MODELING OF HEAT TRANSFER WITHIN THE WET DIVING SUIT

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Abstract
The wet diving suit consists of two layers: the external neoprene layer with air bubbles and the internal textile clothing to improve the insulation. Both layers are connected like the composite because the friction coefficient is very high. The body temperature should be constant and monitored because the change is the sign of hypothermia. The design variables are the geometric coordinates of the layers. The heat transfer in the normal conditions is the steady problem described by the state equation, the boundary and the initial conditions. The internal textile layer contains the textronic systems to transfer the selected medical parameters. Some problems can be solved directly by the integration of the state equation with respect to the boundary conditions. The more difficult solutions are obtained by means of the processing program and visualized by any graphical modulus.
Key words: composite, heat transfer, modeling

1. Problem definition

The protection against the heat loss and consequently the hypothermia of the diver is the diving suit. The most popular and the cheapest one is the wet diving suit which consist of two layers: the external neoprene layer with air bubbles as the additional insulation and the internal textile clothing to improve the heat insulation of the body. Both layers are connected similarly as the composite because the friction coefficient between the neoprene and the internal textile clothing is very high. There is additionally the thin water layer between the body and the textile clothing of the prescribed temperature secured by the body, because there is the so-called wet diving suit. The temperature should be constant during the work and permanently monitored because its change can be the sign of hypothermia. The design variables are the geometric coordinates of the points describing the shape of the layers. The heat transfer is also the steady problem described by the state equation and the set of boundary conditions. The textile layer contains the textronic systems to transfer the selected medical parameters and protect the user against hypothermia. The most simple problems can be solved directly by means of the integration of the state equation with respect to boundary conditions. The more complicated solutions can be obtained by means of the processing programs and visualized by the special modulus, cf. for example program ADINA.

2. Physical model

The wet diving suit consist of two layers. Both materials have the different structures. The external layer is the neoprene foam which is the effect of: (i) the chemical reaction with the special substance during the hardening process; (ii) the nitrogen injected inwards the foam. The internal textile clothing has the typical compact, inhomogeneous structure which can be for example the nylon fabrics or the synthetic fur fabrics. Textile structure consist of the textile elements as well as the water within the free spaces between yarns. Thus, we have to homogenize the wet suit to create the physical model. The homogeneous structure has the same conditions of the heat transfer within the whole domain.

Golański, Terada and Kikuchi [1] introduced the classic *rule of mixture* to determine the substitute heat transfer coefficient in the form

$$\lambda_z = \lambda_{mat}\, \xi_{mat} + \lambda_{wyp}\, \xi_{wyp}\,; \quad \xi_{mat} = \frac{V_{mat}}{V_{mat} + V_{wyp}}\,; \xi_{wyp} = \frac{V_{wyp}}{V_{mat} + V_{wyp}}, \qquad (1)$$

where ξ_{mat} and ξ_{wyp} are the coefficients for the textile material of the volume V_{mat} and the free spaces of the volume V_{wyp}. The second *Turner's model* is developed by the hydrostatic analogy of the substitute coefficient equal to

$$\lambda_z = \frac{\lambda_{mat}\,\xi_{mat}\,K_{mat} + \lambda_{wyp}\,\xi_{wyp}\,K_{wyp}}{\xi_{mat}\,K_{mat} + \xi_{wyp}\,K_{wyp}}. \qquad (2)$$

where K_{mat} is the volumetric strain modulus of the textile material, K_{wyp} is the volumetric strain modulus of the filling.

The neoprene layer can be homogenized by means of the special developed methods. Liang and Qu [2] have determined the substitute coefficient of the material subjected to the different temperatures on the parallel external surfaces. The introduced model includes the radiation of the free spaces filled with gas or liquid, located symmetrically and repeteable within the material. Authors have discussed two shape of the spaces, the cylinder (2D problem) and the sphere (3D problem). The substitute heat transfer coefficient has the form

$$\begin{aligned}\lambda_z = \frac{1}{A} - \frac{1}{3A^2CD^2(T_b - T_a)}\ln\frac{T_b + D}{T_b + D} + \frac{1}{6A^2CD^2(T_b - T_a)}\ln\frac{T_b^2 - DT_b + D^2}{T_a^2 - DT_a + D^2}\\ - \frac{1}{\sqrt{3}A^2CD^2(T_b - T_a)}\left(\operatorname{arctg}\frac{2T_b - D}{\sqrt{3}D} - \operatorname{arctg}\frac{2T_a - D}{\sqrt{3}D}\right)\end{aligned} \qquad (3)$$

where A, B, C, D are the constants given by Liang and Qu [2]. The problem of calculations time come from the scale. The macro scale implicate the 3D problem whereas the micro scale can be treated as the 2D problem. Let us next for simplicity assume that the suit is subjected to the laminar flow which secure the other mechanism of the heat transfer as the turbulent one.

