DESIGNING FILTERING HALF-MASKS

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Abstract: *This work offers an approach to the design of the filter half-mask of a dust respirator with taking into account the anthropometric characteristics of faces of personnel. The ways of obtaining half-mask contours and construction of the obturation band are considered. Two designs of the front parts of the respirators are proposed, which are in comparison with each other by the size of the contact area of the obturator and the face and the calculated values of the coefficient of protection. Based on the data obtained, it is determined that half-masks constructed with consideration for the width and length of the face have better protective performance than with consideration for the length of the face and lips.*

Keywords: *filter half-mask, obturator circuit, protection factor, dimensional features of the face.*

1 INTRODUCTION

Anti-dust filter respirators are widespread in various industries due to their relatively low cost and simple design. However, there are some significant problems with their usage: the lack of a reliable fit of the obturator to the face along the obturation band, short duration of protective action, and others [1], which can significantly reduce the level of protection of personnel. Most of experts are of the opinion that the main disadvantage of filtering half-masks is the lack of reliable protection due to the low degree of conformity to the shape of the face, which is caused by the diversity of anthropometric characteristics of users' faces. It is established that the gaps most often occur in the area of the nasal bridge. It is experimentally determined that about 84% of the gaps are formed in the areas of the nose and cheeks [2]. The worst results when checking the half masks are recorded when talking and tilting the head (facial expressions). Therefore, improving the design of the half-mask and the obturator is an urgent scientific and technical task.

Analysis of publications: The design of personnel protection equipment (PPE) for respiratory organs consists of the development of a technical specification, a sketch and a technical project, design and working documentation. Respiratory PPE are classified into the third category of complexity for which conformity assessment is required [3]. Such procedure involves the internal control of production and checks of assets throughout the use and storage period. Experimental wearing and experimental testing of protective equipment takes extensive periods of time and expensive [4]. In addition, the implementation of such stages is time-consuming and requires high professional training of the developer [5]. Reducing the duration of such process without losing the quality of the filter half-mask can be achieved in various ways, in particular through the use of automated design systems. However, the design of PPEs of respiratory organs is not sufficiently formalized and is usually based on heuristic methods, which rely mainly on the specialist knowledge of the designer [5-8]. This can lead to errors and the loss of time to fix them. It is believed that the most time in the design of PPE of the respiratory system is spent of developing the shape and construction of the face mask [9]. The peculiarity of the design of respiratory organs is in changing a wide range of many parameters, including anthropometric characteristics of the human face; working conditions; changes in the physiological and psychological states of a person using PPE. There are a number of publications investigating the impact of a particular factor on quality, including the reliability of the respirator [10-13]. Therefore, the information database of anthropometric data was formed [10], the influence of the respirator on the physiological state of personnel was investigated [11], changes in the protective effectiveness during long-term use of PPE under different working conditions were evaluated [12], and a structural diagram of the reliability of PPE of respiratory organs was proposed [13]. This makes it possible to create the design of respirators from individual elements, highlighting certain stages of designing process. Leading manufacturers of respiratory protection equipment (Maskpol S.A., Scott Health & Safety) use information technologies to develop new types. The sequence of development of dustproof masks includes such stages [2]: research of anthropometric characteristics of workers' faces with the use of 3D scanning; construction of digital models of workers' heads of several sizes with the use of the main parameters of the face; construction of a 3D surface of a half-mask using NURBS-surfaces, B-splines or other digital models. An important stage is the unification of designs by similar anthropometric data and functional purpose. Depending on the structure of harmful substances (dust, aerosol, evaporation), the selection of an appropriate assemblies of filtering materials is performed. The main tasks are to increase the gapping of the mask to the face for different categories of consumers and increase the time of protective action. The analysis of modern tendencies of designing has shown that the important stage is search of new mathematical models and improvement of existing ways of processing of statistical data of anthropometrical parameters of faces. More precise 3D modeling of the mask surface will allow to take into account changes in facial parameters in the digital image. Such improvements make it possible to speed up and simplify the verification process during the design stages and make corrections during prototype production. Estimated protection times can be determined based on specific application conditions.

