Journal of the Technical University of Gabrovo, Vol. 55’2017 (7-12)

ИЗВЕСТИЯ
на Технически университет
Габрово

ABOUT THE CONSTRUCTIONAL FEATURES OF WATERJET-LASER PROFILED PERFORATION OF THIN-SHEET METAL BLANKS

V.Y. Kholodnyi*, A.F.Salenko, A. Bal, S.P. Melnichuk

Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

Article history: Received 09 February 2017, Accepted 08 March 2017

Abstract

Methods which use to produce specialized holes by the process of perforation of aluminum-magnesium foil are considered. Defects of mechanical and laser perforation of aluminum foil are shown. A fundamentally new design of waterjet-laser head are represented. This construction allows obtaining specialized holes comparable to the profile of the jet stream that is formed by an annular nozzle. Using FlowVision software, mathematical modeling of liquid stream through cavities of newly projected waterjet-laser head, the special feature of which is the presence of ring nozzle head and valve type device, was run which allows liquid inlet into the cavity of the head, using the required amount of points (from 1 to 6 channels of working liquid inlet). Velocity profiles are achieved, the analysis of which allows making conclusions about quality appreciation of inequality of speed fields from the amount of liquid input channels.

Keywords: aluminum-magnesium foil, annular nozzle, perforation.

INTRODUCTION

One of the most significant tasks of modern aerospace technics is the necessity of getting profile holes in different elements of honeycomb panel constructions. Technological drainage holes have an important role: they assure equalization of internal pressure which appears due to alternating loads created by quick pressure change outside as well on the inside of the construction; removing condensate appearing due to temperature differentials; also they support lowering level of noise from the power installations [1].

PRESENTATION

Typical honeycomb construction of aerospace devices is shown at figure 1. It consisti of inner and outer plates joint together with gofferfiller made of aluminum.

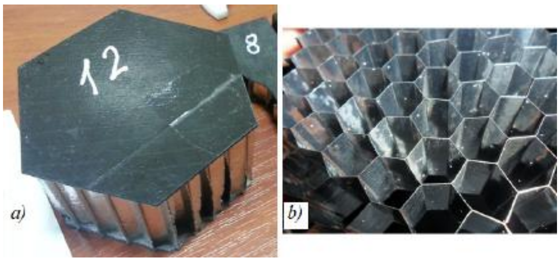


Fig. 1 *– Examples of prepared honeycomb core panel (a) and honeycomb filler with perforation (b): a – sample of honeycomb panel; b – stretched honeycomb filler*

The process of making drainage holes in honeycomb panels is quite labor-consuming and not automated enough. Existing and widely used technologies, like punching with indentor, have a range of disadvantages. The main disadvantages of mechanical perforation method (figure 2) which is dominant in modern production, are appearing tension concentrators, deformation of edges of the hole, geometric uncertainty of the hole as well as difficulty of getting geometrically certain holes.

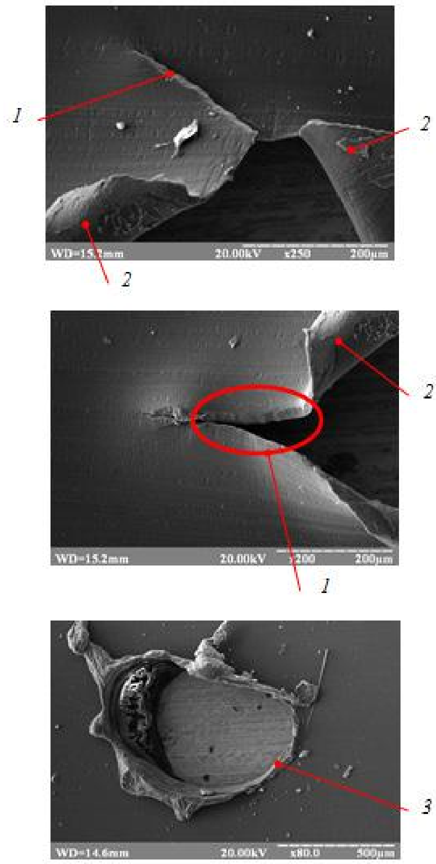


Fig. 2 *– Defects of mechanical perforation with aluminum foil indentor: 1 – foil crack; 2 – foil deformation; 3 – hole of incorrect geometric configuration*

* *E-mail: v.kholodnyi@gmail.com*

Using WJGL (Water Jet Guided Laser) perforation method allows removing all the mentioned disadvantages, as well as achieving substantial advantages during perforating the workpieces with this method due to: easiness of reconfiguring the system due to the new scheme of applying drainage holes; lowering the initial cost of production due to lowering the amount of defective products and decreasing expenses for technologic equipment; increasing the reliability of the honeycomb filler and the production in whole [2] and adding new consumer features.

