Computer modelling of heat energy regeneration process in a reversible heat exchanger

Alijon Naimov¹, Anton Sinitsyn²*, M M Vetyukov³, V A Palmov³, V F Kosmach³, Yu F Titovec³ and I G Akhmetova⁴

¹Vologda State University, Department of Informatics and Computer Technology, 160000 Lenin st., 15, Russia
²Vologda State University, Department of Heat Gas Supply and Ventilation, 160000 Lenin st., 15, Russia
³Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation
⁴Kazan State Power Engineering University, Kazan, Russian Federation

* Corresponding author: sinitsyn.science@mail.ru

Abstract. The article considers approbation of the developed mathematical model of the process of thermal energy accumulation in a stationary switching regenerative heat exchanger using the Matlab computer system. The model was constructed and numerically investigated using a difference scheme. This method is necessary for development of algorithms for calculating the thermal characteristics of heat and mass transfer processes under conditions of regeneration and phase transitions, as well as for analyzing the criteria for optimal control of the operation of this apparatus under nominal and critical environmental conditions.

1. Introduction

While construction of modern buildings and structures, various heat exchangers are used in their systems of heat supply and ventilation, in which complex processes of heat and mass transfer take place [1-5]. At the design stage of these devices, it is necessary to repeatedly calculate its characteristics in order to optimize the operating parameters [6].

To evaluate their efficiency, either complex mathematical models or empirical formulas of limited scope are used. The use of existing methods of calculation is often unacceptable either in terms of counting time or accuracy when going beyond the scope of application [7].

The most difficult problem in analyzing the efficiency of such devices is calculation of the heat and mass transfer processes occurring in them, taking into account the regenerative nature and phase transitions. For such processes, empirical relationships are used, as a rule which are valid for a narrow region of regime and design parameters [8].

At the same time, creation of simple engineering methods for calculating heat and mass transfer processes in various gas-dynamic devices, as, for example, in [9-15], will make it possible to identify their modes of operation, optimize their modes, and promptly evaluate the efficiency of various design schemes during the development of new devices or technologies.

The Matlab system was chosen as a universal tool for solving the problem. The choice of the system is due to the fact that among the analogues Matlab is distinguished by a simple programming language that makes it easy to create one’s own algorithms. The system is specially designed for research on the
development of new equipment, including engineering research. Also, Matlab has powerful visualization tools, which is important when determining the optimal parameters of the designed equipment [16].

The objects of simulation are the processes of heat and mass transfer in a stationary switching regenerative heat exchanger (SSRHE). The existing mathematical and computer models have been developed either for recuperative and mixing heat exchangers, or for regenerative heat exchangers operating at high coolant temperature [17], as well as for regenerative heat exchangers with a rotary nozzle. The most adequate mathematical model developed for the SSRHE is given in [16]. This model was constructed and numerically investigated using a difference scheme. But such issues as the existence and uniqueness of a solution, as well as analytical methods for finding a solution have not yet been investigated. The analytical method of finding a solution to the problem is relevant from the point of view of developing algorithms for calculating the thermal characteristics of the process and optimal control of the operation of the specified apparatus.

2. Development of a mathematical model

We introduce the following notations: \( T_a (\tau, z) \) is air temperature at the time moment \( \tau \) in the point \( z \), where \( \tau \geq 0, 0 \leq z \leq L, ^\circ C; \) \( T_n (\tau, z) \) is nozzle temperature at the time moment \( \tau \) in the point \( z \), where \( \tau \geq 0, 0 \leq z \leq L, ^\circ C; \) \( G_{ac} \) is air consumption at the accumulation stage, \( m^3/h; \) \( c_a \) is air heat capacity, \( kJ/kg\cdot^\circ C; \) \( \rho_a \) is air density, \( kg/m^3; \) \( S_n \) is the cross-section area of channel along which air goes, \( m^2; \) \( P \) is the cross-section perimeter of channel along which air goes, \( m; \) \( \alpha \) is heat transfer coefficient for air, \( W/m^2\cdot^\circ C; \) \( T_{in} \) is temperature of the room, from which the air is supplied, \( ^\circ C; \) \( T_{out} \) is ambient temperature where some part of heat enters, \( ^\circ C; \) \( \lambda_a \) is thermal conductivity of the nozzle material, \( W/m\cdot^\circ C. \)

