Investigation of unsteady heat transfer in a porous medium of a discontinuous heater

A P Koroleva¹, M S Frantsuzov ²

¹ National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14
² Bauman State Technical University, 105005, Moscow, Russian Federation, 2nd Baumanskaya St., Bldg. 5, Block 1
anastykoroleva@mail.ru

Abstract. This paper presents the results of determining the features of heat transfer on the example of a discontinuous heat exchanger with ball filling, used to generate a high-enthalpy flow. In the first part, we developed a one-dimensional mathematical model (an improved model of Schumann) unsteady heat transfer in a porous medium taking into account heat wall heater cooperation. An analytical solution is found in the quadratures of the system of partial differential equations. The second part of the paper is devoted to numerical modeling. The influence of empirical coefficients on heat transfer was revealed. The results of numerical simulation were compared with the results of one-dimensional mathematical model. As a result of the computational study, the correspondence and differences in thermal and hydrodynamic processes using one-dimensional differential models and numerical modeling are established. A significant influence of empirical coefficients on the qualitative and quantitative nature of the temperature distribution of the gas and the solid matrix over time was revealed. The correspondence of results between two approaches is established: the solution of differential equations and numerical modeling. On the basis of the analysis the applicability of mathematical models of different levels for solving a certain class of problems is established.

1. Introduction

To conduct high-speed tests of aircraft and their power plants, a device that simulates the parameters of the air flow as close as possible to full-scale conditions is necessary. At the moment, several methods of heating the air flow are technically implemented in the world practice: fire heating [1], electric arc, and cowper heating [2]. The use of fire and electric arc heating leads to distortion in the chemical composition of the air. Cowper heater does not distort the chemical composition of the air, so it can be attributed to the class of "clean heaters".

The cowper heater is a regenerative heat exchanger, the basic element of which is the working volume intended for filling with a heat-accumulating packed bed from a freely packed solid material through which the coolant circulates. Operation of the heater is organized in several modes. The first mode, or heating mode, is to warm up the heat-accumulating packed bed with a high-temperature gas stream (over 1800 K) obtained from an air-methane fire heater. After reaching the required thermal state of the heat-accumulating packed bed, the operation of the cowper heater passes to the second mode, or to the operating mode, when the air flow with a temperature of about 300 K enters the heater and, having reached certain parameters, is diverted to the subsequent systems of the experimental stand. Due to the conditions of high thermal stress to the filling material and the structure of the filling requirements of high heat content, heat resistance and heat resistance.
Packed bed forming a porous medium is also used in various industrial high-temperature systems [3], such as gas-cooled nuclear reactors [4], drying processes [5] and catalytic reactors [6]. The efficiency of such systems is determined by the behavior of the coolant and filling characteristics. The organization of a complex heat exchange process in a cowper heater is possible with the correct prediction of the behavior of the working fluid in a porous medium. The correct description of thermophysical processes, and hence the determination of the integral parameters of the device is entirely possible only with the use of reliable mathematical models.

One of the approaches to describe the properties of a porous medium is based on its representation as a continuous medium with some effective characteristics [7]. Theoretical and experimental approaches can be used to determine the thermal, hydraulic and integral characteristics of the porous medium.

The theoretical approach can be divided into two methods: the exact solution of differential equations and numerical modeling. The first method is a procedure of averaging the equations of conservation of mass, momentum and energy by volume containing a set of layers of ball packed bed and a certain volume of gas between them. The obtained differential equations represent the relationship between the characteristics of the porous medium (average gas flow rate, solid and gas temperature, gas pressure) in the form of integrals over the surface and volume of the porous layer [8]. Direct calculation of these integrals is quite laborious, so the created mathematical models are one-dimensional and do not take into account a number of phenomena occurring in a porous medium. In this regard, this approach is used to determine the integral unsteady characteristics of the heat exchanger, namely for a porous medium.

The second method is a numerical simulation that allows to obtain not only the integral characteristics, but also to visualize the processes of flow and heat transfer in a porous medium, to identify their features. The use of numerical simulation is complicated by the need to use correct mathematical models describing the interaction in a porous medium. The equations of randomly packed layers are based on physical laws corrected by empirical coefficients determined from experimental studies on laboratory models [9]. In the constructive design of complex technical systems, numerical simulation is the only way to more detailed analysis of the processes occurring in such systems.