While running the modeling of the WJGL impact process the calculations of temperature fields from the impact of laser and coolant were performed. The temperature on the surface is set due to the end of impulse interval.

While piercing the holes the temperature fields are determined in the following way: (1)

$$T(x,z,t)=\frac{q(x)r^2}{\lambda}\left(\frac{a}{\pi}\right)^{1/2}\int_0^t\frac{P(t-\tau)\exp\left[\frac{z^2}{4at}-\frac{x^2}{4a\tau}\right]}{\sqrt{\tau}\left(4a\tau+r^2\right)}d\tau, \quad (1)$$

where $q(x)=q_0\exp\left(^{-}x^2/r^2\right)$, where q_0 is density of emission power in the center of focus spot; r – radius of Gaussian beam; λ – thermal conductivity index; a – temperature conductivity of workpiece material; t – running time; x, z – coordinates; P – power of laser emission.

Impact of liquid flow is considered in the following boundary conditions:

$$c\rho\frac{dT}{dt}-\lambda\Delta T=\frac{(T-T_1)kP}{\pi AB}\exp\times$$
$$\times\left[-2\left(\frac{(x-vt)^2}{c^2}+\left(\frac{y}{b}\right)^2\right)\right]\times\exp(-kz),$$
$$\lambda\left.\frac{dT}{dz}\right|_{z=0}=\alpha(T)(T-T_2),$$

with the liquid flow rate of $Q=\mu f\sqrt{\frac{2}{\rho}\Delta p}$ and its thermal conductivity c. It is taken to attention that the heat radiator is an oval with A and B semi-axis.

Temperature field in case of coaxial flow and emission in case of round nozzle profile and oval emission spot is

$$T(x,y,z,t)=\frac{P}{\pi\frac{1}{2}\rho c}\int_0^t\frac{e^{\frac{(x-v(t-z))^2}{4\alpha\tau+A^2}\;\frac{y^2}{4\alpha\tau+B^2}}}{\left[\left(4\alpha\tau+A^2\right)\left(4\alpha\tau+B^2\right)\alpha\tau\right]^{1/2}}\times$$
$$\times\left[e^{-\frac{z^2}{4\alpha\tau}}-\eta(\pi\alpha\tau)^{1/2}erfc\left(\frac{z}{2(\alpha\tau)^{1/2}}+\eta(\alpha\tau)^{1/2}\right)\times e^{\eta z+\eta^2\alpha\tau}\right]d\tau,$$

where *x, y, z* are coordinates; *t* – time; *η* – heat transition from the workpiece surface index; A and B – major and minor semi-axis of WJGL flow; and $P=\pi qAB$ – power of laser emitter.

As a result, during the WJGL impact the temperature field at the surface in the end of the impulse interval is calculated with the following equation:

$$T(t)=T_{\max}-\frac{q_l\delta}{\lambda}\times\left[\frac{2}{\sqrt{\pi}}\frac{\sqrt{a(t-\tau)}}{\delta}+\right.$$
$$\left.+\exp\left(\frac{a(t-\tau)}{\delta^2}\right)erfc\left(\frac{\sqrt{a(t-\tau)}}{\delta}\right)\right], \quad (2)$$

where δ is the depth of heat penetration, $q_l=f(f_c,p,t)$.

The experimental results achieved are represented in the [3, 4] works.

But the following research showed that in case of necessity of making profile holes (which are different from circles) it is required to assure turbulent stream flow in the space out of nozzle.

Changing the regime of liquid flow is characterized by Reynolds number *Re*, which was taken as a regulated and controlled parameter while assuring different conditions of liquid flow from the nozzle. Ring nozzles with different profile shapes were used for experiments. All the results of registered factors and calculated *Re* are represented in table 1 for a round, oval and square nozzle profiles (figure 3).

