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МАШИНОБУДУВАННЯ. ТЕХНОЛОГІЯ МЕТАЛІВ. МАТЕРІАЛОЗНАВСТВО

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NUMERICAL INVESTIGATION OF THERMAL FIELD EXPANSION IN FIBER REINFORCED COMPOSITES

Р.Ю. Мелентьєв. **Чисельне моделювання теплового поля в волокнистих композиційних матеріалах.** Стаття присвячена проблемам теплоперенесення в багатокомпонентному тілі з анізотропними теплофізичними властивостями, такими як полімерні композиційні матеріали з волокнистим наповнювачем і інші шаруваті системи. ***Мета:*** Мета цього дослідження полягає в визначенні температурного градієнта на поверхні, що нагрівається і оцінці теплоперенесення між компонентами тіла, що моделюється. ***Матеріали і методи:*** Аналітичні методи моделювання ускладнені анізотропією структури і властивостей композиційних матеріалів. Чисельні методи моделювання мають широкий інструментарій, що дозволяє уникнути багатьох припущень, скоротити час обчислень і наочно відобразити висновки. ***Результати:*** В роботі розглянуто становлення теплового поля від кільцевого джерела тепла в площині і просторі, що дозволяє оцінити процес теплового росповсюждення в одному шарі матеріалу і в їх поєднанні. Представлені результати чисельного моделювання дозволили встановити локації максимальної і мінімальної температур тіла, що нагрівається. Теплофізична анізотропія тіла обумовлює асиметричне поширення тепла. На поверхні, що нагрівається, виявлено яскраво виражений хвилеподібний температурний профіль, крім того, встановлено, що температура в деяких секторах крайнього шару значно перевищує середню температуру поверхні. Існування описуваного температурного градієнта знайшло підтвердження в попередньому експериментальному дослідженні автора. З метою спрощення структури моделі і зниження часу обчислення наступних або подібних задач було зроблено спробу зведення анізотропного тіла до ізотропного шляхом підбору теплофізичних властивостей. Отримана ізотропна модель має високий ступінь кореляції до оригінальної, проте вона менш інформативна і повинна коректуватися спеціальними коефіцієнтами.

Ключові слова: чисельне моделювання, теплове поле, температура, теплоперенесення, композиційні матеріали.

R.Yu. Melentiev. **Numerical investigation of thermal field expansion in fiber reinforced composites.** The research is devoted to problems of heat transfer in a multicomponent body with anisotropic thermal properties, such as polymer composite materials with fiberfill and other layered systems. ***Aim:*** The aim of this study is the determination of a temperature gradient on a heating surface and the heat transfer evaluation between components of a simulated body. ***Materials and Methods:*** Analytical modeling methods are complicated by very laborious computations due to an anisotropy of composites structure and properties. Numerical simulation methods have a wide tool package, which allows to avoid many assumptions, to reduce computation time and visualize conclusions. ***Results:*** In the paper discussed a thermal field formation of the annular heat source in plane and space dimensions, that allows to evaluate the process of thermal development in single layer of material and in their connecting. Presented results of numerical modeling establish locations of maximum and minimum temperature of the heated body. Thermophysical body anisotropy leads to asymmetrical distribution of heat. Clearly expressed undulating temperature profile was detected on the heated surface, moreover, temperature in some sectors of outermost layer significantly exceeds the average temperature of the heated surface. The existence of the described temperature gradient has been confirmed in the previous experimental study of the author. In order to simplify a structure of the model and reduce computation time for following or similar tasks has adopted an attempt to translate the anisotropic body to isotropic by adjusting of thermal properties. The resulting isotropic model has a high degree of correlation to the original, but it is less informative and should be corrected by special coefficients.

Keywords: numerical investigation, thermal field, temperature, heat transfer composite materials.

