Development of a model for the study of methods of intensification of heat exchange processes

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Abstract. The research results of the convective heat transfer process and determination of the heat transfer coefficient in order to select effective ways to increase its intensity are presented. A physical model for obtaining experimental data is designed. It is shown that the mathematical description of the process belongs to the class of inverse problems of heat conductivity. The article proposes a solution algorithm based on the use of numerical methods. A computer model is developed that allows to obtain a solution in a real time mode. It includes a module for reading data coming to computer ports from sensors, a calculation module, a visualization and saving results module, and tools for user convenience. It is shown that the obtained solution can be used to study ways to increase intensity of heat transfer when designing equipment in chemical engineering and machine building.

1. Introduction

In chemical engineering and machine building various methods of intensification of heat exchange processes are used. In those cases where it is appropriate, and conditions of the technological process and design features of a particular apparatus allow, heat exchange equipment is supplemented with special technical devices designed to improve the efficiency of heat exchange processes. As a rule, such method always justifies itself, because an increase in efficiency of only a few percent leads to an annual economic effect, estimated at millions of rubles. In this regard, it is of interest to consider the choice of the most rational methods for increasing the efficiency of chemical and petrochemical equipment based on the search for the most optimal ways to intensify heat exchange processes.

As it is known, all methods of intensifying heat exchange processes can be divided into two large groups: active and passive methods. Methods belonging to the first group are more difficult to implement and cannot always be used in practice due to the characteristics of a particular technological process or the hardware design of a production plant. Despite this, active methods have great potential and, in the opinion of many researchers, are extremely promising and are being actively studied. For example, in work [1], a method for intensifying heat transfer through the use of an acoustic wave generator is proposed. The authors presented a numerical model, provided evidence of its adequacy, and compared the results with experimental data. The modelling was performed using CFD Ansys CFX-16.0 computer program. It is shown that such a method can significantly improve a convective heat transfer. Among active methods are also methods using effects on the flow of electromagnetic waves, and vibration.
Passive methods of heat transfer intensification are widely used, including the petrochemical industry. The methods of this class are based on embedding devices for local turbulization of the laminar stream of a heat carrier into the heat exchangers, such as various swirlers, diaphragms, and periodic transverse rolling of pipes. In the wall region of the cylindrical channel, turbulization destroys the boundary laminar layer, which has high thermal resistance, which increases the heat transfer of the surface. For example, in work [2], the efficiency of using an intensifier of the type 'rib-twisted wire' is shown. Research published in [3] showed that it is possible to improve the heat transfer intensity by installing circumferential fins on the outer surface. Besides, the work showed that the best results can be achieved with low Reynolds numbers.

It is obvious that the choice of a specific embodiment of the intensification method strongly depends on the problem to be solved, the features of an apparatus, its location on the site, relationship with other elements of the chemical installation. However, in any case, in order to study acceptable methods for improving the efficiency of heat exchange equipment, one should begin by developing a reliable method of recording research results.

This paper showed the results of solving these problems. Numerical data were obtained from the results of numerical modeling and a full-scale experiment, statistical processing was performed, a sufficiently high adequacy of the models was shown. Tasks were set for the implementation of the next work stage related to the study and selection of the most rational methods of heat exchange intensification from the point of view of petrochemical equipment used at the enterprise.

The mathematical basis of the process under study is a differential equation of transient heat conductivity, which is a second-order equation in partial derivatives, supplemented by initial and boundary conditions. The task of studying the heat transfer intensity is reduced to determining the heat transfer coefficient on the basis of solving the inverse problem of heat conductivity, which is a mathematical model of the incorrectly stated Cauchy problem [4]. According to Hadamard [5], the task is considered correct if three conditions are fulfilled: the existence of a solution, its uniqueness, and stability. The task under consideration satisfies the first two conditions, but does not satisfy the third and, accordingly, can be considered incorrect. The peculiarity of incorrect tasks is that the accuracy of their solution especially depends on measurement errors. To obtain a practical result, solutions based on the Duhamel convolution integral are most often used - in cases where the problem is linear, or of finite-difference approximation methods and the finite element method when a nonlinear problem is solved. For linear problems, you can also use Laplace transformations.

For example, in [6], on basis of determining the temperature perturbation front and additional boundary conditions, an approximate analytical solution was obtained for the stationary heat exchange problem when a fluid flows in a cylindrical channel with a constant parabolic velocity profile (the Gretz – Nusselt problem), which allows to investigate the temperature distribution in the fluid in a wide range of distances from the entrance to the pipe, including small and very small distances. Such an approach made it possible to determine not only the thermophysical parameters, but also the velocity profile and fluid flow.

The solution of the inverse problem of heat conduction in order to determine the heat transfer intensity at the interface in the on-line mode, i.e. directly at the time of the experiment, as noted in [7], is associated with considerable difficulties. The authors of the paper argue that the difficulties are due to the fact that one has to introduce a simplifying assumption about the presence of thermal insulation on heat transfer surfaces, which can lead to a significant error. The solution to the problem was found by adding additional boundary conditions and developing an appropriate algorithm.

