Mathematical modeling of coupled heat transfer on cooled gas turbine blades

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Abstract: *The paper presents a physico-mathematical model for determining the heat transfer parameters between viscous gasdynamic flotations and cooled gas turbine blades made using the technology of composite permeable membranes (CPM). The mathematical model includes equations of dynamic and thermal boundary layers taking into account injection, three-dimensional transient heat conduction in CPM cooled frames, complex hydraulic flow and cooling inside the channels of a cooled blade with air taken from the power plant compressor. A complex problem was solved to determine the thermal state of microrocket engines, where a method was proposed for immersing a multiply-connected domain in a region of the simplest form. A new economical, absolutely stable method is proposed for numerically solving of spatial nonstationary heat transfer problems in multiply-connected domains. The results obtained showed greater cooling efficiency at lower cooling medium costs.*

Key Words: *composite permeable membranes, gasdynamic flotation, cooling efficiency, software package, boundary layer*

1. INTRODUCTION

To increase the power of promising turbojet engines (TJE), it is necessary to increase the temperature and pressure of the working fluid, which contradicts stringent requirements for the strength of TJE structural elements such as combustion chambers and turbine blades.

To cool such structural elements, various cooling systems are used with air taken from the compressor: convective cooling of internal surfaces that are not in contact with a high-temperature gas flow, effusion cooling, blow-in cooling through organized penetrations, etc.

When designing various cooling systems, the question of cooling efficiency is thrown into sharply relief when compromising the various characteristics of cooling systems. They include maximum heat production by the cooling medium at its minimum flow rate and minimum hydraulic pressure losses, as well as minimum gasdynamic flotation pulse losses when the cooling medium is blown into it and, therefore, minimum loss of strength.

In recent years, a direction has emerged in the development of cooling systems based on composite permeable membranes (CPM), which are a multilayer structure with a large number of channels for passing the cooling medium (air) and channels for injecting the cooling medium into the high-temperature gasdynamic flotation [1], [2], [3], [4].

Figure 1 shows the cross-section of a two-layer CPM with seven different modes of flow of the cooling medium in the CPM channels, for which various unit surface conductance α from the coolant to the walls and the temperature T of the cooling medium is determined. For mathematical modeling of the thermal state of such CPM typical elements, it is necessary to define and solve the following problems:

– flows and heat transfer in a viscous gasdynamic boundary layer, as a result of which heat fluxes to the boundary w_1 should be obtained in the form of heat transfer parameters α_{w1} and T_e.

– the coolant flow with heat transfer in the CPM internal channels, as a result of which the heat transfer parameters should be obtained under different modes of cooling medium flow;

– three-dimensional transient heat conduction in multiply-connected domain of CPM frame;

– coupling of all tasks at the heat transfer boundaries, using the continuity of heat fluxes and temperatures at all boundaries, because of which the temperature of all boundaries of the computational domain should be obtained and all other characteristics specified.

A similar complex problem was solved in [5] to determine the thermal state of microrocket engines, where a method was proposed for immersing a multiply-connected domain in a region of the simplest form [6], [7], [8], [9], [10], [11], [12], [13].

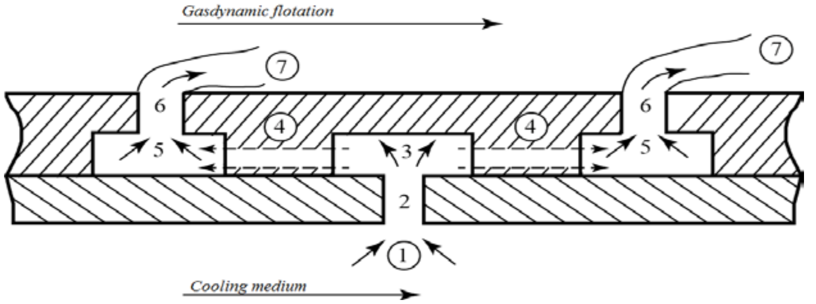

Fig. 1 - Cross section of a two-layer composite permeable membrane

In this paper, this method is applied to solving the complex problem of determining heat transfer in CPM typical elements with analysis of its cooling efficiency.