Introduction. Nowadays, polymer composite materials are able to satisfy needs of almost any industry and this explains a lot of their species. Wide application in cars and aircraft have purchased glass and carbon fiber reinforced polymers (GFRP and CFRP). The distinctive feature of fiberfill materials is their high strength properties with a relatively small weight. With respect to traditional

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construction materials, FRPs are new and the process of their machining studied very superficially. For example, in contrast to metals, FRPs have low heat resistance and ambiguous thermal conductivity of his components. The thermal conductivity of the polymer matrix is 0.14...0.50 W/(m·K) and it is often lower for hundred times than the thermal conductivity of the filler, for example carbon fiber thermal conductivity can range 75…120 W/(m·K) [1]. At temperatures above 570…620 K, begins intensive thermal degradation and decomposition of the polymer binder and at processing such materials as organoplastics – polymeric filler. As a result of these processes, forms a dispersed-destructive layer, which degrades the performance of the components of polymer composites.

Drilling of CFRPs is an important secondary machining process in the aerospace industry and it almost accounts for 50 % of the total cost of machining composites. This is due to the fact that even a smaller private jet has up to $2.5 \cdot 10^5$ to $4.0 \cdot 10^5$ holes and a bomber or a transport aircraft has $1 \cdot 10^6$ to $2 \cdot 10^6$ holes [2]. The drilling process of hole with small diameter characterized by high thermal stress of the cutting process and friction between tool and detail. This fact leads to high temperatures at the surfaces [3] and a heat affected zone [4] that reduces the strength and life of the structure [5]. Decomposition of the resin in the composite started at a temperature of 360, this temperature corresponds well with prior findings [6]. Some works [7, 8] also showed morphology differences of the treated surface at high temperatures during drilling of CFRP, which is a consequence of the redistribution of the cutting forces. Thermal degradation processes are also present in other methods of creating holes, such as vibration assisted drilling [9], laser or electrical discharge machining [10].

The widespread application of these materials is ensured by their high structural properties. Required properties are achieved by selecting of components and orientation scheme in the composite. Commercially produced CFRP of two fibers orientation types: unidirectional and woven. Unidirectional schema consist of layers, each of which has fibers located only in one direction, however direction between layers can be different, usually it is [0/0], [0/90], [0/45/90/135] or [0/78/0/-78]. Unidirectional FRP plate shown in Fig. 1, *a*. Woven type of orientation in each layer has lot of fiber-bundles which knitted under direct angle (Fig. 1, *b*).

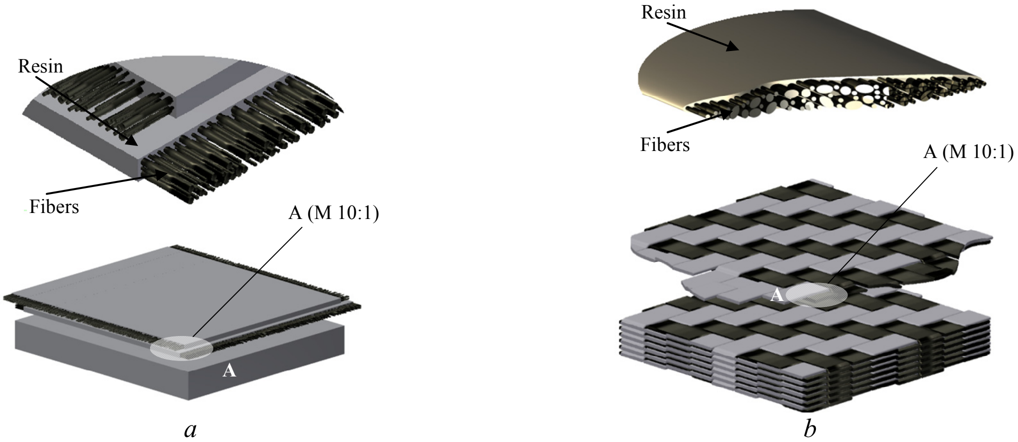


Fig. 1. Types of orientation fibres in polimer matrix: Unidirectional [0/90] (a); Woven [0/90] (b)