The article [8] is devoted to the definition of thermal parameters and the calculation of physical fields in numerical modelling by solving the inverse problem of heat conductivity. The paper presents a hybrid method (ZPSO) based on the particle swarm optimization algorithm (PSO), the normal distribution method and the finite element method (FEM). The essence of the hybrid method is that to solve the inverse problem of heat conductivity, an equivalent process is modelled that requires solving the direct problem of heat conductivity, the parameters of which can be considered as the desired
solution. Analysis of the results shows that convergence of the hybrid method is good, and the rate of convergence is accelerated through the use of ZPSO method.

If the change in the temperature of the heat carrier in time is significant, the inverse problem of heat conductivity becomes nonlinear due to variability of thermophysical properties as the temperature changes and occurrence of boundary radiation conditions. In study [9], to solve the problem, it is proposed to use the Kalman smoothing algorithm (extended Kalman filter). To restore the non-uniform heating conditions on the front surface of the cylindrical sample and to calculate several process parameters, a solution using several sensors is proposed. The paper shows that with such an approach a noticeable decrease in the time lag and a decrease in sensitivity to measurement errors are observed.

The algorithms used to solve problems of intensification of heat exchange processes are in many ways similar to the algorithms for solving problems of intensification of mass exchange processes [10], and the methods for solving mathematical models can be used almost unchanged as external libraries of subprograms.

2. Experimental part
In our work, we developed a solution to two problems: heat transfer for a flat plate and a hollow cylinder. The solution for a flat plate washed by the streams on the left and right walls is obtained on basis of a finite-difference approximation, when the time derivative decomposes into the left difference, and the second derivative with respect to the coordinate - into the central one. The origin of coordinates is located in the geometric center of the plate. Besides, the problem formulation and its solution is carried out in a dimensionless system of quantities. To simplify the solution, as well as to obtain a solution in a generalized form as the desired function, it is useful to use a relative (with respect to the full amplitude of temperature change) and an excess (with respect to the ambient temperature) temperature, which is called a dimensionless temperature:

$$\theta(\tau, x) = \frac{T(\tau, x) - T_{f2}}{T_f - T_{f2}}$$

Then the heat conductivity equation for the problem to be solved in a one-dimensional formulation will be as follows:

$$\frac{\partial^2 \Theta}{\partial \tau^2} = a \frac{\partial^2 \Theta}{\partial x^2}$$

where $a$ (m²/s) is the coefficient of thermal diffusivity of the wall material, which characterizes the material in terms of the rate of a transient temperature field change in it, and can be calculated through the thermal characteristics:

$$a = \frac{\lambda}{c \rho}$$

The boundary conditions after the finite-difference approximation will be written in a dimensionless form as follows:

right boundary:

$$\theta_n^j = \frac{1}{1 + Bi_{f2}} \theta_n^1 + \frac{Bi_{f2}}{1 + Bi_{f2}} \theta_{f2}$$

left boundary:
\[
\theta_i = \frac{1}{1 + Bi_1} \theta_i + \frac{Bi_1}{1 + Bi_1} \theta_f
\]  

(5)

where \( Bi_1 \) and \( Bi_2 \) are Biot criteria calculated, respectively, through heat transfer coefficients on the left and right walls.

\[
Bi_1 = \frac{\alpha_1 \Delta x}{\lambda} \quad Bi_2 = \frac{\alpha_2 \Delta x}{\lambda}
\]

(6)

The Biot criterion is the ratio of thermal resistance of a solid to the resistance of heat transfer on the surface. However, in this case, formulas (6) are obtained as a result of a finite-difference approximation, and instead of the plate thickness \( h \), they include an elementary step in \( \Delta x \) coordinate. This allows us to consider values (6) to be some local Biot criteria for an elementary volume located at the interface between the media.

The initial condition in a dimensionless form is written as follows:

\[
\theta(0,x) = \frac{T(0,x)}{T_{f1}} \frac{T_{f2}}{T_{f2}}
\]  

(7)

The numerical value of the initial temperature is equal to the value lying within the interval \([0..1]\).

After performing the finite-difference approximation procedure, the heat conductivity equation (2) takes the following form:

\[
\theta_i' + (2 + \frac{1}{Fo}) \theta_i' = \frac{1}{Fo} \theta_f
\]

where \( Fo \) is the Fourier criterion, but calculated not by the characteristic time and geometric size, but obtained during the finite-difference approximation by an elementary step in time and coordinate. In this case, it represents a dimensionless time step:

\[
Fo = \frac{a \Delta \tau}{\Delta x^2}
\]

(9)

To solve the problem with obtaining numerical results, it was decided to use the marching method of calculation using the T-shaped D’Souza pattern. The solution algorithm is presented in Figure 1.

Equation (2) can be solved by an asymptotic method - by expanding it into an infinite trigonometric Fourier series:

\[
\theta(\tau, x) = 2 \sum_{k=1}^{\infty} \frac{\sin \mu_k}{\mu_k + \sin \mu_k \cos \mu_k} \cos \left( \mu_k \frac{x}{R} \right) \exp \left( \mu_k^2 \frac{a \tau}{R^2} \right)
\]

(10)

where \( \mu_k \) are integration constants. As the number of members in the series is infinite, the number of constants is also infinite. In practical solutions, the number of members of the series is limited based on the required accuracy of the solution.