Several "theoretical" studies of thermal behavior in packed bed can be found in the literature. In [10] the study of the influence of the filling layer size, fluid flow, particle material and diameter on the thermal behavior of the Packed layer up to 550°C. The one-Dimensional two-phase model with constant properties of liquid and solid, including thermal losses in the side walls, was tested through an experimental installation with a packed layer of steatite using air.

Commercial package CFD Ansys Fluent was used to study the effect of radiation heat transfer, mass flow in two different types of porous media: Packed layer and honeycomb [11-12]. The model considered the geometry of the cylindrical system, the thermophysical properties of the liquid and solid did not depend on the temperature and the influence of heat losses in the side walls on the performance of the heat exchanger at a maximum liquid temperature of 1200°C. Another study was devoted to the behavior of a high-temperature mining system of a heat exchanger using air, taking into account the influence of variable porosity and thermal conductivity [13]. Good agreement between unsteady 3D CFD simulation results and experimental data allowed the authors to assess the importance of radiation heat transfer even at a relatively low temperature (300-350°C) for the energy efficiency of the heat exchanger [14]. The results of the model with two equations were compared with experimental data obtained for a vessel filled with alumina balls using air [15]. The transition temperatures of the liquid and solid in the axial direction of the layer were estimated, while in this case the radial temperature gradient was considered insignificant. The paper [16] presents a comparison of CFD methods and experimental results obtained for the energy storage system with alumina balls. The computational domain in the simulation is represented by an axisymmetric cylindrical tank filled with a porous medium. To calculate the temperature of liquid and solid phases in a porous medium, the authors use a model of local thermal equilibrium, the results show a good agreement with the experiment. In [17], the heat storage system was analyzed using a numerical model that takes into account the constant properties of a liquid and a solid body, neglecting thermal losses.

In the present study, a one-dimensional mathematical model of unsteady heat transfer in a porous medium (a modified Schumann model) was developed, taking into account the thermal losses in the walls of the cowper heater. With the help of the software package CFD Ansys Fluent, calculations of
heat transfer and hydrodynamics in a unsteady two-dimensional formulation were performed, taking into account the design features of the cowper heater. A two-component non-equilibrium model (local thermal non-equilibrium LTNE) was used to calculate the temperature of the gas flow and the temperature of the solid in a porous medium. The influence of empirical coefficients on heat transfer is revealed. A comparison of the results of a one-dimensional mathematical model with the results of numerical simulation is presented and a conclusion is made about the use of an approach to the description of unsteady heat transfer in a porous medium.

2. Mathematical model

2.1. One-dimensional mathematical model of heating of the heat-accumulating packed bed taking into account a heat sink in walls

After a certain volume filled with a porous medium that accumulates heat and having at the initial time a temperature of \( T_{\text{in0}} \), a hot gas begins to flow with a temperature at the inlet to the medium \( T_{\text{in}} \). Gas, passing inside the porous medium, washes the surface and gives part of its heat to the porous matrix, which is heated. The gas is cooled accordingly.

The calculation scheme for this mathematical model is shown in figure 1. The OX axis is directed from top to bottom along the direction of the gas flow through the porous medium. Combustible gas with mass flow rate \( G \) and initial temperature \( T_0 \) in the initial section \((x = 0)\) comes from above (red arrow) and flows down through the porous medium. Giving part of its heat, the cooled gas flows down (blue arrow) from the porous medium. The temperature of the filling elements at the initial time \((t = 0)\) is \( T_{\text{in0}} \). Denote the temperature of the gas in the section \( x \) at time \( t \) through \( T(x,t) \), and the temperature of the filling elements through \( T_{\text{in}}(x,t) \).

![Figure 1. Calculation scheme.](image)

Put the porosity of the filling as the ratio of the volume of pores to the total volume:

\[
\varphi = \frac{V_p}{V}
\]

and, accordingly, the volume fullness of the solid phase:

\[
n = \frac{V_{\text{in}}}{V} = 1 - \varphi
\]

In [8] it is shown that, depending on the method of packing of ball filling elements, the porosity can take values in the range from \((1 - \pi/6) \approx 0.48\) for cubic packing to \((1 - \pi/3\sqrt{2}) \approx 0.27\) for the densest tetrahedral packing. The relative cross-section \((1 - \pi/4) \approx 0.21\) or \((1 - \pi/2\sqrt{3}) \approx 0.09\).

