortex 1 device with opposite phase movement along the radius in vortex mass changing chamber.

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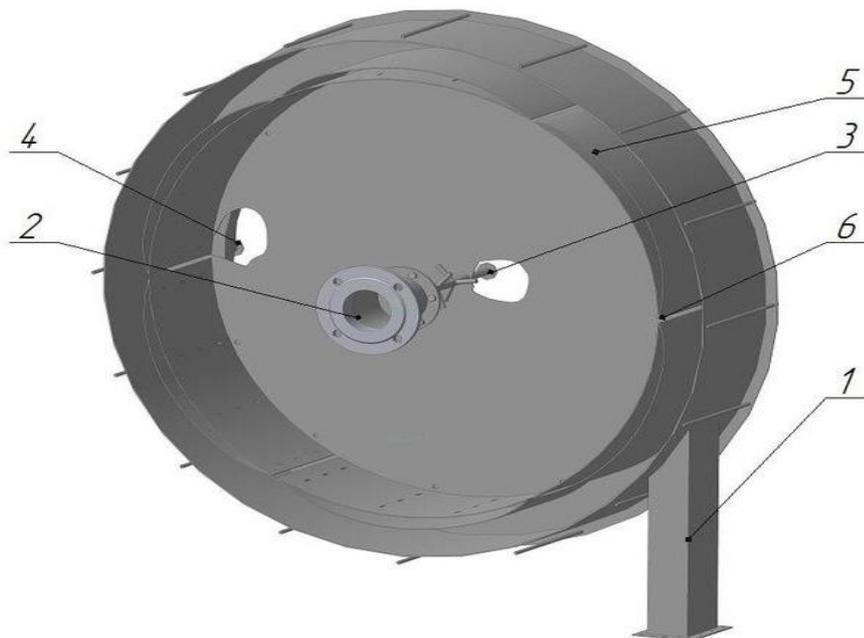


Figure (1) Vortex spray countercurrent mass exchange device (VSCMED) with horizontal axis: 1- tangential input of gas (steam); 2 - gas(steam) extraction; 3 – liquid input into sprayer; 4 – liquid extraction out of the device; 5 – swirler for gas input in the circumferential direction in the vortex mass exchange chamber, 5 – slots for liquid extraction out of the vortex mass exchange chamber.

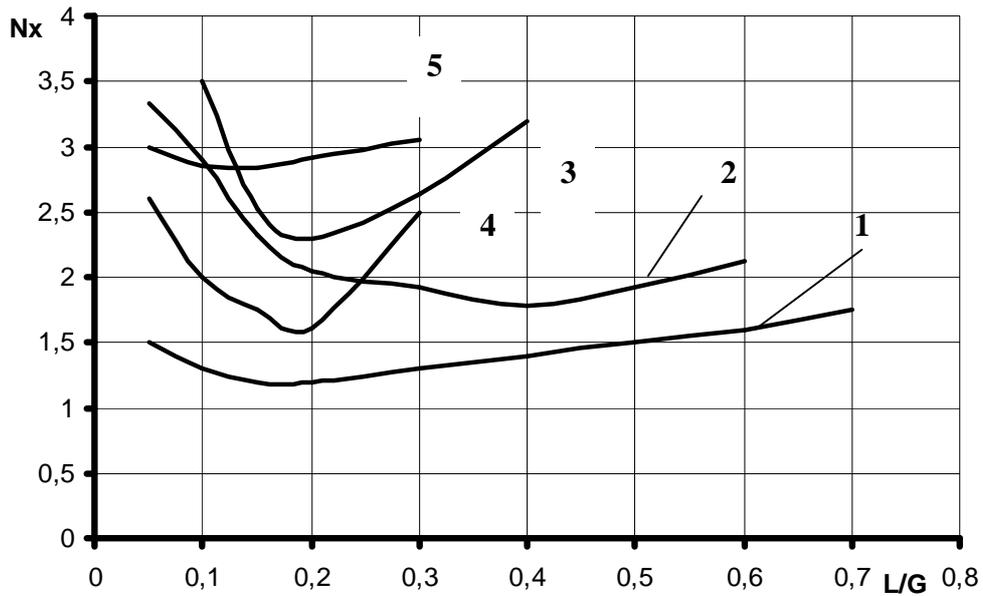


Figure (2) The quantity of theoretical stages of concentration change (N_x) depending on phases load (L/G) at different entry gas(steam)velocity in entry tangential slits of the vortex chamber (V , m/s): 1 – 9,0; 2 – 12,7; 3 – 15,6; 4 – 20,1; 5 – 23,8[20].