We construct a mathematical model of the process of heating the air in the passageway. To do this, we note that \( -G_{ac}c_a \frac{\partial T_n}{\partial \tau} (\tau, z) \) - the amount of heat entering the flow area at point \( z \) at time \( \tau; \) \( c_a \rho_a S_n \frac{\partial T_a}{\partial \tau} (\tau, z) \) is the amount of heat spent on the heating of the flow section at the point \( z \) at the moment of time \( \tau; \) \( \alpha(T_n(\tau, z) - T_a(\tau, z)) \) is the amount of heat transferred from the air nozzle in the flow area at the point \( z \) at time \( \tau. \)

The balance equation of thermal energy in the flow section at the point \( z \) at the moment of time \( \tau: \)

\[
-\frac{G_{ac}c_a}{\partial \tau} (\tau, z) = c_a \rho_a S_n \frac{\partial T_a}{\partial \tau} (\tau, z) + \alpha(T_n(\tau, z) - T_a(\tau, z)), \quad \tau > 0, 0 < z < L.
\]

Equation (1) is a mathematical model of the process of heating air in the passage channel. It is necessary to take into account the initial condition

\[
T_a(0, z) = T_{in} - \frac{T_{in} - T_{out}}{L}, \quad 0 \leq z \leq L.
\]

i.e. at the initial moment of time, the temperature in the flow channel is linearly distributed between \( T_{in} \) and \( T_{out} \), as well as the boundary (edge) condition:

\[
T_a(\tau, 0) = T_{in}, \quad \tau \geq 0.
\]

i.e. at the left end of the passage, the temperature is constant all the time and is equal to room temperature \( T_{in}. \)

Thus, we obtain the initial-boundary (mixed) problem (1), (2), (3) for the unknown function \( T_a(\tau, z) \).

Now we build a mathematical model of the process of heating the nozzle. In the process of heating the nozzle \( \alpha(T_n(\tau, z) - T_n(\tau, z)) \) is the amount of thermal energy supplied from the air nozzle in the flow area at the point \( z \) at the moment of time \( \tau; \) \( c_n \rho_n S_n \frac{\partial T_n}{\partial \tau} (\tau, z) \) is the amount of thermal energy spent on heating the nozzle at point \( z \) at time \( \tau; \) \( -\lambda_n S_n \frac{\partial^2 T_n}{\partial z^2} (\tau, z) \) is the amount of thermal energy transferred inside the nozzle according to the Fourier law.

The balance equation of thermal energy in the cross section of the nozzle at the point \( z \) at the moment
of time $\tau$:
\[
P\alpha(T_a - T_n) = c_n \rho_n \frac{\partial T_n}{\partial \tau} - \lambda_n \rho_n S_n \frac{\partial^2 T_n}{\partial z^2}, \quad \tau > 0, \quad 0 < z < L. \tag{4}
\]

Equation (4) is a mathematical model of the process of heating the nozzle. It is necessary to consider the initial condition:
\[
T_n(0, z) = T_{in} - \frac{T_{in} - T_{out}}{L} \cdot z, \quad 0 \leq z \leq L. \tag{5}
\]
i.e. at the initial moment of time the temperature in nozzle is distributed linearly between Tin and Tout, and the boundary (edge) conditions:
\[
\frac{\partial T_n}{\partial z}(\tau, 0) = 0, \quad \frac{\partial T_n}{\partial z}(\tau, L) = 0, \quad \tau > 0. \tag{6}
\]
i.e. nozzle ends are insulated all the time. Thus, we obtain the initial-boundary (mixed) problem (4), (5), (6) for the unknown function $T_n(\tau, z)$.

The mixed problem (1) - (6) is a mathematical model of the process of accumulation of thermal energy in the thermodynamic air-nozzle system.

3. Approximate solution

The mixed problem (1) - (6) is rewritten as follows:
\[
\frac{\partial T_a}{\partial \tau}(\tau, z) + a \frac{\partial T_a}{\partial z}(\tau, z) + b T_a(\tau, z) = b T_n(\tau, z), \quad \tau > 0, \quad 0 < z < L, \tag{7}
\]
\[
T_a(0, z) = T_{in} - \frac{T_{in} - T_{out}}{L} \cdot z, \quad 0 \leq z \leq L, \quad T_a(\tau, 0) = T_{in}, \quad \tau \geq 0, \tag{8}
\]
\[
\frac{\partial T_n}{\partial \tau}(\tau, z) - c \frac{\partial^2 T_n}{\partial z^2}(\tau, z) + d T_n(\tau, z) = d T_a(\tau, z), \quad \tau > 0, \quad 0 < z < L, \tag{9}
\]
\[
T_n(0, z) = T_{in} - \frac{T_{in} - T_{out}}{L} \cdot z, \quad 0 \leq z \leq L, \quad \frac{\partial T_n}{\partial z}(\tau, 0) = 0, \quad \frac{\partial T_n}{\partial z}(\tau, L) = 0, \quad \tau > 0. \tag{10}
\]