Washed surface per unit length of ball elements:

\[
S = \frac{6nF}{d},
\]
When heating the elements of the cowper heater, the boundary condition for the gas temperature and the initial condition for the ball filling temperature can be written as follows:

\[ T(0, t) = T_0 \]
\[ T_n(x, 0) = T_{n0} \]  

(4)

We write down the first beginning of thermodynamics [18]:

\[ dh_0 = \delta q \]  

(5)

where \( h_0 \) is the total enthalpy of gas; \( \delta q \) is the supply or removal of heat. The movement of gas through a porous medium, in this case through a ball packed bed occurs at significantly subsonic speeds (Mach number \( M \ll 1 \)), so you can take:

\[ dh \approx dh_0 = \delta q \]  

(6)

Moving to the Euler variables, assuming the gas is perfect and taking into account that the enthalpy of the perfect gas \( h = c_p T \), we obtain (the heat sink in the wall is taken into account by the heat transfer coefficient):

\[ \frac{\partial T}{\partial x} = -\frac{\alpha \cdot S}{G \cdot c_p} (T - T_n) - \frac{k \cdot S_w}{G \cdot c_p} (T - T_c) \]  

(7)

g where \( G \) – the mass gas flow rate, [kg/s]; 
\( c_p \) - specific heat of gas at constant pressure, [J/kgK]; 
\( \alpha \) - heat transfer coefficient, [W/m²K]; 
\( S \) – washed by the surface of the packed bed, per unit length, [m²/m],
\( k \) - coefficient of heat transfer from gas to cooler through the wall, [W/m²K]; 
\( S_w \) – washed surface of the cowper wall per unit length, [m²/m]; 
\( T_c \) – temperature of the cooler (water), [K].

To derive the equation for the temperature of the filling elements, we assume that the ball elements touch each other at the point, and the heat transfer from the element to the element through the touch point does not occur (the approximation of the absence of heat conduction effects in the solid matrix). Then

\[ \frac{\partial T_n}{\partial t} = -\frac{\alpha \cdot S}{n \cdot \rho \cdot F \cdot C} (T - T_n) \]  

(8)

where \( n \) – filling of the ball filling, determined by the formula (2); 
\( \rho \) – density of the filling material, [kg/m³]; 
\( C \) - heat capacity of filling material, [J/kgK].

After otraslevaya given \( T_c = T_{nc} \) equations take the following form:

\[ \frac{\partial T}{\partial x} = -A_1 (\bar{T} - \bar{T}_n) - A_2 \bar{T} \]

\[ \frac{\partial \bar{T}_n}{\partial t} = B (\bar{T} - \bar{T}_n) \]  

(9)

\[ A_1 = \frac{\alpha \cdot S \cdot L}{G \cdot c_p} \]
\[ A_2 = \frac{k \cdot S_w \cdot L}{G \cdot c_p} \]
\[ B = \frac{\alpha \cdot S \cdot \tau}{n \cdot \rho \cdot F \cdot C} \]
where \( L \) – the characteristic length, for example, packed bed length, [m];
\( \tau \) - characteristic time, for example, the warm-up time of packed bed, [s];

The transition to Laplace images gives:

\[
pF - 1 = -A_1(F - H) - A_2F
\]

\[
H_t = B(F - H)
\]

Expressing from the first equation \( F \) and substituting into the second, we obtain:

\[
H\tilde{t} = \frac{B}{p + A_1 + A_2}
\]

with initial conditions:

\[
H(p, 0) = 0
\]

The solution to the problem are the functions:

\[
H(p, \tilde{t}) = \frac{1}{p + A_2} - \frac{1}{p + A_2} e^{(p + A_2)B\tilde{t}}
\]

\[
F(p, \tilde{t}) = \frac{A_1}{p + A_1 + A_2}H - \frac{1}{p + A_1 + A_2}
\]