3. Mathematical model

The state variable is the temperature T. The heat energy is described within each layer by the heat transfer equation which is the second-order correlation with respect to the state variable and the first-order with respect to time. The problem has the form described in general by Korycki [3] but can be simplified because the typical diving suit does not contain the heat sources. The transient heat transfer problem has the form

$$\begin{cases}\operatorname{div}\mathbf{q}^{(i)} = c^{(i)}\dfrac{\partial T^{(i)}}{\partial t} \\ \mathbf{q}^{(i)} = \mathbf{A}^{(i)}\cdot\nabla T^{(i)} + \mathbf{q}^{*(i)}\end{cases} \quad \text{within } \Omega;$$

$$\begin{aligned}&T^{(i)}(\mathbf{x},t) = T^{0(i)}(\mathbf{x},t) \;\; \mathbf{x}\in\Gamma_T; \;\; q_n^{(i)}(\mathbf{x},t) = 0 \;\; \mathbf{x}\in\Gamma_q;\\ &q_{nc}^{(i)}(\mathbf{x},t) = h[T(\mathbf{x},t) - T_\infty(\mathbf{x},t)] \;\; \mathbf{x}\in\Gamma_C; \;\; q_n^{(i)}(\mathbf{x},t) = q_n^{(i+1)}(\mathbf{x},t) \;\; \mathbf{x}\in\Gamma_N;\\ &q_n^r(\mathbf{x},t) = \sigma T(\mathbf{x},t)^4 \;\; \mathbf{x}\in\Gamma_d; \quad T^{(i)}(\mathbf{x},0) = T_0^{(i)} \;\; \mathbf{x}\in(\Omega\cup\Gamma); \quad i = 1,2.\end{aligned} \qquad (4)$$

where $\mathbf{q}$ is the heat flux density; $\mathbf{q}^*$ is the initial heat flux density, $\mathbf{A}$ is the matrix of heat conduction coefficients within material, c is the heat capacity, T is the temperature, ∇ is gradient operator, t is the real time, T^0 is the prescribed value of temperature, h denotes the surface film conductance, T_∞ is the temperature of the surroundings water, σ is the Stefan-Boltzmann constant. The problem is accompanied by the set of boundary and initial conditions. The structure contacts the skin, the boundary is also the portion Γ_T and subjected to the first-kind condition. The optimal microclimate is secured by the prescribed temperature

T^0 of the water between the skin and the diving suit. The heat is transported unidirectional from the skin to the surrounding. The heat flux density on the side surfaces Γ_q can be consequently neglected q_n=0 and the structure is subjected to the second-kind condition. The external boundary portion Γ_C is subjected to the third kind boundary condition, i.e. the convectional heat flux. The fourth-kind boundary conditions are defined for the common surfaces of internal boundary, i.e. between the neoprene layer and the internal clothing. The heat flux density normal to this boundary portion has the same value. The heat can be radiated from the external boundary portion Γ_d for the immovable water layers, which surround the diving suit. Some questions concerning the radiation are discussed for example by Bialecki [4]. Li [5] discussed the parameters describing the combined conduction and radiation. The initial condition describes the temperature distribution within the structure.
The problem can be considerably simplified for the steady heat transfer, i.e. for the constant value of state variable T in time. The time derivative of the temperature with respect to time is negligible and the problem has the form

$$\begin{cases} \mathrm{div}\mathbf{q}^{(i)} = 0 \\ \mathbf{q}^{(i)} = \mathbf{A}^{(i)} \cdot \nabla T^{(i)} + \mathbf{q}^{*(i)} \end{cases} \quad \text{within } \Omega;$$

