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MATHEMATICAL MODEL OF HEAT EXCHANGE PROCESSES IN HONEYCOMB PANELS WITH HEAT PIPES

This article presents the analysis results of heat exchange processes in the honeycomb panel and depicts the results of temperature modelling modes for intensive heat loading modes.

Keywords: Honeycomb panel, heat exchange, mathematical modeling.

Nowadays honeycomb panels (HP) are widely used in the design of spacecrafts. Honeycomb panels are characterized by high mechanical durability and very small density. They are used as spacecraft construction units. Electronics packages, assemblies, and heat pipes are placed on them. Normal functioning of electronics requires a special temperature mode corresponding to the external environment. The small density volume of the honeycomb panel construction leads to low heat-transmitting properties of the panel. As a result it's difficult to organize an effective heat rejection from electronics and to secure optimal thermal modes for them. The heterogeneous structure of a honeycomb panel makes the process of computations of the heat exchange and analysis of heat modes of electronics complicated.

Different mathematical models are used for computing spacecraft temperature conditions. One of the most widespread approaches for spacecraft heat exchange process description is the use of heat-balance equations. Unsteady heat mathematical models for this approach had been considered in [1]. Research [2] contains a description of a mathematical model for thermal conditions of devices located on a honeycomb panel. This paper presents a mathematical model of the heat exchange in the honeycomb panel with heat pipes. The model is based on the numerical solution of unsteady heat conduction equations using a finite-difference space splitting scheme. The high efficiency of the methods permits to increase the level of detailing during temperature fields computations. The model is intended for computations of unsteady heat modes of electronics, optimization of the composition, and properties of the honeycomb panel, and also for the optimization of the quantity and arrangement of the heat pipes on the honeycomb panel.

Heat exchange process analysis. A honeycomb panel is a plain panel which consists of two parallels plates (hems *1* and *2*). The space between the plates is filled by honeycombs *3* made of metallic foil (honeycomb-filling) (fig. 1). Honeycombs have low heat-exchange abilities because of small density volume and therefore, heat pipes are used to improve the heat transfer. The highly effective heat-exchange in the heat pipes is reached due to circulation and phase changes of the coolant in the internal duct *4*. Heat pipes are located internally in honeycomb. They are fixed to the hem using landing ground *5*. Heat exchange in the honeycomb is significantly different from the heat transfer in a solid metal panel. First of all, the heat exchange in honeycombs is three-dimensional and anisotropic due to the presence of honeycomb-filling and heat pipes. Secondly, heat transfer in the honeycomb can be performed both by thermal conductivity and radiation.

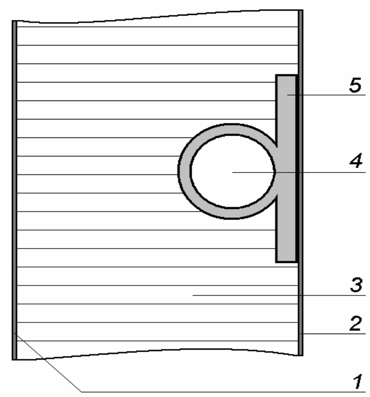

Fig. 1. Fragment of a honeycomb panel with a heat pipe

To determine the process features, let us consider the importance of heat exchange in the volume of a honeycomb. Typically, the density of a honeycomb-filling is approximately 100 times less than the density of material from which the filling is made. Therefore, effective value of heat conduction coefficient λ^* in the transverse location ("hem *1*–hem *2*") is only 0.01 of the heat conduction coefficient value of solid material. If the value of thermal flux is 400 Wt/m^2 and the honeycomb-filling thickness is d = 0,03 m, then the value of the temperature drop is $\Delta T = qd / \lambda^* \approx$ 8K. The density of radiant flux between hem *1* and hem *2* can be estimated using the following formula: $q_R = \varepsilon\sigma_{SB}(T_1^4 - T_2^4)$; where σ_{SB} is the Stefan-Boltzmann constant. Assuming that ε = 0,2, T_1 = 308 K, and T_2 = 300 K, we get $q_R \approx 1$ Wt/m^2. This value is a negligible quantity in comparison with the value of the heat flux which is transferred by the thermal conductivity.