2 EXPERIMENTAL

All PPEs of the kit worker must be mutually consistent. Protective clothing takes into account the shape, size, design features and materials of the filter half-mask.

The purpose of the article is to substantiate the choice of design and technological solution of the model of protective filter face half-mask with improved protective and ergonomic parameters. To achieve the results, the following tasks must be solved: to determine the influence of the size characteristics of a person's face on the performance of half-mask protection; to develop a contour of a half-mask taking into account anthropometric sizes of faces; to select the appropriate filter materials for the production of half-masks and obturators; to develop a way to evaluate the protective characteristics of half-masks at the design stage.

3 RESULTS AND DISCUSSION

In order to solve the priority task, the researches of different authors on the effect of face size on the level of protection of workers when using PPE of respiratory organs are analyzed. It is established that for the production and further testing of respirators, special tables with the distribution of characteristics of testers on such anthropometric characteristics of the face, such as the length and width of the face or the length of the lips are widely used [2]. The studies carried out showed a high and long-lasting degree of protection for workers using half-masks created from the data of such tables.

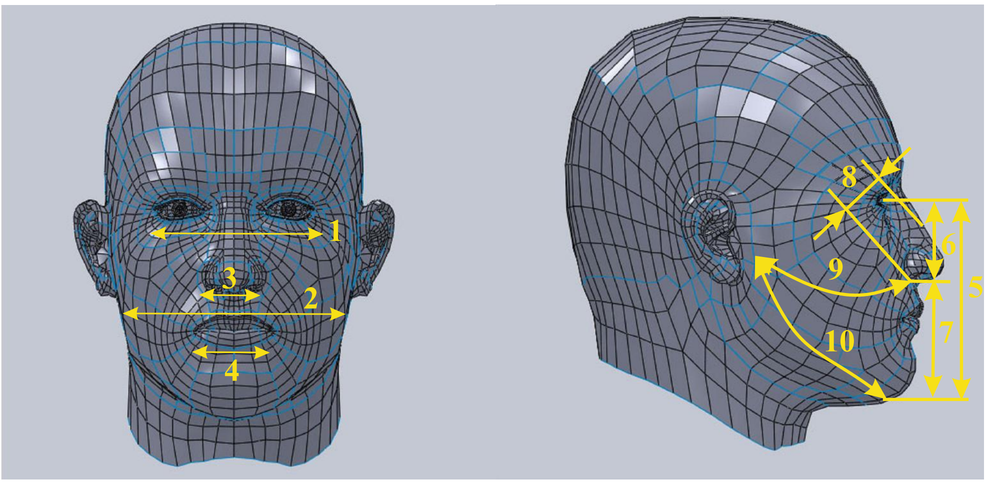
The next step identifies the facial features that are specific to our region. Using the recommendations given in [14], the dimensional features of the face are determined in accordance with Table 1. In order to solve the priority task, the researches of different authors on the effect of face size on the level of protection of workers when using PPE of respiratory organs are analyzed. It is established that for the production and further testing of respirators, special tables with the distribution of characteristics of testers on such anthropometric characteristics of the face, such as the length and width of the face or the length of the lips are widely used [2]. The studies carried out showed a high and long-lasting degree of protection for workers using half-masks created from the data of such tables.

The next step identifies the facial features that are specific to our region. Using the recommendations given in [14], the dimensional features of the face are determined in accordance with Table 1.

The measurement was performed using a caliper and centimeter tape on 400 people, of whom 320 were men and 80 were women. The range of values of the face length of the study subjects ranged from 98.5 mm to 143.2 mm, width ranged from 131.3 mm to 164.9 mm (Table 2).