Despite the widespread use of fibrous materials with an ordered structure, it is known a small number of papers [11, 12], which dedicated to the analytical study of the effective thermal conductivity. There are also dependings [13, 14], that allow to determine reliably the thermal conductivity of isotropic materials. However, their application for determination of the heat transfer in anisotropic bodies with complex boundary conditions of the fourth type (heat transfer between adjacent bodies) hampered by many assumptions, reducing the accuracy of these decisions. When calculating the maximum temperature during the machining of FRPs is adopted that the material is isotropic. Taking into account enormous differences of thermal properties of components, this assumption cannot be considered valid without the error of its application. The author has already made attempts to account a multiphase structure of the heat-conducting body in the determination of thermal conductivity in an elemental volume of the composite [15] and the study of the thermal field in a single fiber, surrounded by a matrix [16]. It was investigated that the temperature on the surface of the epoxy matrix sometimes twice more than the maximum temperature of the carbon fiber. Pointed works suggests that the assumption of isotropic properties of a composite body is not acceptable without assessing thermal interaction of its components.

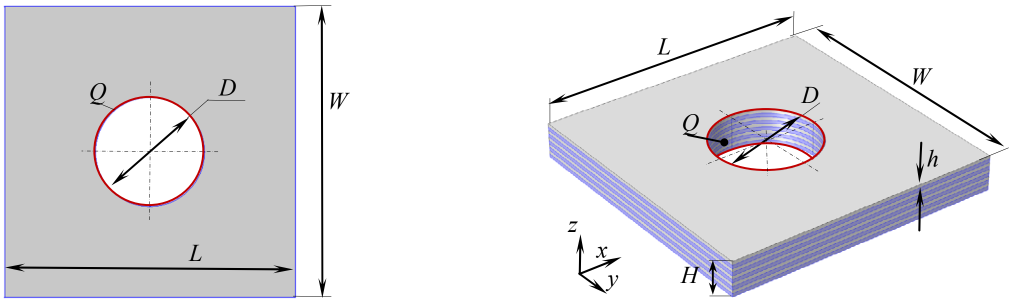
It is assumed that an essential effect of heat-conducting properties of the FRPs has a fiber orientation in layers.

The aim of the research is to highlight of the thermal field propagation in the multilayered fibrous material in drilling patterns. Since the structure of a fabric composite complicated by curved fibers bundles, the lack of regular contact between bundles and conditions of their different sizes, the study considers only unidirectional laminate structure. It is important to determine the distribution of heat in a single layer, to analyze thermal integration between layers with orthotropic fiber orientation, and based on this estimate the difference of heat transfer in anisotropic and isotropic bodies.

Materials and Methods.

Geometry. For the study of heat propagation in an anisotropic body, the simulation was carried out in two stages. At the first stage two-dimensional model was considered that is conditionally displayed a heating in single layer. In the second step the body viewed in three dimensions, which makes it possible to study the thermal interaction between layers. The initial data of flat model for the unidirectional layer is shown in Fig. 2, *a*, is a rectangle with limited dimensions and a hole in the center. On an edge of the hole is performed a heating according to boundary conditions of heat transfer (for details in the relevant section below). The spatial model of plate with unidirectional fibers is shown in Fig. 2, *b*. The plate is composed of ten layers and through hole.

Accepted assumptions: all the layers have uniform thickness, at the interface of layers present perfect thermal contact, material layer is homogenous. The dimensional data for each model are listed in Table 1



a *b*

Fig. 2. Models geometry: Unidirectional 2D (Flat) (a); Unidirectional 3D (Space) (b)

Physical properties. Thermal characteristics of CFRP taken from [15]. As mentioned, the thermal distribution model should be in agreement with anisotropy of the structure. Unidirectional 2D model has two different significantly coefficients of thermal conductivity: on the *x*-axis and the *y*-axis. In the spatial model, each odd layer (on the Fig. 2, *b*, gray layers) has high thermal conductivity along the *x*-axis, each even layer (Fig. 2, *b*, blue layers) has high thermal conductivity along the *y*-axis. This design is supported by the structure of the material and by a study of the process of heat propagation in the fiber-matrix [16]. Numerical data of the thermal properties are listed in Table 1.