The insignificant hem thickness and the low density of honeycomb-filling leads to low honeycomb-filling thermal conductivity in longitudinal directions. At the same time the effective heat conduction coefficient of honeycomb-filling is 5–10 times less than the one on the hems. Thus, one may neglect heat transfer in longitudinal direction for approximate computations. In more exact computations it should be considered as an addition to the heat conductivity of the hems. In general, the addition to the head conduction coefficient depends on direction of the honeycomb-filling's anisotropy. The size of honeycomb has an order of several millimeters, so in the model it is a continuum, which has thermal resistance dependant on honeycomb's parameters.

The estimations witness that heat transfer in the longitudinal direction in honeycombs is carried out mainly on the hems due to the thermal conductivity. The heat transfer in crosswise direction between hems is achieved by thermal conductivity of honeycomb-filling's material. In the presented computational model, the honeycomb panel is considered as two plain solid planes. These planes exchange thermal energy between each other through thermal resistivity of the honeycomb-filling. Radiation is taken into account on the external plane of the honeycomb in the process of heat exchange with the environment.

Mathematical problem definition and computational algorithm. In order to examine the temperature mode of a honeycomb panel, a mathematical model represents a system of two two-dimensional unsteady equations with variable coefficients, which give heat conduction in both hems:

$$c_m(x,y)\frac{\partial T_i}{\partial t}=\frac{\partial}{\partial x}\left[\lambda(x,y)\frac{\partial T_i}{\partial x}\right]+ +\frac{\partial}{\partial y}\left[\lambda(x,y)\frac{\partial T_i}{\partial y}\right]+q_v(x,y,t)-\alpha_v(x,y,t)T_i, \quad (1)$$

where c_m is the material specific volume heat, T_i is the temperature, i = 1, 2 is the index corresponded to the number of the hem, λ is the heat conduction coefficient, t is time, x, y are space coordinates, q_v is the volume power of heat sources and sinks, α_v is coefficient of heat exchange with environment.

Equations (1) are completed by boundary conditions:

$$\left[\lambda\frac{\partial T}{\partial l}+\alpha T\right]_{l=0,L}=q\big|_{l=0,L},$$

where $l = x, y$, and entry conditions:

$$T\big|_{t=0}=T_0(x,y).$$

The value of the heat flux, which proceeded from one hem to another one, is defined as:

$$q(x,y)=\frac{T_1(x,y)-T_2(x,y)}{R}, \quad (2)$$

where T_1 and T_2 are temperatures of hems *1* and *2*, R is the specific thermal resistance of the honeycomb-filling. Equation (2) describes the heat exchange between hems; this has been taken in account in equation (1) with the help of last two members. For example, in order to compute the temperature field of the first hem, the first member is computed as $q_v(x,y)=T_2(x,y)/Rd_1$, the second member as $\alpha_v(x,y)=1/Rd_1$, where d_1 is the thickness of the first hem. Similar expressions are used for the second hem. This algorithm of heat exchange computations between honeycomb panel hems provides stability of the whole computational algorithm. Moreover, thermal flux from electronics, external thermal fluxes and radiation from hems' surfaces is also included in q_v.

The mathematical model takes into account the heat pipes on the hems of honeycomb as zones with high unilateral thermal conductivity and its value of heat conduction coefficient is set for the axial direction, which is selected to be equivalent to the heat transport ability of the heat pipe. The thermal conductivity of the heat pipes' landing ground is also taken into account because it can significantly influence the heat transfer in a crosswise direction.