Table 1 List of dimensional features of the face

Feature number (Figure 1)	Dimensioning symbol	Name of dimensioning	Feature name of dimensioning measurement technique
1	GONI	Width of face beyond eye line	Maximum horizontal width of face between end points in eyes hollows
2	ZYGO	Face width at lower jaw angles	Maximum horizontal face width between jaw arches
3	NOSEBRTH	Nose width	The distance between the right and left points of the wings of the nose
4	LIPLGTH	Lip length	The distance between the right and left points at the corners of the mouth
5	MENSELL	Face length	Distance between lower chin point and upper nose recess
6	NOSEPRH	Nose length	The distance between the lower nose point and the upper nose recess point
7	MSNL	Lower part of face	The distance between the lower chin point and the lower nose point
8	NOSP	Nose protrusion	The distance between the lower nose point and the average nose recess point
9	TRNA	Cheek width	The distance from the lower edge of the ear to the wing of the nose
10	TRMA	Cheek width	The distance from the lower edge of the ear to the chin



a) b)

Figure 1 Indication of the dimensional features of the face at front (a) and side (b)

Table 2 The results of measurements of dimensional facial features

Dimension feature codes	Mathematical expectation and confidence interval of face dimension [mm]		
	men	women	total
1. GONI	144.3 ± 8.9	135.3 ± 6.0	144.5 ± 8.9
2. ZYGO	130.2 ± 9.1	121.1 ± 9.1	128.4 ± 10.1
3. NOSEBRTH	32.7 ± 1.9	29.6 ± 3.3	32.0 ± 3.6
4. LIPLGTH	51.4 ± 3.7	45.0 ± 3.7	48.7 ± 4.8
5. MENSELLH	121.1 ± 8.4	115.2 ± 5.8	119.8 ± 7.8
6. MSNL	49.3 ± 4.5	43.2 ± 3.0	47.7 ± 5.0
7. NOSP	24.1 ± 2.7	22.4 ± 2.2	23.9 ± 2.6

The importance of the result of the work done is due to the need to check the respirators in the laboratory on volunteers who do not need to select according to the results of the size distribution and to remove from the inspection those who failed to find a suitable half-mask. This approach helps to protect the maximum number of employees, not just those whose facial parameters match the theoretical.

The next step is to look for the relationship between the obturator area and the safety metrics. The coefficient of protection K_3 of the respirator is determined by the formula:

$$K_3 = Q_0 / Q_l \quad (1)$$

where: Q_0 is total air flow during respiration [m/s]; Q_l is suction of air through the lines of obturation [m/s].

It is established that air leakage due to spaces between the filter half-mask seal and the face with uniform distribution of contact voltage can be calculated by the following formulas [15]:

$$Q_l = C_g C_u \quad (2)$$

$$C_g = \frac{k^3_{max} \cdot \Delta p}{l\mu} \quad (3)$$

where: k_{max} is the maximum height of the irregularities at the perimeter seal [m]; Δp is pressure drop [Pa]; l is the width of the seal [m]; μ is dynamic air viscosity [Pa.s]; C_u is the leakage permeability coefficient determined by the following formula [16]:

$$C_u = \frac{k_g \cdot \zeta}{8(1 - k_g)} \quad (4)$$

where: k_g is the coefficient of efficiency of use of the surface of the half-mask; ζ is the local loss factor.

In [17] it is recommended to determine the local loss coefficient for cracks by the formula:

$$\zeta = 2{,}5 + 5{,}5 \cdot 10^{-4} \left(\frac{l}{k_{max}} \right) \quad (5)$$

The coefficient of efficiency of use of the surface of the half-mask obturator is determined by the formula:

$$k_g = \frac{F_e}{F_o} \quad (6)$$

where: F_e is the effective surface of the obturator, which is close to the face [m^2]; F_0 is the total area of the half-mask obturator [m^2].

The effective surface of a half-mask mask can be determined in several ways, including the imprint on the soft layer, which is applied to the head of the dummy and by thermography (Figure 2).