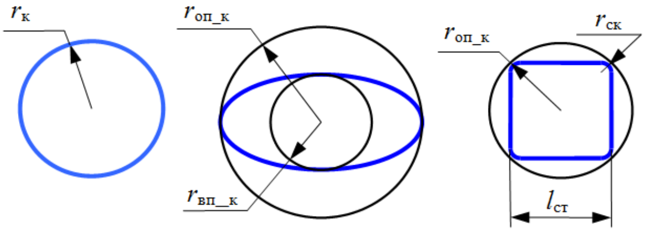


Fig. 3 *– Cross profiles of nozzles at the endings:* *$r_к$ – circle radius; $r_{оп\_к}$ – radius of circumcircle; $r_{ск}$ – rounding radius; $r_{вп\_к}$ – radius of inscribed circle; $l_{ст}$ – length of wall of initial geometric shape*

Running field surveys allowed receiving a range of curves of *I* intensity changes in the function of Reynolds number *Re* (фиг. 4) and obtaining respective regression equations considering connection of relative intensity I/I_{max} and considered factor (table 1).

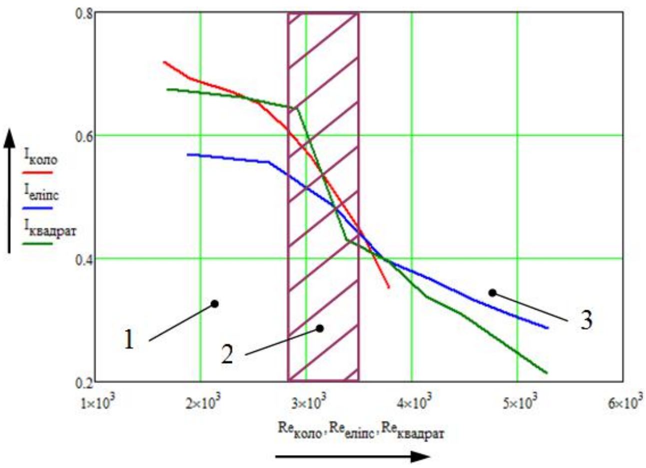
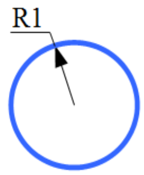
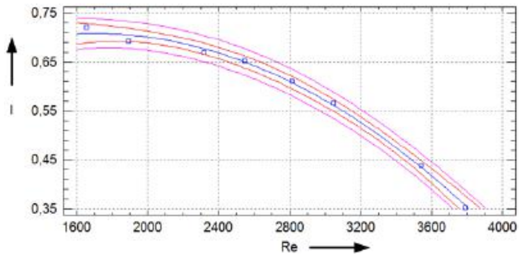
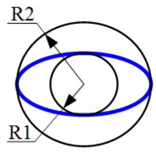
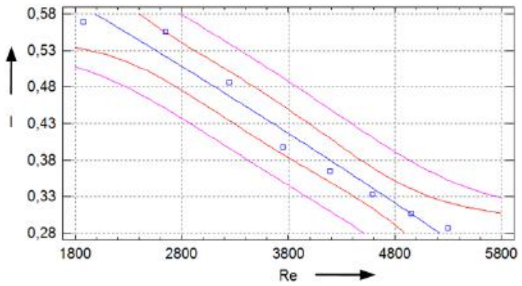
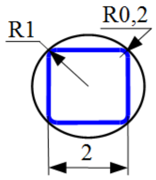
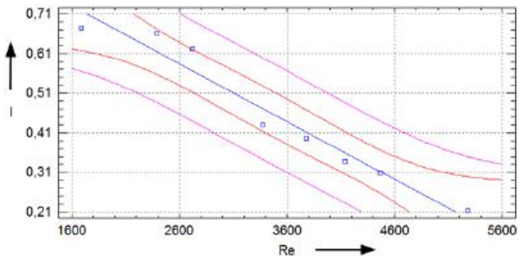


Fig. 4 *– Dependence of emission intensity from Reynolds number* *1 – zone of maximum light transmission;* *2 – transition zone; 3 – zone of active emission dispersal and aligning intensity due to profile*

Table 1 – Liquid stream intensity changes due to nozzle hole shape

№	Nozzle profile shape	Intensity	Polynomial regression	Reynolds number range
1.		$I/I_{max} = 0{,}4811 + 2{,}6926 \cdot 10^{-4} \cdot Re - 7{,}9704 \cdot 10^{-8} \cdot Re^2$		1,650… 3,800
2.		$I/I_{max} = 0{,}7455 - 8{,}0024 \cdot 10^{-5} \cdot Re - 1{,}7399 \cdot 10^{-9} \cdot Re^2$		1,850… 5,300
3.		$I/I_{max} = 0{,}8481 - 5{,}8901 \cdot 10^{-5} \cdot Re - 1{,}3908 \cdot 10^{-8} \cdot Re^2$		1,650… 4,800