Integration constants can be calculated numerically. A graphical interpretation of the problem of finding constants is shown in Figure 2. The intersection point of the graph of function \( \cotg(\mu) \) and straight line \( (\mu/Bi) \) gives the integration constant for the current component of range \( k \).

Comparison of solutions for a flat plate made by numerical and asymptotic methods shows their good agreement.
Similarly, a solution is developed in a cylindrical coordinate system, which is necessary for describing the process of heat conductivity in pipes. The physical model is a two-layer cylinder made of two polypropylene pipes of RF standard GOST 26996–86. Polypropylene has a significantly lower thermal conductivity compared to metals, which gives a significant temperature difference in thickness and is very convenient for solving the modelling problem. The scheme of assembly is shown in Figure 4. Pipe 1 with an outer diameter of 25 mm with a small gap enters pipe 3 with an outer diameter of 40 mm. In the gap with a small local recess, temperature sensor 6 is placed. To eliminate the influence of thermal resistance of the air remaining in the gap, it is filled during assembly with a layer of thermal paste 2 used in computer technology to ensure reliable thermal contact between the central processor and the cooling radiator of the personal computer.

Temperature sensors 4 and 5 are used to monitor the temperature of the heat carrier inside the pipe, as well as to measure its speed. After feeding the Δ-perturbation at the pipeline inlet, it passes through both sensors successively with some delay. The time difference recorded by the program between the passage of the first sensor $t_1$ and the second sensor $t_2$ allows it to calculate the speed of the heat carrier. Due to the fact that the Δ-perturbation shape moving in a pipe approaches the shape of a sinusoid, the time values corresponding to the peak temperatures are taken to calculate moments $t_1$ and $t_2$ (Figure 3). Another sensor monitors the ambient temperature.
DS18B20 digital converters based on One-Wire technology can be conveniently used as temperature sensors. One-Wire is a bidirectional communication bus for devices with low-speed data transfer, where data are transmitted along the power circuit. It is usually used to communicate with inexpensive simple devices, such as, for example, digital thermometers and measuring instruments for environmental parameters.

Sensor systems are connected by One-Wire components, each of which includes everything necessary for the functioning of One-Wire bus. They are connected to a PC using bus converters. One-Wire devices are very convenient for measurements. They do not require a separate power supply, you can connect a whole string of various sensors to the same wire.

Measured signals transmitted over a single bus are fed to one port of a personal computer. This eliminates the need for additional switches. The disadvantage of this protocol is reduction in the speed of data exchange with the receiving device when several sensors are connected. Therefore, the developed measuring circuit includes two separate buses connected to different ports of the computer. After installing the device driver, the numerical values of the signals are available for reading by the program from the corresponding ports of the computer.

The calculation of heat transfer coefficients on the cylinder surfaces is made on basis of the solution of the inverse heat conductivity problem by reconstructing the temperature profile according to the wall thickness and the measured value detected by sensor 6 placed at a known depth inside the wall. Calculations, output, visualization in a graphical form and saving of the results is performed by the same program that reads data from the ports of the computer. The program is designed on a modular basis in an object-oriented environment, has a convenient user interface, and designed to work in the most common operating system.

3. Conclusions
As a result of the research, a solution to a mathematical model was proposed that allows to calculate the heat transfer coefficient based on the results of measuring the temperature inside the wall according to the numerical solution of the inverse problem of heat conductivity. A physical model was designed for testing, equipped with the necessary measuring apparatus using digital temperature sensors. A computer program was developed that allows to model the heat exchange process, to solve the inverse heat conductivity problem numerically, reading the signal values from the temperature sensor, and to output calculation results in text and graphic forms. Using the method of least squares, the program brings the calculated graph (Figure 3) to the reference points determined during the temperature measurement inside the wall by sensor pos. 6. If you do not use experimental data, the program can model the temperature distribution inside the wall and display the process of temperature...
change over time at any internal point under any heat exchange conditions in the internal channel (Figure 4).

![Graph of temperature change over time](image)

**Figure 4.** Calculated graphs of temperature changes of sensor pos. 6 depending on the change in the heat transfer intensity at the boundaries

The peculiarity of the device of this physical model suggests that the temperature sensor is located closer to the internal channel of the pipe. The effect of heat transfer conditions on the outer surface is less pronounced. For example, Figure 5 shows the graphs of the difference between calculated temperatures with increasing heat transfer rate on the outer wall of the hollow cylinder.

The research conducted using polypropylene pipes showed that, firstly, this material is convenient for studying the heat exchange process, and secondly, it may be of interest in some practical cases of designing heat exchanging equipment, despite its low thermal conductivity, rigidity and strength.

![Graph of temperature change over time](image)

**Figure 5.** Graphs of changes in the difference of calculated temperatures with an increase in the intensity of heat transfer on the outer surface.

It is supposed to use the obtained solutions within the framework of the research on the topic of the master’s thesis to study rational ways of increasing the intensity of heat transfer in the chemical and petrochemical industries.

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