where
\[
a = \frac{\gamma c_s}{\rho_s \rho_n} a, \quad b = \frac{\rho_a \rho_n}{\rho_n \rho_n} a, \quad c = \frac{\lambda_n}{c_n \rho_n}, \quad d = \frac{\rho_a \rho_n}{c_n \rho_n}. \tag{11}
\]

Taking into consideration (7) and (8) the function $T_a(\tau, z)$ can be expressed using $T_n(\tau, z)$:
\[
T_a(\tau, z) = \Phi_a T_n(\tau, z), \tag{12}
\]

where
\[
\Phi_a T_n(\tau, z) = \begin{cases} 
  e^{-b\tau} \left( T_{in} - \frac{T_{in} - T_{out}}{L} (z - \alpha \tau) \right) + b \int_0^\tau e^{b(s-\tau)} T_n(s, z + \alpha(s - \tau)) ds, \quad z \geq \alpha \tau, \\
  e^{-b\tau^2} T_{in} + b \int_{\tau - \frac{z}{\alpha}}^\tau e^{b(s-\tau)} T_n(s, z + \alpha(s - \tau)) ds, \quad z < \alpha \tau.
\end{cases}
\]

In view of (9) and (10) the function $T_n(\tau, z)$ can be expressed using $T_a(\tau, z)$:
\[
T_n(\tau, z) = \Phi_n T_a(\tau, z), \tag{13}
\]

where
\[
\Phi_n T_a(t, z) = \int_0^L G(t, z, \eta) \left( T_n - \frac{T_{in} - T_{out}}{L} \right) d\eta + d \int_0^\tau \int_0^L G(t - s, z, \eta) T_a(s, \eta) d\eta ds,
\]
\[
G(t, z, \eta) = \frac{1}{L} \left( e^{-\beta \sigma t} + 2 \sum_{k=1}^\infty \frac{e^{-\beta k t}}{\cos \frac{\pi k}{L} \eta} e^{rac{\pi k z}{L}} \right), \beta_k = d + c \left( \frac{\pi k}{L} \right)^2, k = 0, 1, 2, \ldots.
\]

Integral representations (11) and (12) are derived from well-known formulas for solving mixed problems of the form (7), (8) and (9), (10).

Thus, the mixed problem (7) - (10) is equivalent to the system of integral equations (11), (12). System (11), (12) is solved by the method of successive approximations. Namely, we construct the following sequences of functions:
\[
T_n^{(0)}(t, z) = T_{in}, T_n^{(n)}(t, z) = \Phi_a T_n^{(n-1)}(t, z), T_n^{(n)}(t, z) = \Phi n T_a^{(n)}(t, z)
\]
\[
(13)
\]

The sequence of functions \( n = 1, 2, \ldots \) converges to the solution \( (T_n(t, z), T_a(t, z)) \) of the mixed problem (7) - (10): \( (T_n^{(n)}(t, z), T_a^{(n)}(t, z)) \)
\[
\lim_{n \to \infty} T_n^{(n)}(t, z) = T_n(t, z), \lim_{n \to \infty} T_a^{(n)}(t, z) = T_a(t, z).
\]

Therefore, for large numbers \( n \) a couple of functions \( (T_n^{(n)}(t, z), T_a^{(n)}(t, z)) \) can be taken as an approximate solution \( (T_n(t, z), T_a(t, z)) \) of the mixed problem (7) - (10):
\[
T_n^{(n)}(t, z) \approx T_n^{(n)}(t, z), \quad T_a^{(n)}(t, z) \approx T_a^{(n)}(t, z).
\]

For large numbers \( n \) and fixed points in time \( \tau \), the function graphs \( (T_n^{(n)}(t, z), T_a^{(n)}(t, z)) \) are shown in Figures 1, 2.