Therefore, the analysis of received patterns proved that there is a certain range of Reynolds numbers (from 1,600 to 2,800), where no essential weakening of emission intensity for all shapes of nozzle profile with maximum size up to 4.0 mm is observed (figure 4, zone 1). Further increasing of Re and, respectively, disturbance of flow stream leads to quick decrease of emission intensity (zone 2), dynamics of which, when the level of Re = 3,800 excesses, is also decreased.

Apparently it can be mentioned that active mixing of the flow is going to take part in the jet, including patches of multiple refraction of beams, which leads to changing the shape of emission intensity curve in the jet profile. As the regime of liquid flow in the space out of the nozzle changes when being distanced from the nozzle profile, the postulated equation of

$$I_{\min} = B_0 + B_1 l_a + B_2 l_d + B_3 s_k + B_4 \,\mathrm{Re} + \ldots$$

allows connecting the controlled intensity at the edges of jet stream with Re as well as with s_k removal.

The performed complex of experiment researches allowed approving theory antecedents of dependence of emission disposal which is able to perform high-intensity heating of surface with liquid flow which is coolant at the same time. Reconfiguration of intensity described with corresponding diagram appears due to partial beam scattering which happens in the jet flow. Therefore optical abilities of flow, determined by Reynolds number, definitely determine the emission energy loss as well as its reconfiguration along the jet profile. It is determined that increase of Reynolds number leads to proportional intensity decrease in the impact center and causes emission increase in the peripheries.

For engineer practice, determining the patterns of dimples in time from the activity of WJGL stream (figure 5) with certain energy characteristics has particular significance. Due to above mentioned, determining the dimple depth h, form fault Δ and destructive zone width T_d for certain materials in the function of technology processing regimes, particularly the impulse amount N for certain impulse power (its duration while generating certain energy), discharges of technologic liquid and diameter (and shape) of obtained hole (due to maximum size) d_{max} can be achieved with obtaining respective regression equations (3 – 5). As far as nomenclature of materials used in the constructions of honeycomb panels of aerospace crafts is limited, additional parameters, heat capacity, temperature conductivity, reflection index are not considered with the aim of simplifying the models, and the models are going to be achieved for certain materials.

For the analyzed parameters of N (amount of impulses), Q (liquid flow rate, sm^3/sec), d (diameter of stream at the surface of the pool, mm) regression equations for determination of h, mm, Δ, mm, T_d, mm are received:

$$h = -0{,}0858 + 0{,}0253 \cdot N + 0{,}4678 \cdot Q + 0{,}3757 \cdot d - 3{,}6619 \cdot 10^{-5} \cdot N^2 - 0{,}0283 \cdot N \cdot Q - 0{,}0104 \cdot N \cdot d - 12{,}1375 \cdot Q^2 + 1{,}8125 \cdot Q \cdot d - 0{,}3167 \cdot d^2 \quad (3)$$

$$\Delta = 1{,}4744 - 0{,}0475 \cdot N - 4{,}5277 \cdot Q - 1{,}424 \cdot d + 1{,}2291 \cdot 10^{-3} \cdot N^2 + 0{,}02 \cdot N \cdot Q - 0{,}01 \cdot N \cdot d + 14{,}7141 \cdot Q^2 + 0{,}5 \cdot Q \cdot d + 0{,}8754 \cdot d^2 \quad (4)$$

$$Td = 0{,}5569 - 0{,}0193 \cdot N - 1{,}9069 \cdot Q - 0{,}4481 \cdot d + 6{,}7611 \cdot 10^{-4} \cdot N^2 + 0{,}0133 \cdot N \cdot Q - 0{,}0117 \cdot N \cdot d + 6{,}7271 \cdot Q^2 + 0{,}0 \cdot Q \cdot d + 0{,}3762 \cdot d^2 \quad (5)$$

The most important construction unit while using this perforation method is the WJGL nozzle head which joins the laser beam with the jet of technologic liquid. Synova company is the world manufacturer and leader in the section of selling complexes with jet-laser technology.