Boundary conditions. To determine the temperature field and the creation of a visual reflection of the temperature distribution in a complex body with anisotropic thermal conductivity, the simulation was carried out in the program complex COMSOL Multiphysics. To use COMSOL not necessary to obtain an analytic solution (which, for example, need to work in the program MathCAD). To simulate a specific task is enough to have an original differential equations and boundary conditions. Embedded in the program complex mathematical apparatus for solving thermal tasks presented in the form:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \nabla T = \nabla (k \nabla T) + Q, \qquad (1)$$

where ρ — density;

C_p — thermal capacity;

T — initial temperature;

t — heating time;

k — coefficient of thermal conductivity;

Q — power of heat source.

Table 1

Simulation data

Model			Unidirect 2D	Unidirect 3D
Parameter	Symbol	Units		
Geometries				
Length	L	mm	16	16
Width	W	mm	16	16
Height	H	mm	…	2
Height of layer	h	mm	…	0.2
Hole diameter	D	mm	6	6
Physical properties				
Density	p	kg/m^3	1640	
Thermal capacity	C_p	J/(kg·K)	1020	
Thermal conductivity	k_x	W/(m·K)	72 (gray segments) 1.16 (blue segments)	
	k_y	W/(m·K)	1.16 (gray segments) 72 (blue segments)	
	k_z	W/(m·K)	1.16 (gray segments) 1.16 (blue segments)	
Boundary conditions				
Boundary heat source	Q	W/m^2	$1.25 \cdot 10^6$	
Time	t	s	1	
Initial temperature	T_0	K	293.15	
Size of finite elements				
Maximum element size		mm	0.16	0.32
Minimum element size		mm	0.00032	0.0032
Max. element growth rate			1.1	1.3
Curvature factor			0.2	0.2
Resolution of narrow reg.			1	0.7

In a more known form the heat equation has next form [13]:

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + V\frac{\partial T}{\partial z}, \qquad (6)$$

Where T — temperature;

τ — action time of thermal source; temperature conductivity $a = k / \rho C_p$;

x, y, z — coordinates;

V — moving speed of thermal source.

An advantage of the Eq. (1) that the coefficient of thermal conductivity can be set as a function, whereas in the Eq. (2) as a constant only.

In both models, on a ring face of holes acts the heat source power Q during the time t. The initial temperature of the body is equal to room temperature. Accepted assumption: a border between layers present perfect thermal contact; a remaining open surfaces are insulated; thermal conductivity does not change with respect to body temperature. The numerical data is presented in Table 1.

Options of finite elements. By default, COMSOL builds a triangular for two-dimensional mode and a tetrahedral mesh for three-dimensional. The error of calculation is mainly related to the grid size. The grid size can be set through a natural minimum and maximum element size. Element growth rate is responsible for the degree of condensation, it is from one to infinity, that closer to one is more uniform mesh. Mesh curvature factor — the smaller value defines boundaries of the curve accurately, the big value builds broken line in place of the curve. Resolution of narrow region specifies the minimum number of elements at the short border. Selected parameters of grid shown in Table 1. The geometry of a meshing is shown in Fig. 3.