One of the main criteria when selecting a computational method to solve the problem is the efficiency and stability of the algorithm. Moreover, the nature of the task requires an algorithm which allows using one directional component of heat conduction coefficients λ_x and λ_y which are different because of the heat pipes presence. The algorithm of summary approximation [3] suits these requirements using task spatial coordinates splitting. A two-dimensional unsteady problem is solved in two steps at each time step. At every step a local one-dimensional problem is solved with the help of the implicit difference scheme.

A grid function $T^j_{n,m}$ and intermediate function $U^j_{n,m}$ are introduced. They correspond to the values of the temperature in the nodes of the computational coordinate grid:

$$x_n=(n-1)h_x,\ y_m=(m-1)h_y,\ t_j=(j-1)\tau.$$

At the first step, a local one-dimensional problem is solved. It takes into account only the λ_x component of the heat conduction coefficient. The problem is solved for each y_m in the direction x. In result, all values of the intermediate function $U^j_{n,m}$ are determined.

For n = 1:

$$U^j_{2,m}-\left(1+\frac{\alpha_{0,x}h_x}{\lambda_{3/2,m}}+\frac{(c_v\rho)_{1,m}h_x^2}{2\lambda_{3/2,m}\tau}+\frac{\alpha_{V1,m}h_x^2}{4\lambda_{3/2,m}}\right)U^j_{1,m}+\frac{q_{0,x}h_x}{\lambda_{3/2,m}}+ +\frac{h_x^2}{2\lambda_{3/2,m}}\left(\frac{q_{V1,m}}{2}+\frac{(c_v\rho)_{1,m}}{\tau}T^{j-1}_{1,m}\right)=0, \quad (3)$$

For n = 2, ..., N–1:

$$U^j_{n+1,m}-\left(1+\frac{\lambda_{n-1/2,m}}{\lambda_{n+1/2,m}}+\frac{(c_v\rho)_{n,m}h_x^2}{\lambda_{n+1/2,m}\tau}+\frac{\alpha_{Vn,m}h_x^2}{2\lambda_{n+1/2,m}}\right)U^j_{n,m}+ +\frac{\lambda_{n-1/2,m}}{\lambda_{n+1/2,m}}U^j_{n-1,m}+\frac{h_x^2}{\lambda_{n+1/2,m}}\left(\frac{q_{Vn,m}}{2}+\frac{(c_v\rho)_{n,m}}{\tau}T^{j-1}_{n,m}\right)=0. \quad (4)$$

For $n = N$:

$$-\left(1+\frac{\alpha_{0,x}h_x}{\lambda_{N-1/2,m}}+\frac{(c_v\rho)_{N,m}h_x^2}{2\lambda_{N-1/2,m}\tau}+\frac{\alpha_{VN,m}h_x^2}{4\lambda_{N-1/2,m}}\right)U^j_{N,m}+U^j_{N-1,m}+ +\frac{q_{L,x}h_x}{\lambda_{N-1/2,m}}+\frac{h_x^2}{2\lambda_{N-1/2,m}}\left(\frac{q_{VN,m}}{2}+\frac{(c_v\rho)_{N,m}}{\tau}T^{j-1}_{N,m}\right)=0. \quad (5)$$

At the second step a similar local one-dimensional problem, which takes into account only the λ_y component of heat conduction coefficient, is solved. The problem is to solve x_n in each the direction of y. In result, all values of the grid function $T_{n,m}^{j+1}$ on the next time step are determined.

Algebraic equations (3)–(5) are solved by a sweep method. Entry parameters of the program include: the geometrical characteristics of honeycomb panel, materials, their thermo physical properties, and electronic heat generation parameters.

Results of computations. The choice of differential steps sizes is very important in the computations. In order to obtain adequate computational results without significant smoothing of the temperature gradients, the step size shouldn't exceed the typical scale of temperature fields' heterogeneousness. In the present task, the typical scale is defined by heat pipes. So, the lateral dimension of the heat pipes, which is approximately equal to 10 mm, defines the value of the differential spatial steps as $h_x = h_y = 10$ mm.