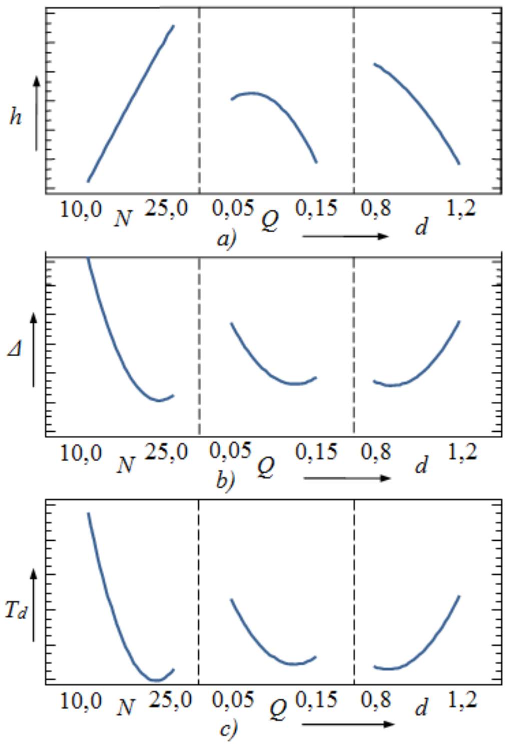


Fig. 5 *– Main effects of dimple depth h, mm increasing (a), deviations from hole roundness Δ (b) and changes of defective layer thickness T_d, mm (c) in the N, Q, d function*

The existing nozzle head constructions using the coaxial joint of liquid and laser beam [5] as the main working principle have a range of disadvantages: working liquid pressure limitation in the mixing chamber (glass allowing entering the laser beam into the liquid being in the mixing chamber); partial misfocusing of laser beam while passing the see-through window; impossibility of obtaining profile holes different from round; impossibility of obtaining exactness and smoothness of required edge of the profile hole.

For removing all mentioned disadvantages, the personnel of Department of Processes and Equipment of Mechanical and Physical-Technical Work of Kremenchuk National University of Mykhailo Ostrohradskyi (Ukraine) worked out a principally new jet-laser nozzle head which allows joining laser beam with liquid jet beyond its limits, as well as obtaining profile holes of different configuration.

The previous experiments showed [5] that emission dispersion along the jet profile is set directly with conditions of liquid flow in the channel of jet-forming nozzle. If changing the speed of liquid flow with setting the required pressure and discharge of liquid in the hydrosystem is not a problem, then assuring flow regimes (flow Reynolds numbers) is quite difficult because the shape of nozzle channel, particularly its profile at the ending, can be any. As far as the previous works showed that deturbulizers of the flow can greatly improve the flow conditions and approximate the liquid flow to the laminary flow, it can be supposed that the conditions of liquid inlet into the nozzle chamber determine the regime of its flow in the flow part. In works [6, 7] different flow regimes are achieved with controlling the flow on the entrance to the nozzle, and as a result a conception of controlled multipoint liquid inlet into the nozzle camera. Changing the amount of liquid inlet amount with the equal total discharge $Q_в$ and permanent pressure P_b allows obtaining the required *Re* number due to required flow intensity and geometric size of spot at the worked out surface.

In order to change *Re* in the flow part of the nozzle it is offered to use the slot valve of ring type, which allows inletting liquid from one, two, three, four, five or six channels. Depending on the inlet scheme vortex liquid flow regime or the one close to laminary is assured, which depends on the set task. The processed solid model is shown at the figure 6, and its work is illustrated in table 2.

Using ring nozzle consisting of stream channel inner part *1* and outer nozzle part *2* is the basis of worked out nozzle head model for jet-laser work (Fig. 7).

One of the basic elements of this construction is using the mechanism constructed at the principle of ring type slot valve work, which consists of outer *3* and inner holder *4*. This mechanism allows regulating the amount of liquid flowing out of the nozzle and influence the flow stream. This means there is a possibility of influencing the liquid flow while forming the jet. This is done with the help of flow-regulating handle *5* attached from connection *6* to the channels of valve-type device channels.