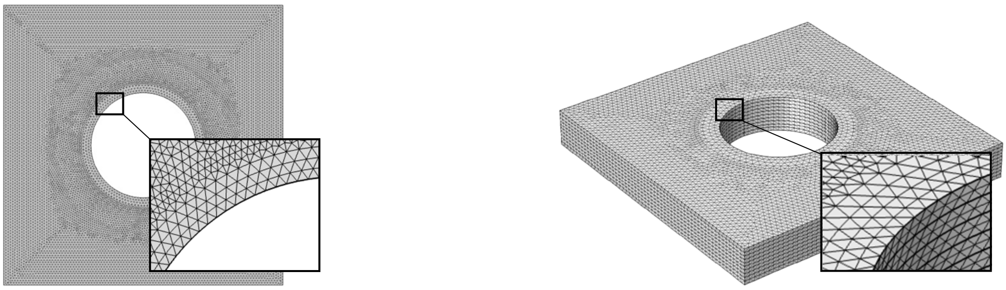
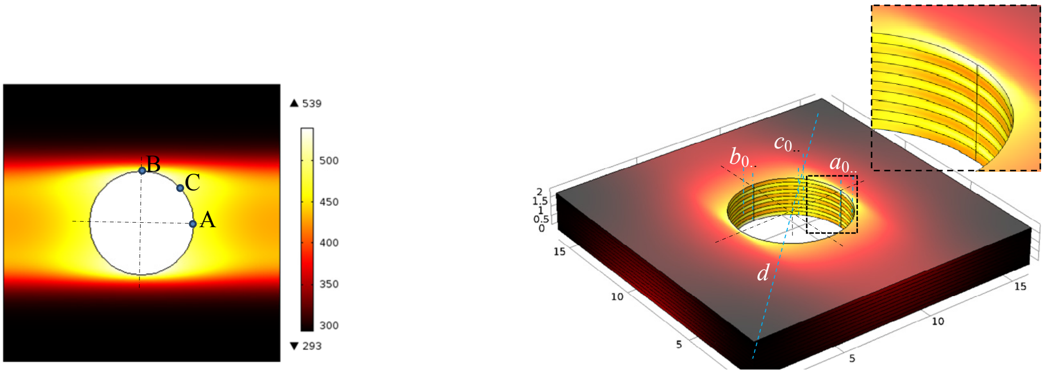

a *b*

Fig. 3. Models mesh: Unidirectional 3d (a); Woven 3d (b)

Result and Discussion. According to the large difference of thermal conductivity k_x and k_y, in the unidirectional 2D model there is a great heat movement in the direction x only, which provides a smooth temperature distribution of the surrounding heating surface (Fig. 4, *a*). Since k_y is very small, the heat can't quickly move deep into the material in the y-axis direction and therefore concentrates on the bounder surface. The temperature in the points A, B, and C reached 474, 544 and 508 K, respectively.



a *b*

Fig. 4. Models mesh: Unidirectional 2D (a); Unidirectional 3D (b)

With the transition to unidirectional spatial model, the maximum temperature dropped to 60 K (Fig. 4, *b*). This is connected with the heat distribution in adjacent layers, more heated areas transfer heat in less heated zones of adjacent layers. This mechanism leads to equalization of temperature in the layers that provides substantially flat annular heat distribution in the plate. The temperature on the hole surface varies depending on the layer and a circle sector. To study a temperature profile on the hole surface and at a distance from the surface, were produced probes of temperature due to lines a_n, b_n, c_n as shown on Fig. 4, *b*. Data of lines location a_n, b_n, c_n indicated in Table 2.