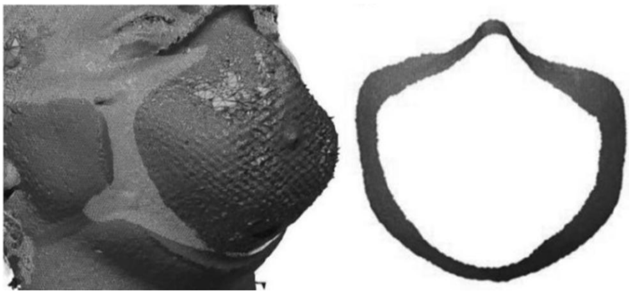


Figure 2 Determination of effective half-mask obturator area

The thermogram allows to determine the locations of the tight fit and, accordingly, the penetration of the aerosol along the obturation band by the intensity of the thermal radiation of the surface of the obturator in the infrared range. The reflection of the thermal field on the thermal imaging display is given in color, where the places of aerosol penetration into the sub-mask space through the slits between the obturator and the face are of particular color. The location of the local temperature anomaly on the surface of the obturation band is determined by the change in thermogram color.

In the second stage, two variants of the shape/line contour of the half-masking strip of the obturator are considered. The first takes into account the width of the face, the width of the nose and the distance from the nose to the chin. In the second embodiment, besides the points indicated, the width of the face behind the jaw is taken into account. On the basis of the obtained results of the measurements given in Table 2, the placement of critical points for the construction of an obturation strip on the face is proposed (Figure 3).