2. PHYSICO-MATHEMATICAL MODEL FOR DETERMINING HEAT TRANSFER PARAMETERS

The general complex physico-mathematical model includes the following problems, each of which has an independent value.

1. The problem of flow and heat transfer in dynamic and thermal multicomponent boundary layers with a pressure gradient in the coordinate system x, y:

– equation of conservation of momentum in the projection onto the axis O_x:

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right);\ x > 0;\ 0 < y < \delta \quad (1)$$

– equation of conservation of momentum in the projection onto the axis O_y:

$$O = -\frac{\partial p}{\partial y}, \text{or } p = p_e(x), x > 0, y = \delta \tag{2}$$

– continuity equation:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\rho y} = 0, x > 0, 0 < y < \delta \tag{3}$$

– equation of energy conservation:

$$\begin{aligned}\rho u\frac{\partial I}{\partial x} + \rho v\frac{\partial I}{\partial y} = \frac{\partial}{\partial y}\left[\frac{\mu}{Pr}\frac{\partial I}{\partial y} + \mu\left(1 - \frac{1}{Pr}\right)\frac{\partial u^2}{2\partial y}\right] \\ - \frac{\partial}{\partial y}\left[\left(\frac{1}{Le} - 1\right)\rho D_{12}\sum_i h_i\frac{\partial C_1}{\partial y}\right],\ x > 0, 0 < y < \delta\end{aligned} \tag{4}$$

– equation of state of i - th component:

$$p_i = \rho_i R_i T \tag{5}$$

– Bernoullis relation:

$$p_e(x) = p_0 - \frac{\rho_e(x)u_e^2(x)}{2} \tag{6}$$

– boundary conditions:

$$y = 0: u = 0, v = 0, T = T_{w1}, \rho_w = p_e/RT_{w1} \tag{7}$$

$$y = \delta(x); u = u_e(x);\ \rho = \rho_e(x);\ p_e(x) = p_0 - \frac{\rho_e u_e^2(x)}{2}; T = T_e(x) \tag{8}$$

$$x = 0, p = p_0, T = T_0, \rho = \rho_0, u = 0, v = 0 \tag{9}$$

Here x is the longitudinal coordinate along the outer boundary of the turbine blade; y – coordinate along the external normal to the outer boundary; u, v, ρ, p, T – respectively, the longitudinal and transverse components of the velocity vector, density, pressure, temperature; C_1 – concentration of the i -th component; μ – dynamic coefficient of viscosity; Pr – Prandtl number, Pr $= \mu \cdot c_p/\boldsymbol{\lambda}$; $c_p, \boldsymbol{\lambda}$ – heat capacity, thermal transmittance; Le – Lewis number, Le $= D_{12}c_p/\boldsymbol{\lambda}$; D_{12} – binary diffusion coefficient; δ, δ_T – thicknesses of the dynamic and thermal boundary layers; R – individual gas constant; I – total enthalpy, I $= h + u^2/2$; h – static enthalpy, $h = \sum_i c_i h_i$; c_i – concentration of the i-th component; $h_i = \int_0^T c_{pi} dT$.

Indices: e – the outer boundary of the boundary layer; w_1 – wall; 0 – slow-down characteristics.

2. The problem of spatial transient heat conduction in the structural s –layer CPM element ($s = 2$ or 3):

– spatial transient heat conduction equation

$$p_s c_s(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_s(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_s(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_s(T)\frac{\partial T}{\partial z}\right), \{x, y, z\} \in V \tag{10}$$

– convective and conductive heat transfer at the outer boundary w, in contact with hot gas with an effective temperature T_e

$$\alpha_{w1}(T_e - T_{w1}) - \lambda_1(T)\left.\frac{\partial T}{\partial n}\right|_{w_1} = 0, \{x, y, z\} \in \mathrm{B}_{w1}, t > 0 \tag{11}$$

where

$$\left.\frac{\partial T}{\partial n}\right|_{w_1} = \frac{\partial T}{\partial x}\cos\left(\overline{n^0}, \bar{\imath}\right) + \frac{\partial T}{\partial y}\cos\left(\overline{n^0}, \bar{\jmath}\right) + \frac{\partial T}{\partial z}\cos\left(\overline{n^0}, \bar{k}\right) \tag{12}$$

where $\overline{n^0}$ is the vector of the unit external normal to the boundary w_1, $\bar{\imath}$, $\bar{\jmath}$, $\bar{k}$ – the unitary vectors of the basis vectors, B_{w1} – the boundary in contact with the gasdynamic flotation;