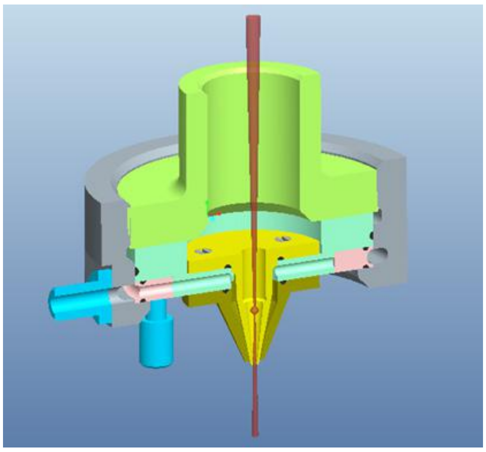


Fig. 6 *– 3D model of head for jet-laser work with slot valve*

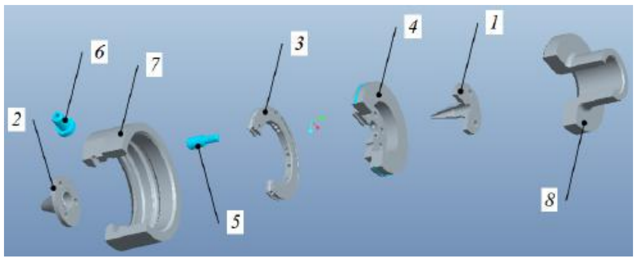


Fig. 7 *– Construction of worked out model of head for jet-laser perforation*

While inletting the liquid to the ring nozzle one of six versions of liquid inlet can be chosen. This means that when using one channel vortex flow and liquid swirls take place. When using two, three, four, five or six channels of liquid flow forming it becomes straighter and more like laminary regime. Fixation of WJGL nozzle head takes place via thread joint of its base *6* to the element of laser construction *7*.

To prove the above-mentioned hypothesis we have run the modeling of liquid flow with FlowVision means, using solid models of flow part generated with SolidWorks. We have appreciated the speed arrangement in plane of perpendicular axis of the stream as well as in plane of this axis. Modeling with such regimes: flow speed in the channel is 20 m/sec, liquid pressure at the entrance into the flow part of the nozzle – 0.5 MPa, liquid discharge – 0.3 dm^3/sec, diameter of inlet channel - 2.5 mm, shape of nozzle hole – circle, size of channel hole – 0.2 mm, pressure at the exit of the nozzle – 0.1 MPa.

Speed curves were obtained, the analysis of which allows making the following conclusions (table 2). For quantity appreciation of inequality of speed arrangement in the inlet channel, using flow inequality index k_v is offered:

$$k_v = \frac{\sum \frac{V_{\max} - V_{\min}}{V_{\max}}}{n_{\max}}, \qquad (6)$$

where n is the amount of liquid inlet ($n_{max} = 6$);
V_{max} та V_{min} are *max* and *min* speeds measured due to controversially placed beams counterclockwise.

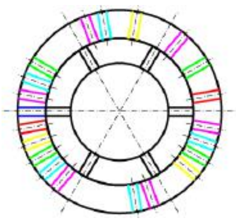
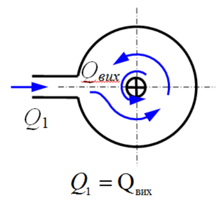
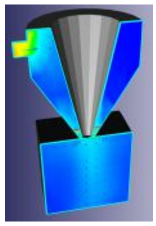
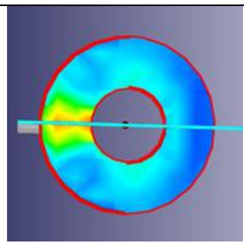
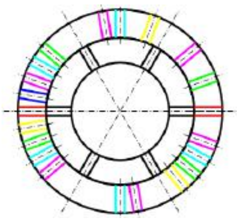
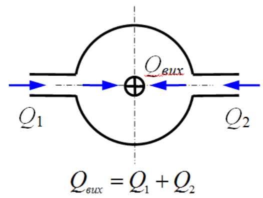
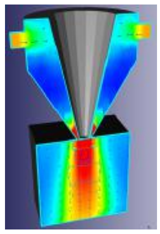
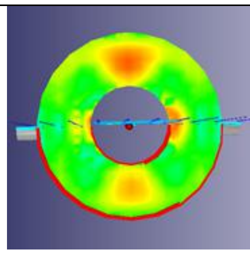
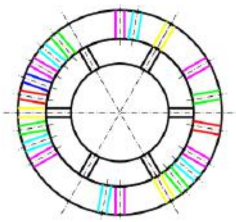
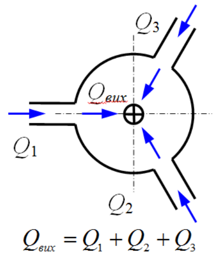
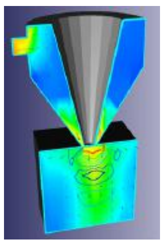
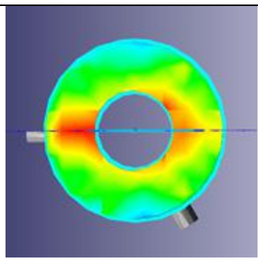
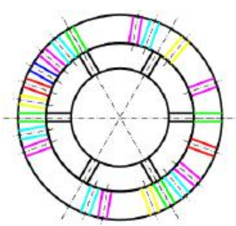
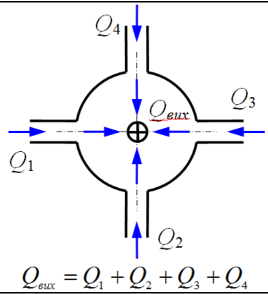
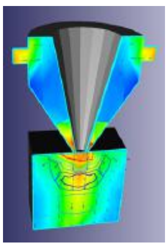
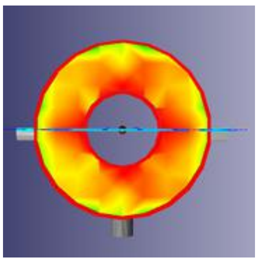
As far as the construction of jet device foresees 6 versions of liquid inlet (with the amount of simultaneously used channels being from 1 to 6), 12 sectors of flow speed V_i control are taken to attention.