$$T^{(i)}(\mathbf{x}) = T^{0(i)}(\mathbf{x}) \;\; \mathbf{x} \in \Gamma_T; \;\; q_n^{(i)}(\mathbf{x}) = 0 \;\; \mathbf{x} \in \Gamma_q; \;\; q_n^{(i)}(\mathbf{x}) = q_n^{(i+1)}(\mathbf{x}) \;\; \mathbf{x} \in \Gamma_N; \tag{5}$$

$$q_n^r(\mathbf{x}) = \sigma\, T(\mathbf{x})^4 \;\; \mathbf{x} \in \Gamma_d; \;\; q_{nc}^{(i)}(\mathbf{x}) = h[T(\mathbf{x}) - T_\infty(\mathbf{x})] \;\; \mathbf{x} \in \Gamma_C; \;\; i = 1,2.$$

4. Solutions of heat transfer problems

The steady heat transfer problem can be solved in the micro scale by means of the analytical methods. Let us introduce the same thickness of the composite layers. The problem can be consequently defined as the 1D. Let us for simplicity assume the negligible vector of the initial heat flux density $\boldsymbol{q}_{nw}^{*}=0$. The textile composite is made of two layers.

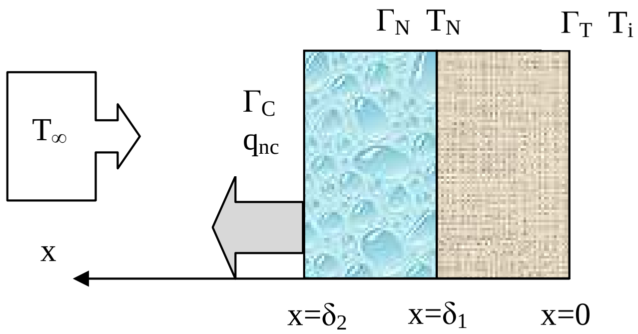

Figure 1. Boundary conditions of diving wet suit, example 1

Boundary conditions can be formulated by means of the physical analysis of the problem, cf. Fig.1. The internal surface contacts the thin layer of the water between the body and the composite. The layer has the prescribed temperature T_i and this portion Γ_T is subjected to the first-kind condition. The boundary between the neoprene layer and the additional clothing is subjected to the same heat flux density and the temperature on this part Γ_N is equal to T_N as the consequence of the existing heat flux. There is also the fourth-kind condition. The external boundary Γ_C is subjected to the third-kind condition and the convectional heat flux is determined. The correlations (5) can be reformulated for the i-th layer to the following

$$\frac{d^2T^{(i)}}{dx^2} = 0.$$

$$T^{(i)}(x) = T^{0(i)}(x) \quad x \in \Gamma_T; \quad q_n^{(i)}(x) = 0 \quad x \in \Gamma_q; \quad q_n^{(i)}(x) = q_n^{(i+1)}(x) \quad x \in \Gamma_N;$$
$$q_{nc}^{(i)}(x) = h[T(x) - T_\infty(x)] \quad x \in \Gamma_C; \quad i = 1,2. \tag{6}$$

The solution of temperature can be obtained by the integration with respect to *x* as follows

$$T^{(i)}(x)_{,xx}=0 \ ; \ T^{(i)}(x)_{,x}=C_1^{(i)} \ ; \ T^{(i)}(x)=C_1^{(i)}x+C_2^{(i)} \ ; \tag{7}$$

The integration constants are determined by means of the physical analysis of the problem as well as the boundary conditions. Introducing the first layer of the thickness δ_1 and the temperatures T_i and T_N; we determine the temperature distribution according the correlation

$$T^{(1)}\Big|_{x=0} = T_i; \quad T^{(1)}\Big|_{x=\delta_1} = T_N; \ \Rightarrow \ T^{(1)} = \frac{T_N - T_1}{\delta_1}x + T_1. \tag{8}$$

The second layer is subjected to the mixed boundary conditions, i.e. the first- and the third-kind conditions. It follows immediately that the temperature is the following function

$$T^{(2)}\Big|_{x=\delta_1} = T_N; \quad q_n\Big|_{x=\delta_2} = \lambda \frac{dT}{dx}\Big|_{x=\delta_2} = h\left(T\big|_{x=\delta_2} - T_\infty\right)$$
$$\Rightarrow \ T^{(2)} = h\frac{T - T_\infty}{\mathbf{A}}(x - \delta_1) + T_N. \tag{9}$$

We see at once that both functions of state variables are linear with respect to coordinate x.
The more complicated structures should be solved approximately, by means of the different numerical methods. Let us define the steady problem by the state equations and the boundary conditions in the form of Eqs.(5). The structure and the boundary conditions are additionally defined in Fig.2.