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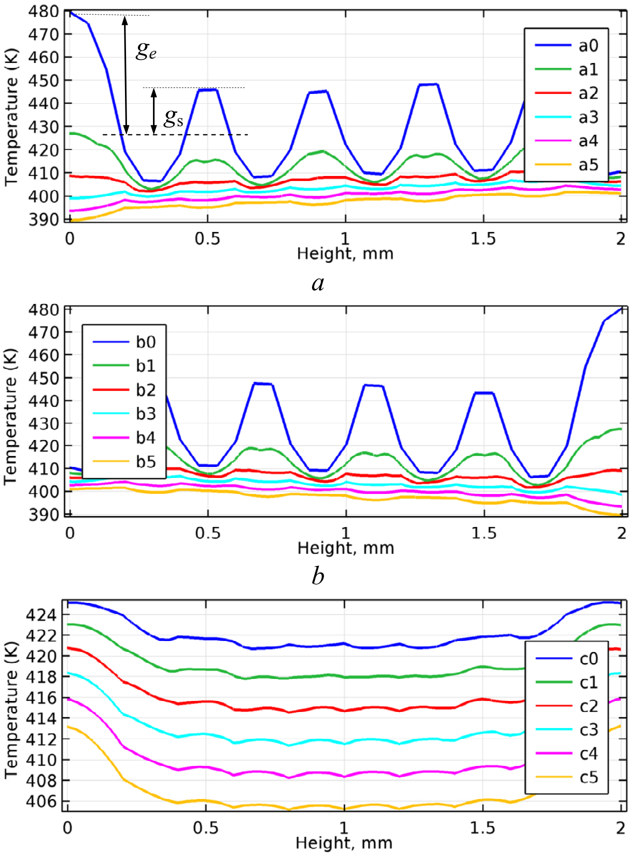
Table 2

Direction	Name of lines					
x	a_0	a_1	a_2	a_3	a_4	a_5
y	b_0	b_1	b_2	b_3	b_4	b_5
xy	c_0	c_1	c_2	c_3	c_4	c_5
	Distances from hole surface, mm					
	0.0	0.1	0.2	0.3	0.4	0.5

Sounding lines a and b indicate temperature gradients at the surface of various layers approximately for 40 K (Fig. 5, a and b). Seclusion from the surface for 0.1 and 0.2 mm, this value decreases to 12 and 5 K, respectively. Deeper, the temperature is same for all layers. A jump in temperature of about 35 K occurs in outermost layers, as heat into neighboring layers is carried out only in one direction of the z-axis. Average level of surface temperature estimated as 421 K, meanwhile temperature there changes for $g_s = 20$ % and $g_e = 46$ % for maximum temperature on the hole edge. Thus, edges of the hole have the highest temperature. This conclusion is in agreement with the experimental data [17], where, during drilling of glass FRP, with increasing cutting speed was seen burning some part of the hole edge (Fig. 6, a) and a destruction of some sections of hole surface (Fig. 6, b). Lines $c_0 ... c_5$ show the temperature gradient of only 5 K, which indicates the uniformity of thermal movement in this hole region. It is should to notice, that the temperature profile at the hole surface and inside of material is not constant and depends on many factors: density of the heat source, heating time, thickness of layers and their thermal properties.



a

b

c

Fig. 5. Temperature of unidirectional 3D model in lines: a_n (a); b_n (b); c_n (c)

a *b*

Fig. 6. Thermal degradation of hole edge (a) and hole surface (b) during drilling GFRP [17]

Isothermal analysis in Fig. 7 indicates that the temperature distributes from holes surface by substantially correct rings. Since the lower layer is a good heat conductor in the horizontal direction (x-axis), and the upper layer in vertical (y-axis), it creates some asymmetry of isothermal picture. This asymmetry will decrease with plate thickness increasing. However, analysis shows that the thermal field in the plate with unidirectional layers must be considered comprehensively in view of high heat immigration there.