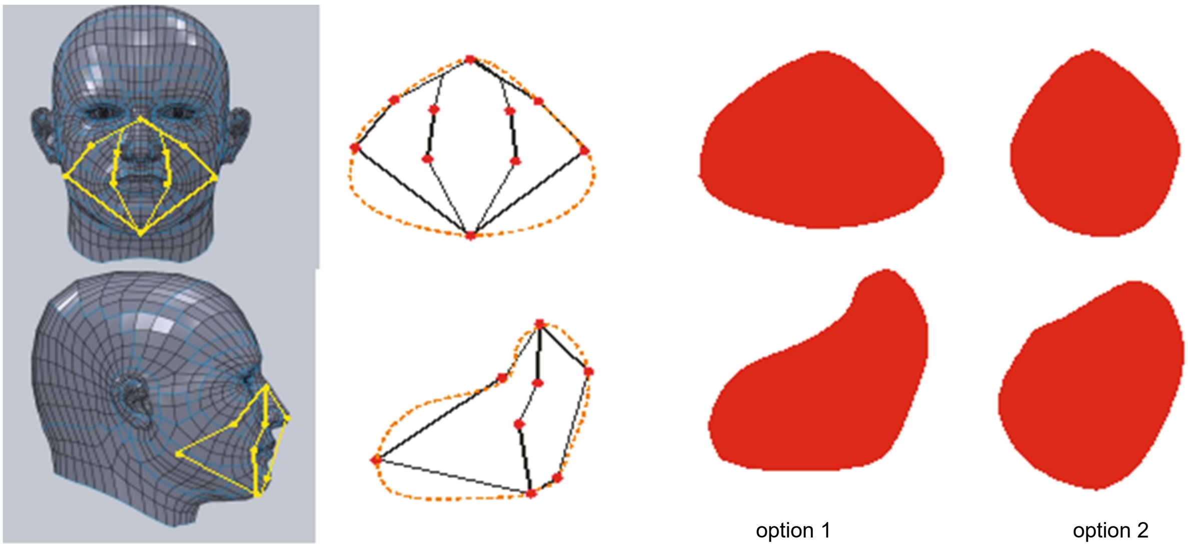


Figure 3 Schemes of the contour stripes

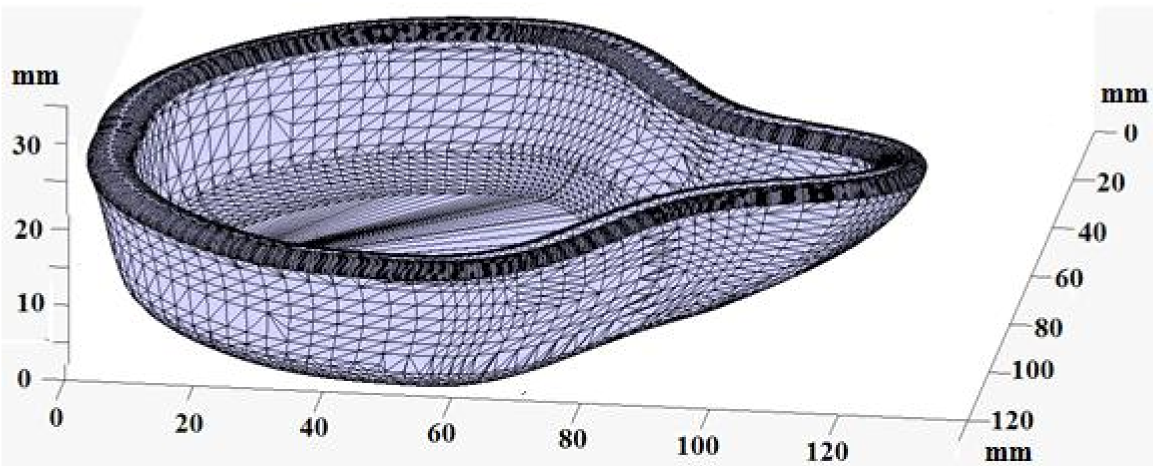


Figure 4 Surface view of the filter half-mask in the second option

The same is true for both options, such as the width of the nose and the distance from the nose to the chin. The difference is the choice between the width of the face and the length of the lips. Thus, the defined contour of the obturator is narrow at the top of the face and extended to the bottom to cover the cheek. It is experimentally proved that in the first option the influence of facial expressions during conversation and head turns is reduced, while in the second the contour is centered around the nose and mouth, and, as a consequence, there will be less material consumption of the filter and protective layers. The mask shape was obtained according to the coordinates of anthropometric points obtained during digitization of the scanned face shapes. The rough edges are smoothed using the appropriate Corel software. A sample of the constructed surface of the filter half-mask is shown in Figure 4.

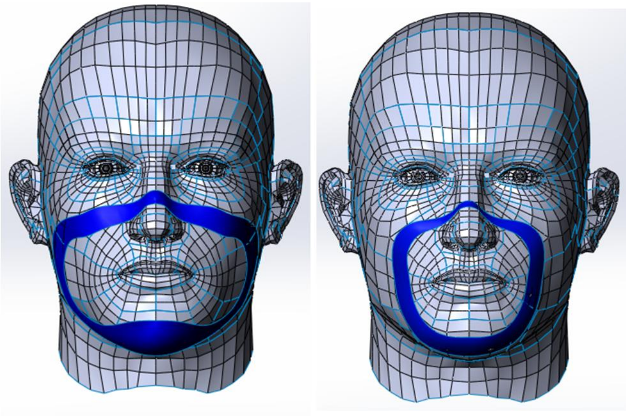
Further studies consisted of combining a half-mask with a head model to determine the contact area along the obturation band. The contact area between the head and the half-mask is provided as a non-uniform ring, which is bounded by the inner and outer boundary curves. We consider the surface of the contact area symmetrical and the possible asymmetry of the head in the first approximation is not taken into account. Some of the contact areas are manually adjusted because there are some inconsistencies with the computerized implementation in the 3D image of the half-mask. The most problematic area is the convex and in the half-mask image this area does not partially coincide with the size of the bridge. In real half-mask models, there is a plate that can improve the degree of fit by clamping down on the force in the bridge. Therefore, we assume that such actions do not make a significant error in determining the contact area. The simulation result is given in Table 3 and Figure 5.

Table 3 The results of calculating the area of the obturation band

Option number	Calculated contact area between half-mask and face areas [cm^2]				Total contact area [cm^2]
	bridge	right cheek	left cheek	chin	
1	2.2	3.1	3.1	4.0	12.4
2	1.2	2.2	2.2	2.6	8.2

The next step is to make a reasonable choice of materials for the manufacture of half-masks and obturator. It is advisable to make dust masks multilayered (Figure 6).