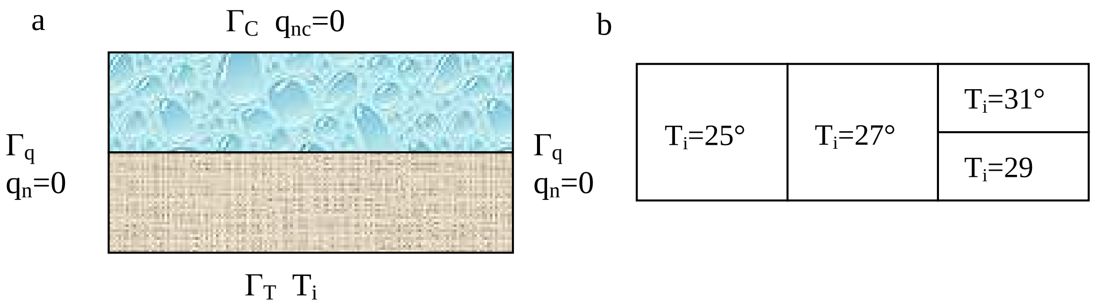

Figure 2. Structure and boundary conditions of diving wet suit, example 2

The structure is the typical one. The surface contacting the thin layer near the skin is subjected to the first-kind boundary condition, cf. Fig.2a. The temperature is determined for the different sub-surfaces, cf. Fig.2b, and changes from T_i=25°C to T_i=31°C. Thus, the temperature distribution is non-symmetric and there is in fact the 3D problem. The side surfaces are characterized by the second-kind boundary conditions and the heat flux density is negligible. The part contacting the water is subjected to the laminar flow and the heat transfer mechanism is the heat convection. The environment temperature is assumed equal to 0°C. The radiation is assumed as insignificant for the water environment. Thus, we introduce in fact the mixed boundary conditions.

Let us next assume that the fabrics of the internal clothing has the isotropic thermal properties and can be characterized by the heat conduction coefficient equal to $\mathbf{A}^{(1)} = 0{,}030\ \mathrm{W/(mK)}$ and the volumetric heat capacity of dry fibers $c^{(1)}=1610\cdot10^3 \mathrm{J/(m^3K)}$. The external neoprene layer is defined by the heat conduction coefficient $\mathbf{A}^{(2)} = 0{,}050\ \mathrm{W/(mK)}$ and the volumetric heat capacity of the material $c^{(2)}=2500\cdot10^3 \mathrm{J/(m^3K)}$. Both layers are homogenized by means of the classic *rule of mixture* method. The solution strategy is shown in Fig.3. The applied finite element net is shown in Fig.4 in two different axonometric views.

Problem definition

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Physical model

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Mathematical model

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Introduction of (i) procedure solution of differential equation
(ii) boundary conditions

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Analysis stage: Finite Element Method
4-nodal, 3D elements

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Visualization of results = maps of temperature distribution.