– continuity of heat fluxes and temperatures at the boundaries of the breakdown of thermal and physical characteristics

$$\lambda_s \left.\frac{\partial T}{\partial n}\right|_{ws}^{-} = \lambda_{s+1}\left.\frac{\partial T}{\partial n}\right|_{ws}^{+}, T_{ws}|^{-} = T_{ws}|^{+}, s = 1, 2, 3, t > 0 \tag{13}$$

– convective and conductive heat transfer at the boundaries wi, in contact with the cooling medium

$$\alpha_{wi}\left(T_{wi} - T_{cooler\_i}\right) + \lambda_s(T)\left.\frac{\partial T}{\partial n}\right|_{w_i} = 0, \{x, y, z\} \in wi, i = \overline{1.6}, s = 1, 2, 3, t = 0 \tag{14}$$

– at the borders of contact with similar typical elements

$$\lambda_s \left.\frac{\partial T}{\partial n}\right|^{-} = \lambda_s \left.\frac{\partial T}{\partial n}\right|^{+}, s = 1,2,3, t > 0 \tag{15}$$

– initial condition

$$T(x, y, z, 0) = T_{begin} = const. \tag{16}$$

3. The problem of determining the heat transfer parameters $\alpha_{wi}, T_{cooler\_i}$ at the boundaries $wi, i = \overline{1.6}$, in contact with the cooling medium. For different modes of the cooling medium flow, the heat removed by the cooling medium in each of the sections shown in Figure 2 is determined by the following relations borrowed from [14], [15], [16], [17], [18], [19], [20], [21], [22] (below Q_i have a strength dimension).

Vent section (1st section):

$$Q_i = 1.6\sqrt{g \cdot \mu \cdot} c_p(T_{w1} - T_1)\sqrt{h_1 - d_1}, T_1 = (T_{cooler\_0} + T_{cooler\_1})/2, T_{cooler\_1} = T_{cooler\_0} + Q_1/c_p \cdot g \tag{17}$$

Section of the round channel (2nd section):

$$Q_2 = 2.65 \cdot c_p(T_{w2} - T_2) \cdot \mathrm{Pr}^{-2/3}\sqrt{g\mu\delta_1}\left(1 + 1.53\sqrt{\frac{\mu\delta_1}{g}}\right), \tag{18}$$

$$T_2 = (T_{cooler\_1} + T_{cooler\_2})/2, T_{cooler\_2} = T_{cooler\_1} + Q_2/c_p \cdot g$$

Section of jet impingement and obstacle (3rd section):

$$Q_3 = 35 \cdot \mathrm{Pr}^{-2/3}(\mathrm{Re}^{0.5} - 5.05 \cdot z/d_1)c_p(T_{w3} - T_3)\mu d_{1,}$$
$$T_3 = (T_{cooler\_2} + T_{cooler\_3})/2, T_{cooler\_3} + Q_3/c_p \cdot g \tag{19}$$

Two-dimensional channel section (4th section):

$$Q_4 = 1.33(g\mu b)^{1/2}c_p(T_{w4} - T_4)\mathrm{Pr}^{-2/3}\left[\frac{(\beta+y)l_1}{z} - \frac{1}{2\beta}\left|\ln\frac{\gamma-\beta}{\gamma+\beta}\right|\right], \beta$$
$$= 3.46\sqrt{\frac{\mu b}{g}}, \gamma = \sqrt{\beta^2 + \frac{z}{l_1}}, \tag{20}$$
$$T_4 = (T_{cooler\_3} + T_{cooler\_4})/2, T_{cooler\_4} = T_{cooler\_3} + Q_4/c_p \cdot g$$