4. Numerical solution

We find the approximate values of solution of the mixed problem at the grid points \( \Omega(N_x, N_z) = \{ (\tau_i, z_j): i = 0, N_x + 1, j = 0, N_z + 1 \} \), where \( \tau_i = (i - 1)h, \quad z_j = (j - 1)h, \quad h = \frac{b - a}{N_z} \).

The values of the required functions \( T_a(t, z), T_n(t, z) \) in each point \( (\tau_i, z_j) \) of the grid we denote as follows: \( T A_i j = T_a(\tau_i, z_j), \quad T N_i j = T_n(\tau_i, z_j) \). At the given grid \( \Omega(N_x, N_z) \) the two matrices are unknown \( TA = (T A_i j)_{i=0}^{N_x+1}^{j=0} \), \( TN = (T N_i j)_{i=0}^{N_x+1}^{j=0} \).

For a mixed problem, we will find out what conditions the required TA and TN matrices should satisfy. According to the initial conditions, the first rows of these matrices are known: \( TA_i j = T_a^0(z_j), \quad T N_i j = T_n^0(z_j), \quad j = 1, N_z + 1 \). For the TA matrix, in view of boundary condition we know the first column:
\[
T A_i 1 = T_a^1(\tau_i), \quad i = 1, N_x + 1.
\]

Now we find out what the system of integral equations with respect to the grid \( \Omega(N_x, N_z) \) turns into. For the first integral equation we have:
\[
T_a(\tau_i, z_j) = \begin{cases} 
e^{-b \tau_i} T_a^0(\tau_i, z_j) + b \int_0^{\tau_i} e^{b(s-\tau_i)} T_n(s, z_j + a(s - \tau_i)) ds, & \text{if} \ z_j \geq a \tau_i, \\ e^{-b \tau_i} T_n^0(\tau_i, z_j/a) + b \int_0^{\tau_i} e^{b(s-\tau_i)} T_a(s, z_j + a(s - \tau_i)) ds, & \text{if} \ z_j < a \tau_i, \end{cases}
\]
where \( i \geq 2, \ j \geq 2 \). We should note that for the introduced notations:
where

\[ z_i \geq a \tau_i \Leftrightarrow (j - 1) a h_z \geq a(i - 1) h_z \Leftrightarrow j \geq i, \quad z_j - a \tau_i = (j - 1) h_z - a(i - 1) h_z = (j - i) h_z = z_{j-i+1}, \]

\[ \tau_i - \frac{z_i}{a} = (i - 1) h_t - (j - 1) \frac{h_z}{a} = (i - j) h_t = \tau_{i-j+1}, T_0^a(z_j - a \tau_i) = T_0^a(z_{j-i+1}) = TA_i, j-i+1, \]

\[ T_a^1(\tau_i - \frac{z_i}{a}) = T_a^1(\tau_{i-j+1}) = TA_{i-j+1}. \]

Next, we replace each integral with a finite sum, applying the following rectangle formula:

\[ \int_0^\beta f(s) \, ds \approx h \sum_{k=1}^N f(s_k), \text{ where } h = \frac{\beta - a}{N}, \quad s_k = a + h \cdot (k - 1). \]

In case of the first integral we assume \( a = 0, \beta = \tau, N = i - 1 \). So

\[ h = \frac{\beta - a}{N} = \frac{\tau - 0}{i - 1} = \frac{(i-1) h \tau}{i - 1} = h \tau, \quad s_k = \alpha + h(k - 1) = h \tau(k - 1) = \tau_k, \]

\[ z_j + a(\tau_k - \tau_i) = (j - 1) h_z + (k - i) h_z = z_{k+i-j} \tau \tau, \quad z_j + a(\tau_k - \tau_i) = T_n(\tau_k, z_j + a(\tau_k - \tau_i)) = T_n(\tau_k, z_{k+i-j}) = TN_{k, k+i-j}. \]

\[ \int_0^{\tau_i} e^{b(s-\tau_i)} T_n(s, z_j + a(s-\tau_i)) \, ds \approx h \tau \sum_{k=1}^{i-1} e^{b(s_k-\tau_i)} T_n(s_k, z_j + a(s_k - \tau_i)) = \]

\[ = h \tau \sum_{k=1}^{i-1} e^{b(\tau_k-\tau_i)} T_n(\tau_k, z_j + a(\tau_k - \tau_i)) = h \tau \sum_{k=1}^{i-1} e^{b(\tau_k-\tau_i)} TN_{k, k+i-j}. \]