Figure 3. Solution strategy of heat transport problem

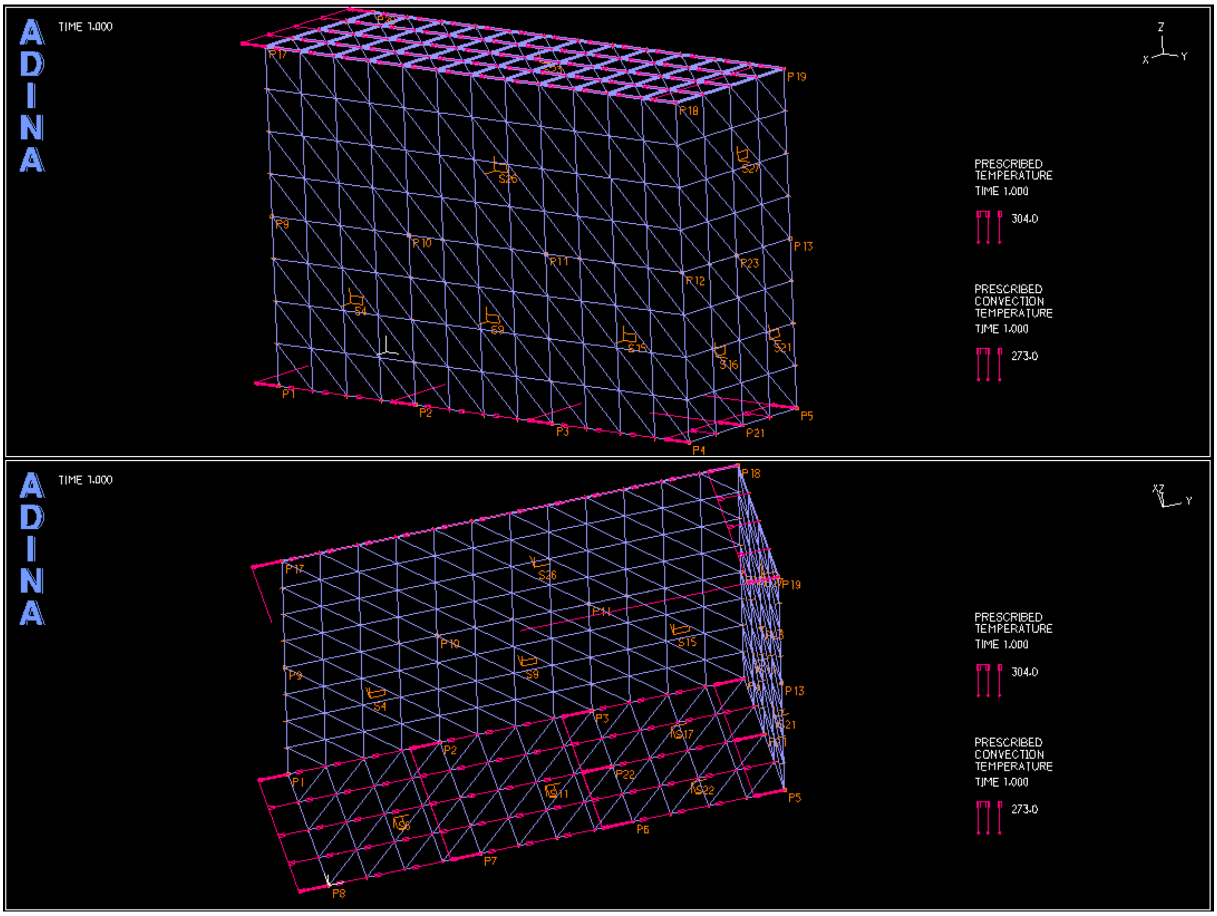

Figure 4. Space net of finite elements, example 2

The obtained temperature is visualized by means of the ADINA program which has the graphic modulus. The temperature distribution is shown in Fig.5. We have applied the space net because the problem is 3D (the different temperatures on the lower surface contacting the skin) as well as the program does not contain the linear model of the heat convection. We introduce also the upper surface subjected to this phenomenon.