First, specificities of the heat exchange in a honeycomb panel had been examined on the model task in which the honeycomb panel had the following parameters: lateral dimensions of the honeycomb panel were 600 × 300 mm^2, hem thickness was 0.4 mm, the distance between hems was 30 mm, specific heat resistance of the honeycomb-filling was R = 10 m/Wt. The external hem of the honeycomb panel was a radiant surface. This surface emits a heat flux which corresponds to the radiation of outer space with emissivity equal to $\varepsilon = 0.7$. There is a heat-generating device on the left half of the internal hem. Its slot sizes are 300 × 300 mm^2. The power of the device is 50 Wt. It's assumed that the heat flux from the device is spread uniformly in the area of the slot. In order to improve the heat transfer, two heat pipes had been installed on the honeycomb panel.

The duration of the modeling process had been selected in such a way that the process had time to achieve a steady-state regime. The computation results are presented in fig. 2 and 3. The temperature fields for the internal and external honeycomb panel hems are marked by isolines and gradations of a gray color. The temperature interval between the isolines is 1 ^{o}C. As shown in fig. 2, the heterogeneity of temperature distribution in the internal hem is high. Maximal temperature drop in the hem is about 26 ^{o}C. This is due to low heat-exchange abilities of the hem in the normal direction of the heat pipes. The temperature range in the external honeycomb panel hem is more even (fig. 3). Its maximal temperature drop is approximately equal to 20 ^{o}C.

Significant heterogeneities in temperature distributions make it almost impossible to ensure reliable control of optimal electronic mode temperature. In order to make the temperature range more even, special heat stabilized plates are placed on the honeycomb panel hem. The plates are made from a metal with a high heat conductivity coefficient. Temperature drop is decreased proportionally to the plate thickness. For example, using aluminum plates with a thickness of 6 mm, leads to a decrease in temperature drop to 2 ^{o}C.

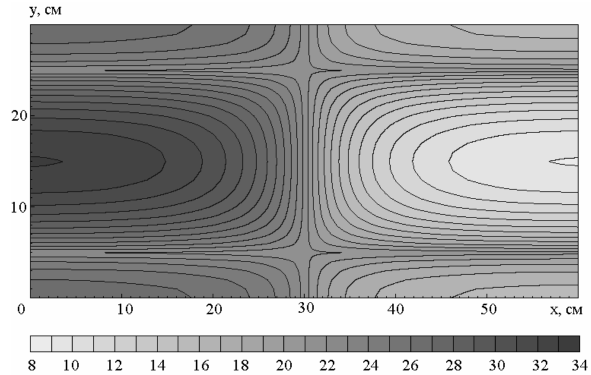

Fig. 2. Temperature field of a honeycomb panel internal surface

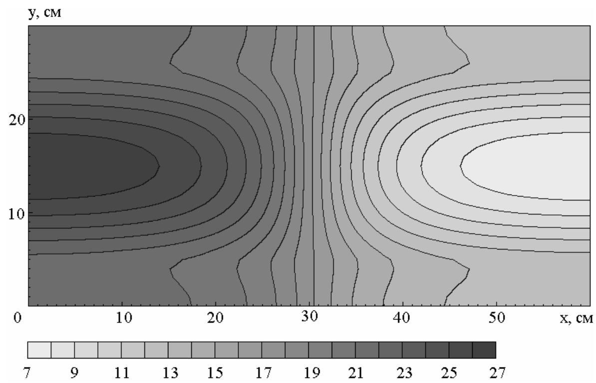

Fig. 3. Temperature field of a honeycomb panel external surface

The increase of the plates' thickness leads to a significant increase of the whole construction's weight. In the future, it seems reasonable to use hyper heat-conducting materials for increasing heat-transmitting capabilities, instead of heat stabilized plates. The results of the computations show, that hyper heat-conducting plates with a thickness of 2 mm and λ_{ef} = 5 000 Wt/(m×K) provide almost homogeneous temperature ranges in the internal hem, with temperature drops of less than 0,5 ^{o}C, because the high heat-transmitting ability of hyper heat-conducting plate effectively levels the influence of heat from devices and external heat fluxes on radiating surfaces.