In case of the second integral by assuming \( a = \tau_i - \frac{z_i}{a}, \quad \beta = \tau_i, \quad N = j - 1 \), we get:

\[ h = \frac{\beta - a}{N} = \frac{\tau_i - \frac{z_i}{a} - a(i - 1) h \tau}{a(j - 1)} = h \tau, \]

\[ s_k = \alpha + h(k - 1) = \tau_i - \frac{z_i}{a} + (k - 1) h \tau = (k + i - j - 1) h \tau = \tau_{k+i-j}, \]

\[ z_j + a(\tau_{k+i-j} - \tau_i) = (j - 1) h_z + (k - j) h_z = (k - 1) h_z = z_k, \quad T_n(\tau_{k+i-j}, z_k) = \]

\[ \int_{\tau_i}^{\tau_i} e^{b(s-\tau_i)} T_n(s, z_j + a(s_k - \tau_i)) \, ds \approx \]

\[ \approx h \tau \sum_{k=1}^{j-1} e^{b(\tau_k-\tau_i)} T_n(\tau_{k+i-j}, z_j + a(\tau_{k+i-j} - \tau_i)) = h \tau \sum_{k=1}^{j-1} e^{b(\tau_k-\tau_i)} TN_{k, k+i-j}. \]

Thus, the first integral equation in the grid \( \Omega(N_t, N_z) \) takes the following form:

\[ TA_{i,j} = \begin{cases} e^{-b \tau_i} TA_{1, j-i+1} + bh \tau \sum_{k=1}^{i-1} e^{b(\tau_k-\tau_i)} TN_{k, k+i-j}, & \text{if } j \geq i, \\ e^{-b \tau_i} TA_{i-j+1, 1} + bh \tau \sum_{k=1}^{j-1} e^{b(\tau_k-\tau_i)} TN_{k+i-j, k}, & \text{if } j < i, \end{cases} \]

(15)

where \( i = 2, \ldots, N_t + 1, \quad j = 2, \ldots, N_z + 1. \)

For the second integral equation we have:
\[ T_n(\tau_i, z_j) = \int_0^L G_m(\tau_i, z_j, \eta) T_n^0(\eta) d\eta + d \int_0^\tau \int_0^L G_m(\tau_i - s, z_j, \eta) T_a(s, \eta) d\eta ds, \]

where \( i \geq 2, j \geq 1, \)

\[ G_m(\tau, z, \eta) = \frac{1}{L} \left( e^{-\beta_0 \tau} + 2 \sum_{k=1}^{m} e^{-\beta_k \tau} \cos \frac{\pi k}{L} z \cdot \cos \frac{\pi k}{L} \eta \right), \]

\[ \beta_k = d + c \left( \frac{\pi k}{L} \right)^2, \quad k = 0, 1, 2, \ldots. \]

The first integral is replaced by a finite sum using the formula of rectangles:

\[ \int_0^L G_m(\tau_i, z_j, \eta) T_n^0(\eta) d\eta \approx h \sum_{l=1}^{N_z} G_m(\tau_i, z_j, \eta_l) T_n^0(\eta_l), \]

where

\[ h = \frac{L-0}{N_x} = h_z, \quad \eta_l = h_z (l - 1) = z_l, \quad T_n^0(\eta_l) = T_n^0(z_l) = T_{N_1, l}. \]

Consequently,

\[ \int_0^\tau \int_0^L G_m(\tau_i - s, z_j, \eta) T_a(s, \eta) d\eta ds \approx h_z \sum_{l=1}^{N_z} G_m(\tau_i - \tau_k, z_j, \eta_l) T_a(\tau_k, z_l) T_{A_{k, l}}. \]

The first integral equation in the grid \( \Omega(N_r, N_z) \) takes the following form:

\[ T_{N_1, j} = h_z \sum_{l=1}^{N_z} \left[ G_m(\tau_i, z_j, z_l) T_{N_1, l} + d h_z \sum_{k=1}^{N_x} G_m(\tau_i - \tau_k, z_j, z_l) T_{A_{k, l}} \right], \]

where \( i = 2, \ldots, N_r + 1, \quad j = 1, \ldots, N_z + 1. \)

Thus, the required matrices TA and TN must satisfy conditions (14), (15), (16). These conditions together represent a mixed problem with respect to the grid \( \Omega(N_r, N_z) \). In other words, (14) - (16) are a discrete analogue (discretization) of the mixed problem.