The structure of the package consists of materials different in purpose and other characteristics of layers. The first layer is the outer frame. Its purpose is to remove the largest particles of dust from the air stream, to protect the filter material from mechanical damage and deformation. The second and third are filter layers designed to refine the air of harmful impurities. Such layers determine the degree of protective effectiveness of the respirator. The fourth is the inner layer, which supports the filter material and directly contacts the face of the user. The material of the fourth is the layer is smooth, does not contain substances that cause irritation or allergy, improve the conditions of use (absorb moisture during breathing).



a) b)

Figure 5 Layout of half-mask obturation band on head model: a) option 1; b) option 2

Figure 6 Package of materials for the manufacture of half-masks: 1) inner layer; 2) fine refinement filter; 3) coarse refinement filter; 4) outer frame layer

The obturator is made of identical materials, and special materials (polyurethane foam, silicone, rubber) are used to increase the insulating characteristics. The developed half-mask samples are made of three layers of polypropylene filter material of different density (Table 4) and the inner layer is made of cotton fabric (Figure 7).

Table 4 Basic parameters of the filter layers from which the samples are made

	Filter layer indicators		
	first	second	third
Fiber radius α [μm]	10.0	3.0	7.0
The fiber packing density β	0.03	0.05	0.03
Thickness [mm]	4.0	3.0	3.0

a) b)

Figure 7 Appearance of filter half-masks: a) option 1; b) option 2

To ensure the necessary duration of the protective effect of half masks, their filters are made of several layers of materials of different density and thickness. The number of layers depends on air dustiness and operating mode.

$$K = \frac{C \cdot Q \cdot t_k}{\rho_d \cdot V_{\max}}, \quad (7)$$

where: K – number of filter layers; C – dust concentration in the air of the working area [kg/m^3]; Q – air volume discharge [m^3/s]; t_k – time in use [s]; ρ_d – dust deposit density [kg/m^3]; V_{max} – maximum dust volume [m^3].

One of the main steps in the manufacture of half-masks is to determine the attachment points of the headband to ensure a uniform distribution of the clamping forces along the obturation band. This is a prerequisite for providing protective performance. To solve this problem, you can use a calculation method based on the construction of models of external forces acting on the half-mask (Figure 8), or use a special measuring system, for example, Tactile free form sensor system (Sensor Products Inc., Madison, N.J.).

The solution to the latter problem is due to the process of thermographing the manufactured half-masks on several testers. Such tests give the opportunity to check the protective properties of the respirator at the stage of the test sample, and then make appropriate adjustments to the design of the obturator. Air flow through the half-mask was taken at 95 dm^3/min (according to [18]), the average resistance of the half-mask to the air flow was 75 Pa. The obtained thermal images are shown in Figure 9.

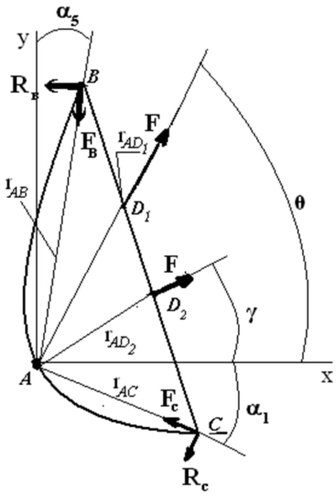
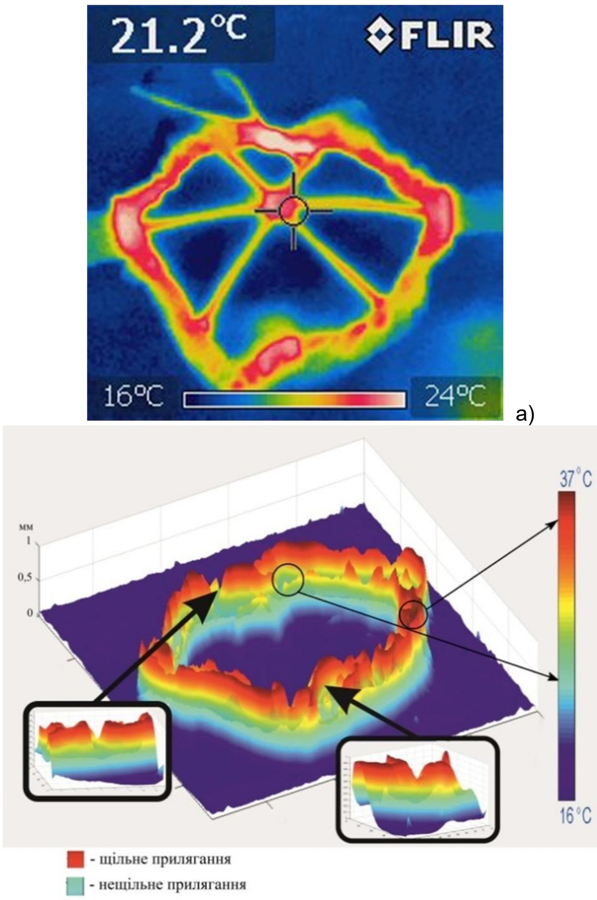