Vent section in the second layer (5th section)

$$Q_5 = 1.6\sqrt{g \cdot \mu} \cdot c_p(T_{w5} - T_5)\sqrt{b - d_2},$$
$$T_5 = (T_{cooler\_4} + T_{cooler\_5})/2, T_{cooler\_5} = T_{cooler\_4} + Q_5/c_p \cdot g \tag{21}$$

Section of the cylindrical channel of the second layer (6th section)

$$Q_6 = 2.35c_p(T_{w6} - T_6)\mathrm{Pr}^{-2/3}\sqrt{g\mu\delta_2}\left(1 + 1.53\sqrt{\frac{\mu\delta_1}{\frac{\mu\delta_2}{g}}}\right) \tag{22}$$
$$T_6 = (T_{cooler\_5} + T_{cooler\_6})/2, T_{cooler\_6} = T_{cooler\_5} + Q_6/c_p \cdot g$$

The section of injection into the gasdynamic boundary layer (7th section) is characterized by a decrease in heat flux to the wall due to the cooling medium curtain. The effect of the curtain is determined empirically by the parameter θ_{cur}

$$\theta_{cur} = 17.07\Phi^{-0.844}, \theta_{cur} = \frac{T_\gamma - T_{ad}}{T_\gamma - T_{cooler\_6}}, \Phi = \frac{x \cdot \rho_e u_e}{s \cdot (\rho v)_w} \tag{23}$$

Then the heat flux to the wall in the area of the curtain is determined by the formula

$$q = \alpha_r(T_\gamma - T_w) - \alpha_r(T_\gamma - T_{cooler\_6})\theta_{cur} \tag{24}$$

In the relations (17) – (24), the following notations are adopted: g – cooling medium consumption; T_{wi} – temperature of the inner boundary; h_1 – half the distance between the holes with a diameter d_1; T_i – the average temperature of the cooling medium between two adjacent sections; $\delta_{1,}\delta_2$ – the length of the cylindrical channel in the lower and upper membrane; d_2 – the diameter of the channel in the second membrane; Re – Reynolds number, $\mathrm{Re} = 1{,}27g/\mu \cdot d_1, b, z, l_1$ – width, height and length of a two-dimensional channel; T_{ad} – temperature of the adiabatic wall; T_γ – recovery temperature, $T_e \approx T_\gamma$.

3. METHODS FOR SOLVING PROBLEMS REGARDING HEAT CONDUCTION AND HEAT TRANSFER

Problem (1) – (9) regarding flow and heat transfer in dynamic and thermal boundary layers is solved numerically by the finite-difference method of the second-order accuracy according to spatial variable methods described in [9].

The temperature profile in the thermal boundary layer obtained because of a numerical solution is differentiated with respect to the variable y at $y = 0$ then this derivative is multiplied by the heat conduction of the gas at the wall temperature, because of which we obtain the heat flux $\alpha_{w1}(T_e - T_{w1}) = \boldsymbol{\lambda} \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{y}}\Big|_{\boldsymbol{w1}}$ for substitution into the boundary condition (11).

The three-dimensional nonstationary heat conduction problem (10) – (16) in a multiply-connected domain is solved by the immersion method using the fractional step method of N. N. Yanenko, described in detail in [5].

For a multiply-connected domain, which is the CPM element, the immersion method involves immersing the multiply-connected domain in a region of classical form, for example, in a parallelepiped.

Then, the scalar sweep method along a coordinate line intersecting a multiply-connected domain is realized throughout with the selection of internal nodes that have fallen into the internal air cavity.

Moreover, the approximation of the boundary condition (14) (as well as the boundary condition (11) contains conservative terms that take into account the accumulation of thermal energy in the boundary nodes.

These terms are absent in the heat flux balances (11), (14) and arise at finite-difference approximation.

In the boundary conditions (14) at the boundaries in contact with the cooling medium T_{cooler_i}, it is accepted as T_i: $T_i = T_{cooler\_i}, i = \overline{1.6}$, and the unit surface conductance $\alpha_{wi,}\ i = \overline{1.6}$ is calculated using relations (17) – (22), if Q_i is divided by the difference $(T_w - T_i)S_i$ where S_i is the surface area of the i-th section washed by the cooling medium.