Discrete problem (14) - (16) is solved by the method of successive approximations. To do this, we set the number of iterations (approximations) - the positive integer \( n \). Next, we do the following:

1. For the TN matrix, we define a zero approximation, by assuming

\[ T_{N_1}^{(0)}(z_j), \quad i = 1, N_r + 1, \quad j = 1, N_z + 1. \]

2. We consistently find the matrices \( TA^{(1)}, TN^{(1)}, \ldots, TA^{(n)}, TN^{(n)} \) using the following formulas:

\[ TA_{1, j}^{(iter)} = T_{A_1}^0(z_j), \quad TA_{1, i}^{(iter)} = T_{A_1}^0(\tau_i), \quad i = 1, N_x + 1, \quad j = 1, N_z + 1, \]

\[ TA_{i, j}^{(iter)} = \begin{cases} e^{-b(\tau_i - \tau_j) T A_{i, j - 1}} + b h \sum_{k=1}^{N_x} e^{b(\tau_k - \tau_i - \tau_j) T A_{k, k + j - i - 1}} & \text{if } j \geq i, \\ e^{-b(\tau_i - \tau_j) T A_{i, j - 1}} + b h \sum_{k=1}^{N_x} e^{b(\tau_k - \tau_i - \tau_j) T A_{k, k + j - i - 1}} & \text{if } j < i, \end{cases} \]

\[ i = 2, N_r + 1, \quad j = 2, N_z + 1, \]

\[ TN_{1}^{(iter)}(z_j), \quad j = 1, N_z + 1. \]
\[
TN_{ij}^{(\text{iter})} = h_z \sum_{l=1}^{N_z} \left[ G_m(\tau_i, z_j, z_l)TN_{i1} + d h_\tau \sum_{k=1}^{i-1} G_m(\tau_l - \tau_k, z_j, z_l)TA_{kl}^{(\text{iter})} \right].
\] (20)

\[i = 2, N_\tau + 1, \quad j = 1, N_z + 1, \quad \text{iter} = 1, \ldots, n.\]

3. We take \( TA \approx TA^{(n)}, TN \approx TN^{(n)} \) is approximate numerical solution of the discrete problem (14) - (16).

The question of the error of an approximate numerical solution, i.e. at every point \((\tau_i, z_j)\) of the grid \(\Omega(N_\tau, N_z)\) the values \( TA^{(n)}_{ij}, TN^{(n)}_{ij} \) are slightly different from \( TA(\tau_i, z_j), TN(\tau_i, z_j) \) exact solution \( TN(\tau, z), TA(\tau, z) \) of the mixed problem. For this, it is necessary to estimate the difference moduli \( |TA^{(n)}_{ij} - TA(\tau_i, z_j)|, |TN^{(n)}_{ij} - TN(\tau_i, z_j)| \) in each point \((\tau_i, z_j)\) of the grid \(\Omega(N_\tau, N_z)\).

5. Features of computerization of the mathematical model

- **Initial data input:**
  - \( L, c_a, \rho_a, S_a, c_n, \rho_n, S_n \)
  - \( G_{ac}, P, \alpha, \lambda \)

- **Input of initial \( T_n^0, T_n^0 \) and boundary conditions \( T_n^I \)**

- **Input of the grid parameters:**
  - \( N_\tau, N_z, h_\tau, h_z \)

- **Initial matrix construction \( TN^{0(0)} \)**

- **Finding \( n \) consecutive matrix values \( TN^{0(1)}, TN^{0(2)}, \ldots, TN^{0(n)} \)**

- **Function chart output**
  - \( TA(\tau), TN(\tau), \quad i = 1, N_\tau + 1. \)

**Figure 1.** The block diagram of the algorithm for calculating the mathematical model in the Matlab system.

**Figure 2.** Plotted function \( TA(\tau, z) \).
Figures 2 and 3 show air temperature and nozzle temperature change along the nozzle, respectively. Moreover, each graph shows the temperature change at the initial (τ1) and final (τ4) time points, as well as for a pair of intermediate moments with an interval of 4 s.