Figure 8 Calculation model for determining the placement of a headband



a)

b)

Figure 9 Infrared image of a respirator according to variants: a) thermal imaging test; b) after processing in the Matlab package

Table 5 The results of the calculations of the protective effectiveness of half-masks

Number of variants	Pressure drop [Pa]	Total air flow rate Q_0 [m/s]	Maximum height of irregularities k_{max} [m]	Efficiency factor k_g	Indicator C_g [m^3/s]	Permeability factor C_u	Protection factor K_3
1	75	0.0015	0.04	0.8	$5.2 \cdot 10^{-5}$	1.25	28.7
2			0.06	0.7	$8.4 \cdot 10^{-5}$	0.74	17.9

The results of experimental studies and mathematical modeling were processed according to formulas (1 - 6) and maximum heights of irregularities and protective indices were determined (Table 5)

3.1 Discussion of the results

The tests made it possible to formulate an improved sequence of work on the design of filter half-masks. The characteristic dimensional features of the faces of potential consumers are identified. We use the obtained average dimensions as the initial information for mathematical 3D model of the head. According to the results of the simulation, the contour of the half-mask mask was constructed the area of contact with the face and the strip of the obturation were calculated, which makes it possible to choose the shape of the half-mask. It is known that the larger the contact area and the obturation band, the less gaps are formed during various movements of the head. Respiratory elements are selected: material type, number of material layers, exhalation valve, headrest, nose clip. The structure of the respirator depends on a number of factors: concentrations of harmful dust, particle size; type of filter material. Note that the available filter materials make it possible to provide the desired degree of air purification for all types of dust. In the third stage, we check the protective properties of the prototype by the magnitude of the air suction due to the tightness of the obturation band. Based on the mathematical model, the magnitude of the protection coefficient, we estimate the design taking into account the structure of the package of materials of half-mask, as well as the impact of each layer. The proposed algorithm differs from the known presence of a preliminary check of protective properties using a mathematical 3D model at the design stage.

4 CONCLUSIONS

As a result of the performed researches the main stages of designing half-masks were determined. The following sequence is proposed: determination of anthropometric face sizes; development of contours of the obturator and calculation of the area of contact with the face; selection of appropriate filter material; preliminary evaluation of the protective properties under the simplified procedure - thermography.

The basic statistical anthropometric sizes of faces of people for regions of Ukraine are defined. Two variants of designing the surface of facial half masks are considered. In the first variant as initial parameters are used: width of a face at the level of a nose; width of a nose and distance from nose bridge to a chin. In the second variant are used: the width of the face under the lower jaw, the width of the nose and the distance from the nose bridge to the chin.

The results of mathematical modeling showed that in half masks, which are built on the size of the width of the face and nose and the distance from the bridge to the chin, the area of the skirt is 1.5 times larger than in half masks, which were built on the second version. Laboratory tests have shown that the protection coefficient of the half-mask in the first variant is 40% higher than in the second variant.

A filter media assembly has been selected for the selected half-mask design. A three-layer assembly has been used in which the first layer is a frame layer, the second and third layers are designed to capture large and fine aerosols.

A technique has been developed to check the quality of the respirators based on the determination of the area of contact of the half-mask and the pressing force of the half-mask to the face. It has given the chance: to calculate factor of protection of a respirator at designing; to reduce errors at formation of a structure skeleton and a face seal design.

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