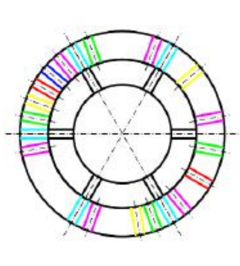
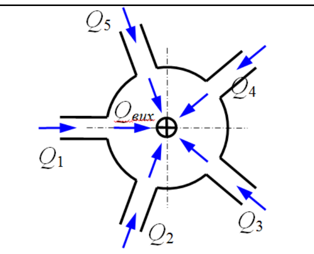
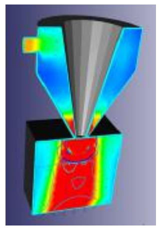
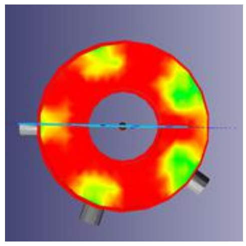
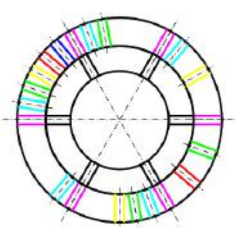
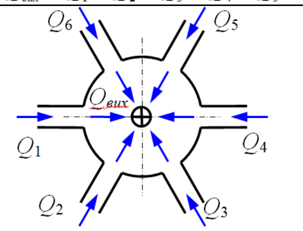
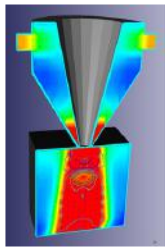
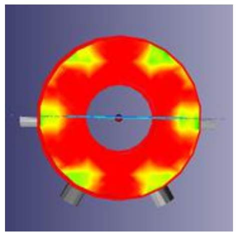
As a result of the analysis (figure 8, figure 9) the following is stated.

Presence of one inlet channel causes significant curvature of jet shape. The uneven number of channels, which is three or five, also causes curvature of jet shape, and at the same time the even amount of channels (two, four, six) assures symmetry of the flow. As a result, it can be stated that location of the channels significantly influences the compactness of the jet, especially for nozzles, the profile form of which has a shape different than circle.

As a result of calculations, modeling liquid flow and analysis the following is stated: one inlet channel causes prominent curvature of jet shape. The uneven number of channels, which is three or five, also causes the curvature of the jet shape, while even number of channels (two, four, six) assures flow symmetry. As a result, it can be stated that the arrangement of channels significantly influences the compactness of jet, especially for nozzles, profile of which has a different shape than circle.