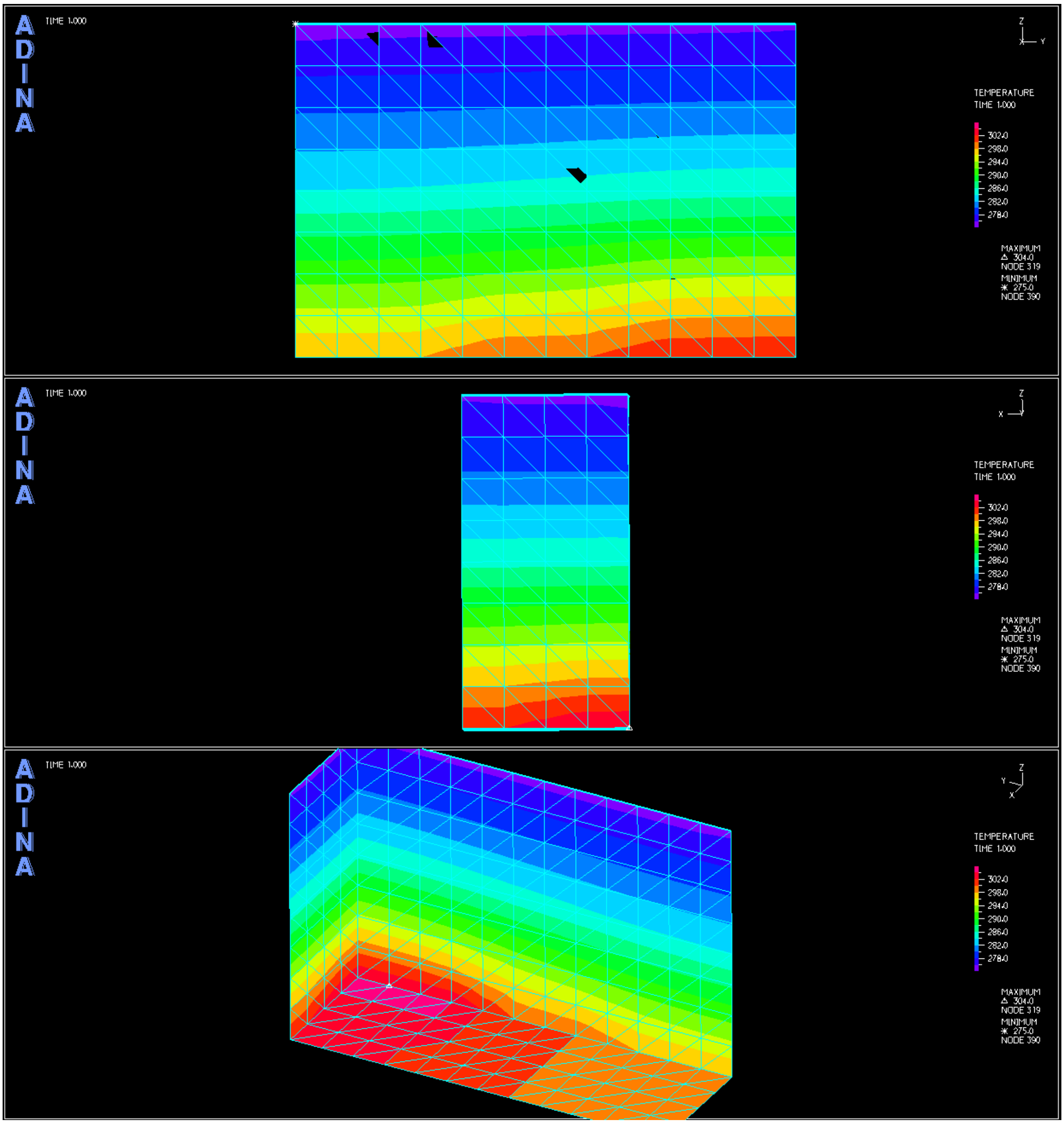

Figure 5. Distribution of temperature, example 2

The obtained distribution has the irregularities caused by the different values of temperature within the elements of the lower surface. Thus, the obtained distribution is disturbed within the textile layer but the irregularities are relatively small. Practically speaking, the external neoprene layer has the sandwich distribution of temperature.

The next example has the same boundary conditions but we introduce additionally the radiation on the external surface of the diving wet suit. The heat radiation to the environment

exists for the specific conditions, i.e. for the stationary, immovable water layers surrounding the diving suit. We have introduced the standard description of the radiation heat transfer, proportional to the temperature. The emissivity of the neoprene layer is assumed as ε=0,9. The surrounding temperature is always the same, i.e. T_∞=0°C.
The obtained state variable is visualized by means of the ADINA program. The distribution of the temperature is shown in Fig.6. We introduce also the upper surface subjected to the heat radiation and heat convection because the program does not contain the linear conduction and radiation. The finite element net is the same as in previous example, cf. Fig.4.