Solution (13) satisfies the conditions of existence of the original image. Using the rules of finding the originals [19] and table [20], we obtain a solution for the dimensionless temperature of the gas and filling elements:

\[
\bar{T}(\bar{x}, \bar{t}) = e^{-A_2\bar{x}} - e^{-B\bar{t}} \cdot A_1 \cdot \int_0^{\bar{x}} e^{-A_2\xi} e^{-(A_1 + A_2)(\bar{x} - \xi)} \cdot I_0(2\sqrt{A_1Bt} \cdot \sqrt{\bar{x} - \xi}) \, d\xi
\]

\[
\bar{T}_n(\bar{x}, \bar{t}) = e^{-A_2\bar{x}} - e^{-B\bar{t}} \cdot e^{-(A_1 + A_2)\bar{x}} \cdot I_0(2\sqrt{A_1Bt} \cdot \sqrt{\bar{x}}) - A_1 \cdot e^{-B\bar{t}} \cdot \int_0^{\bar{x}} e^{-A_2\xi} e^{-(A_1 + A_2)(\bar{x} - \xi)} \cdot I_0(2\sqrt{A_1Bt} \cdot \sqrt{\bar{x} - \xi}) \, d\xi
\]

where \( I_0(x) \) – modified Bessel function of the first kind.

Thus, a solution is found in quadratures for a system of partial differential equations expressing a mathematical model of heating the heat-accumulating packed bed taking into account the heat sink in the walls of the cowper heater.

2.2. One-dimensional mathematical model of cooling of the heat-accumulating packed bed taking into account a heat sink in walls

The mathematical model of cooling the heat-accumulating packed bed is described by similar partial differential equations as the mathematical model of heating (9), but with other boundary and initial conditions:

\[
\bar{T}(0, \tilde{t}) = 0
\]

\[
\bar{T}_n(\bar{x}, 0) = 1
\]

The course of further transformations is similar to the above for the mathematical model of heating the heat-accumulating packed bed. The result is the following expressions for the originals:
\[ T(\tilde{x}, t) = e^{-Bt} \cdot A_1 \cdot \int_0^x e^{-\frac{(A_1+A_2)(x-\xi)}{2}} \cdot I_0(2\sqrt{A_1Bt} \cdot \sqrt{\xi}) \, d\xi \]

\[ T_n(\tilde{x}, t) = e^{-Bt} \cdot e^{-\frac{(A_1+A_2)x}{2}} \cdot I_0(2\sqrt{A_1Bt} \cdot \sqrt{x}) + 
+ (A_1 + A_2) \cdot e^{-Bt} \cdot \int_0^x e^{-\frac{(A_1+A_2)(x-\xi)}{2}} \cdot I_0(2\sqrt{A_1Bt} \cdot \sqrt{\xi}) \, d\xi \]

### 3. Numerical model

Heat exchange processes and flow in the cowper air heater have a number of features associated with the design and operating modes: the presence of a large internal space, boundary phenomena associated with the entry of gas into a porous medium occupied by a porous volume; the presence of a pressure drop caused by the resistance of the bulk layers; relatively low gas flow rates through the free internal volume and through the filling; non-equilibrium nature of the temperature distribution of the gas and the filling material, both in time and in the thickness of the layers.

Modern numerical simulation tools allow to simulate not only the flow and heat exchange in the main volume of the cowper heater, but also to take into account the design and operating features, which gives a more complete picture of the processes occurring in the heater.

The results of numerical simulation are obtained using the commercial software package CFD Ansys Fluent.

The geometric model is a two-dimensional axisymmetric cylindrical tank with an internal diameter of 220 mm and a height (only the volume occupied by the heat-accumulating packed bed is taken into account) of 1800 mm. A structured computational grid adapted to the surface for the resolution of thermal and dynamic boundary layers is constructed. The total number of elements amounted to approximately 35 thousand. The minimum cell size was determined by examining grid convergence.