Table 2 – Schemes of liquid inlet and modeling of its flow in the worked out head for jet-laser perforation

№	Amount of liquid input channels	Construction of slot valve	Flow of liquid in the head to the exit from the nozzle head	Linear speed filling in color	Filling in the color of speed module (additional cross cut)
1.	1 liquid input channel				
2.	2 liquid input channels				
3.	3 liquid input channels				
4.	4 liquid input channels				

5.	5 liquid input channels		 $Q_{вих} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$		
6.	6 liquid input channels		 $Q_{вих} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$		

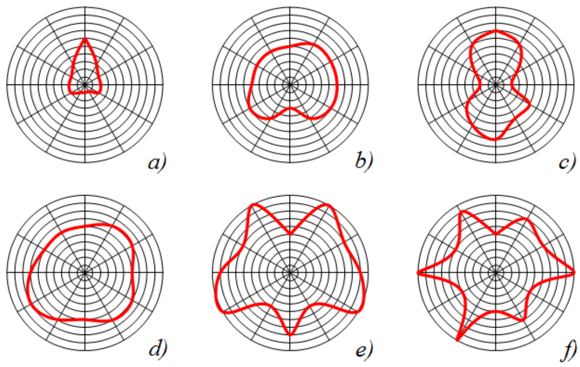


Fig. 8 *– Circle diagram of speed allocation in the analyzed profile in case of one (a), two (b), three (c), four (d), five (e) and six (f) channels of liquid inlet*

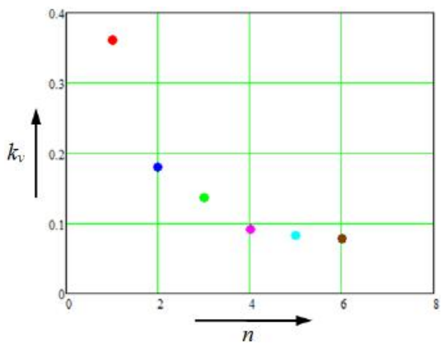


Fig. 9 *– Results of calculating dependence of inequality speed field index from the amount of liquid inlet channels*

CONCLUSIONS

Therefore, the offered construction allows widely changing the liquid flow regimes, setting them due to required pattern of intensity of laser emission through the stream profile. The possibility of setting profiled nozzles with required nozzle profiles is kept. Testing the nozzle showed its high effectiveness and wide technological possibilities.

Using such nozzle allows receiving small-size perforation holes (sized 0.1-1.2 mm) exactly and reliably, decreasing the thickness of destruction layer (up to 0.02 mm) and assuring higher exploitation criteria of the honeycomb production.

LITERATURE

[1] Anoshkin A.N. Calculation-experimental research of resonating many-layer sound-absorbing constructions / A.N. Anoshkin, A.H. Zakharov, N.A. Horodkova, V.A. Chursin // Vestnik PNIPU. Mechanics. – 2015. – No.1. – P. 5-20.

[2] Slivinskyi M.V. Classification of technological defects of honeycomb fillers made of polymer paper and ways of bringing it out for increasing their quality / M.V. Slivinskyi // Discovered information and computer integrated technologies: anthology of scientific works of National Aerospace University of N.E. Zhukovskyi “HAI”. – Issue 36. – Kh., 2007. – P. 85-99.

[3] Salenko A. Changing the spot of local destruction of samples at water jet guided laser processing with appropriate profiling jet / A. Salenko, V. Kholodnyi // Вісник Національного технічного університету України «Київський політехнічний інститут» серія Машинобудування./ Вип. №73. – Київ: НТУУ «КПІ», 2015. – С. 57-64.

[4] Kholodnyi V.Yu. Using jet-laser method of treatment for perforating honeycomb filler for aviation sandwich-panels / V.Yu. Kholodnyi, A.F. Salenko // East Europe Magazine of advanced technologies / Issue 1/5 (79). – Kharkiv, 2016. – P. 19-20. DOI: 10.15587/1729-4061.2016.59870

[5] Salenko A. Special features of researching small-size profile hole for jet-laser material work process / A. Salenko, V. Kholodnyi // Unitech – 2013 : International Scientific Conference, November 22-23, 2013. – Gabrovo, 2013. – Ch. III-139 – III-145.

[6] Dormidontov A.K. Improving valve camera of periodic burn for increasing frontal draft of pulsing reactive engines / Autoabstract of dissertation in candidacy for technical science candidate. Specialty 05.07.05 – Warmth, electric rocket engines and energy installations of flying apparatus. – Rybinsk: Rybinsk State Aviation Technical University of P.A. Soloviov. – 2012.

[7] Kariakin Yu. E. Number modeling of laminary flows of thick liquids in the channels of random shape, Minsk: ANK Institute of warmth- and mass exchange of A.V. Lykov, Science Academy of Belorussian SSR. – 1991. – 44 pages.