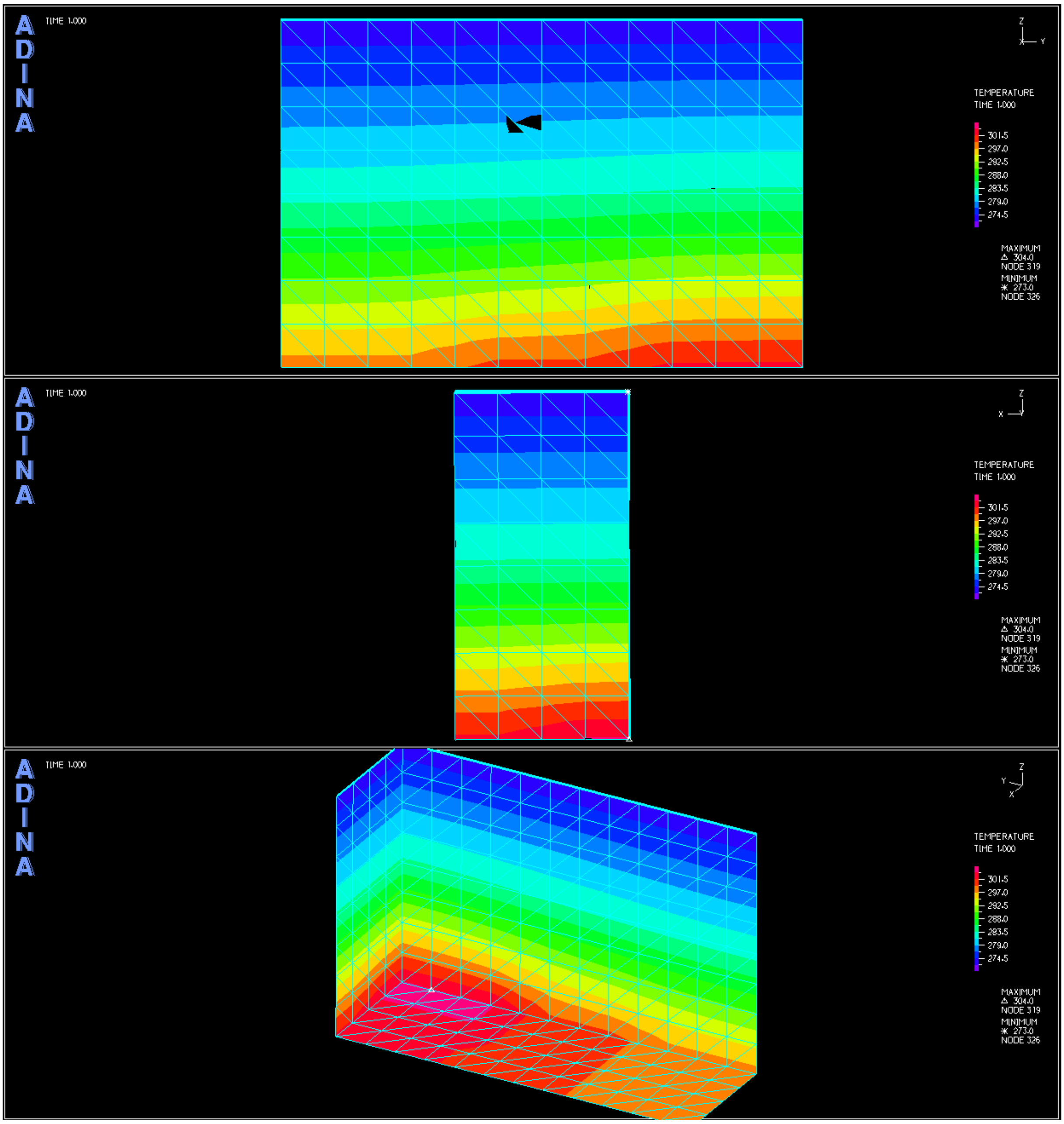

Figure 6. Distribution of temperature, example 3

We see at once that the distribution of temperature is slightly changed. The heat is transported to the surrounding by two phenomena, i.e. the convection and the radiation. There is the same sandwich distribution of temperature in the textile layer but there are some changes of the lower temperature in the neoprene layer contacting the surrounding.

5. Conclusions

Heat transport is the main factor of the user's comfort as well as the safety during the extreme environmental conditions, for example during the diving. Steady heat transfer problems are simple to solve and some can be solved analytically. The transient problems are complicated and solved approximately by means of the different numerical methods.

State equation is the heat energy equation supplemented by the set of boundary and the initial conditions (for the transient problems only). Boundary conditions are formulated by means of the phenomena within the composite structure of the wet suit and on the external and internal boundaries. Distribution of temperature is visualized by the graphical modulus within the processing program ADINA.

The presented results shown, that the discussed methods are an effective tool to generate the distribution of state variables within the composite structure. Distribution of temperature can be the analysis stage of the more complex problem. The synthesis stage can be the optimization or identification of the structure. Of course it is beyond scope of the paper and it is necessary to introduce the various optimization methods to solve the problem.

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7. References

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