Flow and heat transfer in a porous medium is modeled by the equations of continuity (17), momentum (18) and energy. The momentum equation takes into account the viscous and inertial dissipation of the momentum.

\[
\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = 0
\]

\[
\rho f (\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v}) = -\rho \nabla p + \rho \mathbf{v} \frac{\partial \mathbf{v}}{\partial t} + \frac{\mu}{K} \nabla^2 \mathbf{v} + \rho F \frac{\sqrt{\mathbf{v} \cdot \nabla} \mathbf{v}}{d^3}
\]

where \( K \) is the permeability and \( F \) is the inertial coefficient:

\[
K = \frac{150(1-\varphi)^2}{d^2}
\]

\[
F = \frac{3,5}{d} \frac{(1-\varphi)}{d^3}
\]

There is a significant gradient between the gas temperature and the packed bed temperature, that is, the temperature difference between the solid and gas phase must be taken into account in the calculation. Thus, the porous medium and the gas are not in thermal equilibrium (local thermal non-equilibrium LTNE), so the double cell approach is used. This approach involves the separation of a region of the solid phase that spatially coincides with the region of the gas phase, and this solid phase interacts with the gas with respect to heat transfer. The energy conservation equations are solved separately for the solid and gas phases. The energy conservation equations for gas (19) and solid (20) are presented as:

\[
\frac{\partial}{\partial t}(\rho f T_f) + \nabla \cdot (\rho f \mathbf{v} T_f + p) = \nabla \cdot (\rho f c_p \nabla T_f - \sum_i h_i \mathbf{j}_i + (\mathbf{v} \cdot \mathbf{v}) + S_i^f + h_f A_f (T_s - T_f))
\]
\[
\frac{\partial}{\partial t} (1 - \gamma) \rho_s E_s = \nabla \cdot \left( (1 - \varphi) k_s \nabla T_s \right) + S^h_f + h_{fs} A_{fs} (T_f - T_s)
\]

where
\[E_f\] – the total energy of the gas;
\[E_s\] – the total energy of the solid phase;
\[\rho_f\] – gas density;
\[\rho_s\] – the density of the solid phase;
\[\varphi\] – the porosity of the medium;
\[k_f\] – thermal conductivity coefficient for gas (including turbulent thermal conductivity \(k_t\));
\[k_s\] – thermal conductivity coefficient of solid phase;
\[h_{fs}\] – internal heat transfer coefficient between gas and solid phase;
\[A_{fs}\] – interphase specific area, that is, the ratio of the area of gas and solid to the volume of the porous zone;
\[T_f\] – the temperature of the gas phase;
\[T_s\] – the temperature of the solid phase;
\[S^h_f\] – source member of enthalpy in liquid medium;
\[S^h_s\] – source term of enthalpy for solid phase.

In contrast to the one-dimensional mathematical model of heat distribution in a porous medium is also using the mechanism of thermal conductivity, that is, the transfer of heat between the filling elements. Since the porous medium and the liquid are not in thermal equilibrium, the heat transfer coefficient \(h_{fs}\) is specified in the program. The heat transfer coefficient is obtained using criterion dependences [21]. Changing the intensity of heat transfer between the gas and the solid (that is, changing \(h_{fs}\)) under equal temperature conditions and filling parameters can be adjusted by changing the gas flow rate.

Initial and boundary conditions are determined depending on the operation mode of the cowper heater. At the heating mode, the temperature of the heat-accumulating filling and gas is taken to be the minimum \(T_{min}\), the total pressure in the volume of the heater is taken to \(P\), at the input boundary is set to \(T_0\) and \(G\). The temperature, pressure distribution obtained at the end of the mode is used as the initial condition for the cooling mode. The input boundary "swaps" with the output boundary, and the gas flow comes from the output boundary with a minimum temperature of \(T_{min}\). On the walls of the cowper heater, a boundary condition of 3 kinds is set, taking into account the thermal losses to the environment. The variability of the thermophysical properties of the gas is taken into account by the polynomial dependence on temperature.

4. Results

Numerical modeling and calculation on one-dimensional mathematical model both for a heating mode, and for a cooling mode are carried out. As a heat-accumulating packed bed, ball elements made of corundum are used. The following parameters specified in tables 1 and 2 were used for the calculations.

| Table 1. The value of the parameters for the heating mode. |
|-----------------------------------------------|
| \(\varphi = 0.35\) | porosity ratio |
| \(G = 0.1\) kg/s | Mass flow rate |
| \(\alpha_1 = 145\) W/m\(^2\)K | Heat transfer coefficient of filling elements |
| \(\alpha_2 = 100\) W/m\(^2\)K | Heat transfer coefficient to the wall |
| \(\lambda_w = 20\) W/mK | Coefficient of thermal conductivity of the wall |
| \(\delta_w = 10\) mm | Wall thickness |
\[ \alpha_c = 10000 \text{ W/m}^2\text{K} \]