According to the developed SPO software package, mass calculations of the thermal state of the CPM elements were carried out in order to identify the effectiveness of composite permeable membranes.

Below are the results for three values of the unit surface conductance on an impermeable wall: $\alpha_{w1} = 0.714 \cdot 1.016$ and $1.26\ kW/m^2 \cdot K$ and six values of the coolant-flow rate $g = 0.01; 0.02; 0.03; 0.04; 0.05$ and $0.1\ g/s$ (18 options in total). The remaining characteristics took the following values:

– geometrical dimensions (Figure 1) in millimeters: $a = 5; b = 5; c = 2; d = 2; l = 1.5; f = 1.5;\ \delta_i = 0.5;\ \delta_2 = 0.5;\ \delta_3 = 0;$ (two-layer CPM); $\delta_4 = 0.5;\ \delta_5 = 0.5;\ r = 0.5;$

– thermal and physical characteristics of the frame materials: $\lambda_i = 0.5042\ kW/m \cdot K;\ \rho_1 = 7800\ kg/m^3;\ c_1 = 1.26\ kj/kg \cdot K;\ \lambda_2 = 0.1512\ kW/m \cdot K;\ \rho_2 = 7800\ kg/m^3;\ c_2 = 1.26\ kj/kg \cdot K; \lambda_3 = \rho_3 = c_3 = 0;$

– gasdynamic flotation characteristics: $T_e = 1600\ K;\ u_e = 200\ m/s; \mathrm{Pr} = 0.71; p_e = 0.1\ kg/m^3$.

Figure 3 shows the results of calculating the cooling efficiency θ of CPM depending on the unit surface conductance α_{w1} from the gasdynamic flotation and the coolant-flow rate g, where $\theta = (T_e - T_{w1})/(T_e - T_{cooler})$.

It can be seen from the figure that the lower the unit surface conductance α_w on the impermeable wall, the higher the CPM efficiency, since the relative temperature of the frame increases faster with increasing heat fluxes than the relative temperature of the cooling medium.

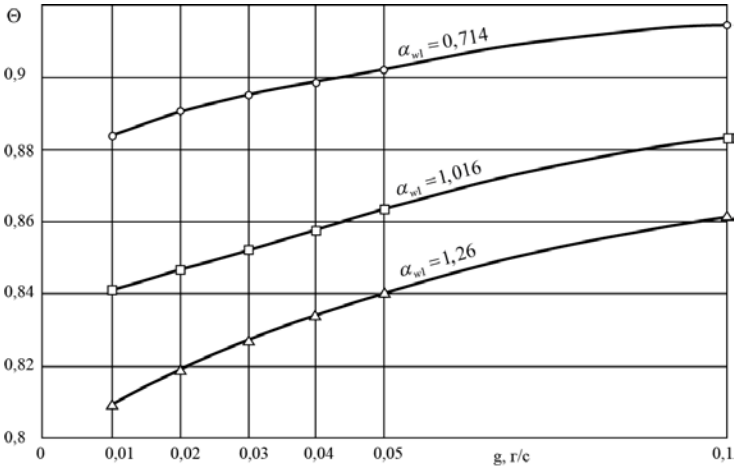

Fig. 2 - The dependence of the CPM effectiveness $\theta = (T_e - T_{w1})/(T_e - T_{cooler})$ on the coolant-flow rate and the unit surface conductance from the gasdynambic flotation.

4. CONCLUSIONS

Based on the developed mathematical model, numerical methods, and software package, the cooling efficiency of heat-stressed structural elements of gas turbine engines made based on the technology of composite permeable membranes (CPM) was studied.

The dependences of the cooling medium temperature (air taken from the compressor) at different CPM sections are obtained depending on the heat fluxes at high-temperature gasdynamic flotation and on the coolant-flow rate. It was found that the cooling efficiency is significantly higher at low heat fluxes on the wall in contact with the gasdynamic flotation.

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