Real honeycomb panel constructions can contain a sufficiently larger number of heat-generating devices and heat pipes. An example of the computations is presented on the fig. 4; in it the distribution of temperature on the internal hem of honeycomb panel is presented. The boundaries of device slots are outlined in a white color. Given temperature ranges with heterogeneous "spotty" structure is a result of joint action of different mechanisms: the device's heat generation, heat transfer in the hems, and heat pipes, heat-exchange between the hems and radiation from the external hem. In our opinion, the applied mathematical models are the most actual for the computation of the modes in the complex design of honeycomb panels, because these computational experiments permit to obtain the most detailed information about thermal mode results in various external conditions.

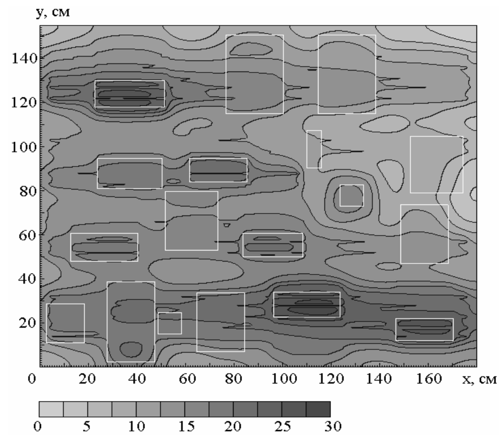

Fig. 4. Temperature field of a thermal-loaded honeycomb panel internal surface

It should be noticed that computational experiments for honeycomb panels with complex construction require a significant volume of different input information like thermophysical characteristics and geometric parameters of the constructions (sizes, coordinates of the device slots), mass, etc. The collection of such information requires much time. The time consumption increases significantly if it's necessary to make a number of computational experiments for different honeycomb panel constructions in order to find the optimal temperature mode. To decrease the consumption it's reasonable to automatize the process of input information gathering. The information should be read from the CAD-system database. To realize this approach, we are currently developing a software complex for the computation of honeycomb panel thermal modes on the base of the presented mathematical model. This complex is integrated with a CAD-system. It will allow significant simplifying of the input procedure, output, edition, and visualization of the input and calculated data.

The developed computational model allows the conducting of computations for honeycomb panel hems' temperature fields, considering the detailed information on the honeycomb panel design, heat generation of electronics, and external thermal conditions. In order to find the optimal thermal modes for electronics, it's possible to use this model to optimize the honeycomb panel's construction, and to select the most appropriate arrangements of the devices and heat pipes in the panel's hems.

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TESTING THE ALGORYTHM OF THE "CATERPILLAR"-SSA METHOD FOR TIME SERIES RECOVERY

The basic algorithm of the "Caterpillar"-SSA method is considered and tested.

Keywords: trend allocation, periodicals finding, silencing, decomposition of time series into components.

One of the significant problems in the analysis of time series is the separation of trend and periodicals presses from the noise. This research is about a robust method of time series analysis: "Caterpillar"-SSA, which is currently being developed.

Let's investigate the functioning of this algorithm and state, in what its specificity is exactly. The variant of the algorithm described below doesn't essentially differ from the basic one [1], it has only been simplified without any changes in result.

We consider the given time series F:

$$f_0, f_1, \ldots, f_{N-1}, \qquad (1)$$

where N is its length. Further we assume that F is a nonzero series.

The algorithm consists of four consistent steps: investment, singular decomposition, grouping, and diagonal averaging.

The investment procedure converts the time series F into a sequence of multidimensional vectors called the trajectory matrix.