Heat transfer coefficient of a wall with the cooler

\[ \tau_0 = 3000 \text{ s} \]

Characteristic time

\[ T_{\text{min}} = 300 \text{ K} \]

Minimum filling temperature

\[ T_0 = 1650 \text{ K} \]

Maximum gas temperature

\[ P = 10^5 \text{ Pa} \]

Total gas pressure

Table 2. The value of the parameters for the cooling mode.

| Parameter | Value |
|-----------|-------|
| \( \varphi \) | 0.35  |
| \( G \) | 0.2 kg/s |
| \( \alpha_1 \) | 184 W/m\(^2\)K |
| \( \alpha_2 \) | 100 W/m\(^2\)K |
| \( \lambda_w \) | 20 W/mK |
| \( \delta_w \) | 10 mm |
| \( \alpha_c \) | 5000 W/m\(^2\)K |
| \( \tau \) | 1500 s |
| \( T_{\text{min}} \) | 300 K |

\[ \tau = 7 \text{ s} \]

\[ \tau = 54 \text{ s} \]

\[ \tau = 138 \text{ s} \]

Figure 2 shows the distribution of the gas temperature in a porous medium at different times for the heating mode obtained using numerical simulation. As you can see, the temperature gradient in the axial direction between the packed bed layers is most pronounced at the beginning of the cowper heater, as it warms up, approaching the exit, it is less noticeable. The temperature of the flow near the wall is noticeably lower and in the radial direction there is a temperature gradient increasing towards the outlet, apparently this is due to the influence of the wall.

Figures 3 - 6 show a comparison of the gas temperature at the outlet of the filling and the gas temperature along the length of the cowper heater, obtained using a one-dimensional mathematical model and numerical simulation.
Figure 3. The change of dimensionless gas temperature at the outlet of the packed bed during the heating period.

Figure 4. The change in the dimensionless temperature of the gas during the heating step.
As can be seen from the presented graphical dependence, the results are quite well coordinated qualitatively. There are differences in quantitative indicators. In the heating mode, the temperature at the outlet of the packed bed obtained numerically differs from that obtained by the one-dimensional method, which is due to some temperature irregularity in the radial direction, which can be seen in figure 3. It is also worth noting that the process described by the one-dimensional mathematical model enters the stationary mode with some delay from the process described numerically. This is due to the fact that the one-dimensional mathematical model does not take into account the heat propagation associated with the heat conduction mechanism. Also it is noticeable on the chart the temperature of the gas along the length of the packed bed. The increase in the gas flow rate leads to an increase in the heat transfer coefficient between the filling and the gas, which affects the heating/cooling time of the filling, so the cooling mode of the heat accumulating filling is faster than the heating mode.
This qualitative discrepancy of results can be excluded. The heat transfer coefficient in a one-dimensional mathematical model is a multiparameter value, changing which can be varied by the intensity of heat exchange and the nature of the behavior of the temperature distribution. A comparison of the temperature at the outlet of the filling, obtained numerically, with the temperature obtained by a one-dimensional model with a modified heat transfer coefficient $\alpha_1$, obtained a qualitative coincidence of the results. Heat transfer coefficients $h_{fs}$ and $\alpha_1$ have a difference of 16%.

5. Conclusion
As a result of this work, the peculiarities of heat exchange processes in a porous medium are established. Two approaches were used for this purpose: exact solution of differential equations and numerical modeling. As a result of solving differential equations, an unsteady solution for the temperature of the gas and the porous medium in quadratures is obtained. It is shown that the behavior of this dependence is determined by the empirical coefficients included in the dimensionless complex of parameters. The double cell approach used in the numerical simulation of heat transfer in a porous medium, which is based on the lack of thermal equilibrium between the porous medium and the gas, also showed a strong influence of empirical coefficients. A comparative analysis of two different approaches revealed that using a one-dimensional mathematical model, it is possible to accurately describe the temperature behavior of gas and backfill, taking into account the influence of different mechanisms of heat transfer and the multidimensionality of the process in the heat transfer coefficient.

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