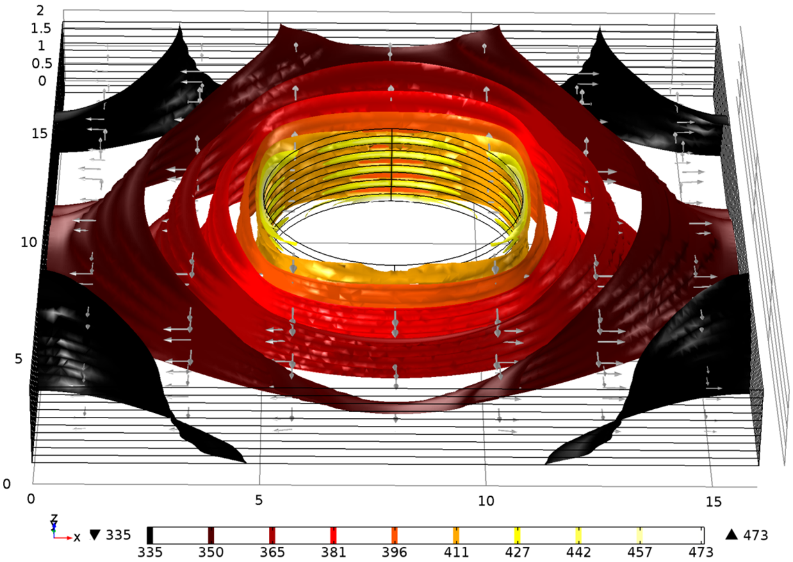


Fig. 7. Isothermal contours unidirectional 3d model

It was adopted an attempt to replace the described model to an isotropic structure. The isotropic model would be much more convenient for the further modeling of thermal processes in parts of complex shape, as the process of its construction and the conversion takes much less time. Geometry, finite element mesh, initial and boundary conditions of the isotropic model is fully comply with the previous model, except that there are no layers and the thermal conductivity is same for all directions. By method of selection, was set a coefficient of thermal conductivity, which provides comparable maximum temperature and the nature of its decreasing in the diagonal direction (Fig. 4, line *d*), with respect to different time points (Fig. 8). For these conditions the thermal conductivity is 34 W/(m·K). This value is much greater than the thermal conductivity of the polymer matrix, however it is supported by some theoretical search of the thermal conductivity of materials [12]. Comparison of the results shows a high correlation between two models of $R^2 = 0.9347$. Nevertheless, this correlation is valid only for the temperature in the line d, isotropic model does not account a temperature on the edges and a stepped temperature profile on the hole surface, which in this model varies for 46 and 20 % of a surface temperature in isotropic model (421 K). Also, found coefficient is valid only for the geometry, thermal properties and boundary conditions adopted in this simulation.

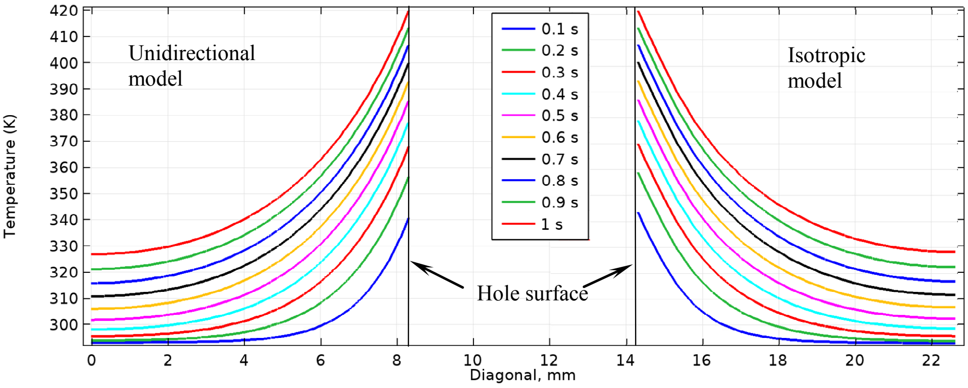


Fig. 8. Temperature during diagonal line in unidirectional and isotropic 3D models according to heating time

Conclusions. Numerical modeling of heat distribution in the unidirectional fibrous materials allowed to establish the fact of a heat integration between layers with different fiber orientation. Hole edges is heating faster, it conducts to their degradation primarily and after a remaining region. The hole surface has a different temperature, however, the difference almost disappears at a distance of 0.3 mm from the surface. Based on the isothermal analysis was concluded that the layered structure with anisotropic properties while drilling takes heat by circular isotherms, like isotropic body. To simplify the modeling of thermal processes in fibrous composites, the internal structure of details can be transformed to homogeneous. The disadvantage of this simplification is the temperature gradient on the heating surface and edges of the hole.

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