From the graphs in Figure 2 and 3 it can be seen:

1) When visualizing the proposed mathematical model in Matlab environment, the graphical results to a certain extent correspond to the actual heat exchange processes in the SSRHE;
2) The density of the nozzle affects the uniformity of heating of the nozzle, i.e. the greater the density of the nozzle, the more uneven it is heated;
3) Heat transfer coefficient $\alpha$ depends on the air flow $G_{ac}$;
4) With an increase in the value of the heat transfer coefficient $\alpha$, the uneven distribution of temperature along the nozzle increases.

6. Conclusions
As a result of the work, a computer simulation of the process of heat energy regeneration in a reversible heat exchanger was carried out. The proposed method can be used to develop algorithms for calculating the thermal characteristics of heat and mass transfer processes under conditions of regeneration and phase transitions, as well as for analyzing the criteria for optimal control of the operation of this apparatus under nominal and critical environmental conditions. Compiled and proposed algorithm allows one to:

1) Change the values of initial data, initial and boundary conditions, so it becomes possible to determine the optimal parameters and conditions for real experiments;
2) Change the grid parameters and the number of iterations, thereby changing the accuracy of the calculations;
3) Adjust and add individual steps for calculating the mathematical model.

The work was carried out on the basis of the results of research conducted with the support of the Ministry of Education and Science of the Russian Federation as part of the fulfillment of the state task to higher educational institutions for project No. 1816.

References
[1] Kostenko V A, Gafiyatullina N M, Semchuk A A and Kukolev M I 2016 Geothermal heat pump
in the passive house concept *Magazine of Civil Engineering* **68**(8) pp 18–25

[2] Egorov M Y 2018 Methods of Heat-Exchange Intensification in NPP Equipment *Atomic Energy* **124**(6) pp 403–7

[3] Ivanov N, Ris V, Tschur N and Zasimova M 2016 Numerical simulation of conjugate heat transfer in a tube bank of a subsea cooler based on buoyancy effects *J. of Physics: Conference Series* **745**(3) p 032058

[4] Mityakov V, Gusakov A, Seroshtanov V and Grekov M 2018 Investigation of flow and heat transfer at the circular fins *MATEC Web of Conferences* **245** p 06001

[5] Antonova O V, Boldyrev Y Y, Borovkov A I and Voinov I B 2017 On the Development of a Design Procedure of the Hydrodynamic Characteristics of Hydrogenerator Thrust Bearings Taking into Account the Heat Exchange *J. of Machinery Manufacture and Reliability* **46**(6) p 572–8

[6] Sinitsyn A A 2013 *Life Science Journal* **10**

[7] Sinitsyn A A and Belyanskiy D A 2014 *Measurement Techniques* **56**

[8] Sinitsyn A A, Belyanskiy D A and Sukhanov I A 2013 *Life Science Journal* **10**

[9] Vasil’ev V A 2010 Methods for calculating thermal processes in a stationary switching regenerative heat exchanger (SPb)

[10] Danilishin A M, Kozhukhov Y V, Neverov V V, Malev K G and Mironov Y R 2017 The task of validation of gas-dynamic characteristics of a multistage centrifugal compressor for a natural gas booster compressor station *AIP Conference Proceedings* **1876** p 020046

[11] Aksenov A A, Danilishin A M, Kozhukhov Y V and Simonov A M 2018 Numerical simulation of gas-dynamic characteristics of the semi-open 3D impellers of the two-element centrifugal compressors stages *AIP Conference Proceedings* **2007** p 030025

[12] Galerkin Y, Soldatova K and Drozdov A 2018 The application of mathematical models for industrial centrifugal compressor optimal design *ACM International Conference Proceeding Series* pp 187–91

[13] Lebedev A, Gileva L, Danilishin A and Sokolov M 2018 Surge protection system development in centrifugal compressor with an indicative method using numerical simulation of unsteady processes and analysis of pressure fluctuation signals *MATEC Web of Conferences* **245** p 09010

[14] Aksenov A, Kozhukhov Y, Sokolov M and Simonov A 2018 Analysis and modernization of real gas thermodynamic calculation for turbocompressors and detander units *MATEC Web of Conferences* **245** p 09005

[15] Rekstin A F, Semenovskiy V B, Galerkin Y B and Sokolov A A 2018 The analysis of design and measured gas-dynamic characteristics of the centrifugal compressor within turboexpander aggregate *AIP Conference Proceedings* **2007** p 030028

[16] Sinitsyn A A and Nikiforov O Y 2013 *World Applied Sciences J.* **27**

[17] Klein H and Eigenberger G 2001 *Int. J. of heat and mass transfer* **44**