ELECTRIC HEATER MATHEMATICAL MODEL FOR CYBER-PHYSICAL SYSTEMS

N. PANKRATOVA, I. GOLINKO

Abstract. The article discusses the heat and mass transfer dynamic model for an electric heater with lumped parameters, which allows transient processes simulation for the main influences. The proposed model is recommended to be used in cyber-physical systems for forecasting and evaluating the effectiveness of control systems integrated into a single information management system. The developed model can be used by specialists for the analysis and synthesis of control systems for balanced ventilation systems or industrial air conditioners. As an example, a numerical simulation of transient processes along the action main channels for an electric heater HE 36/2 manufactured by VTS CLIMA was carried out. The significant advantage of the proposed model is the possibility for using it for the synthesis and analysis of multidimensional control systems.

Keywords: cyber-physical system, digital twin, mathematical model, state space, electric heater.

INTRODUCTION

In the modern world, the managing technical systems tasks are closely intertwined with the social sphere of human activity. The growth and complexity of management situations in technical systems requires the use of new scientific approaches to management. The computer-integrated control systems properties study from the interaction view point of physical and computational component is a priority in the modern science about cyber-physical systems [1]. To date, such systems have not yet received a generally accepted definition, since they lie at the intersection of several human spheres of activities. Their common characteristic is the interaction between computing and physical processes, where the computing system constantly receives data from the environment and uses them to further optimize the physical processes control. Cyber-physical systems include, for example, networked intelligent control of power supply or transport, automated control systems in production and agriculture, and much more.

While designing cyber-physical systems, it is necessary to solve a variety of interrelated problems. One of the important tasks is the development of real object’s digital twin based on mathematical modeling [2, 3]. A digital twin is a digital model obtained based on information from sensors installed on a physical object, which allows you to simulate object’s behavior in the real world. Fundamentally, a digital twin can be defined as an ever-changing digital profile containing historical and most current data about a physical object or a production...
process. The digital twin is created to predict the real object’s behavior in the “virtual space” and to adopt a control strategy. Sometimes the time required to simulate a mathematical model can exceed the physical process flow, and the calculated data becomes outdated. For this reason, the adequate mathematical models’ development for technical systems that can be used for calculations in “real time” is an urgent task.

The heat power industry plays an important role in modern society as a tool for creating material wealth and a means of servicing human life. The one of main units in heat power engineering is a heat exchanger, which takes on “various forms” in a particular human activity area. Heat exchangers include heaters, which are designed to heat the air due to the heat flow from the primary heat transfer fluid. In industry, air heaters are often used to heat air in heating, ventilation, air conditioning systems, various dryers and other technical systems [4].

In the mining and coal industries, the most important underground mining task is to organize the effective ventilation [5]. This problem has both technical and economic aspects. In technical terms, the key issue in organizing the mine ventilation is heating the air supplied to the mine to the temperature above 0 °C (from +2 °C to +5 °C). For many decades, the main technical solution for heating the air supplied to the mine has been provided by the water heaters use. Despite the design simplicity, using water heaters creates a variety of problems associated with complex installation, water treatment, continuous maintenance, the danger of water freezing in heaters and, as a consequence, the need to maintain the supplied to the mine air temperature above the optimum level.

Recently, the industry began to use air heating systems, which have established themselves as fast-acting systems with low specific capital investments. For air heating of shopping and business centers, warehouses and industrial buildings, centralized ventilation and air conditioning systems are used, in which air heaters are the main equipment [6]. Residential air heating systems use low-power electric heaters with a distributed automatic control system [7].

Considering the above, in recent years, electric heaters of high power (up to 30 kW) are increasingly used for heating air in various industries. Electricity transportation has many advantages over other types of heat carriers, and the use of thermoelectric heaters (TEH) can significantly increase the air heater's efficiency and design air heaters with a wide heat output range. In addition, electric heaters are efficient at outdoor temperatures down to –50 °C and do not lose their functionality in the event of an emergency power outage.

**RESEARCH PROBLEM STATEMENT**

The aim of this publication is to develop the heat transfer process dynamic model for an electric air heater, which can be used as a digital twin for a cyber-physical system. An additional requirement for the mathematical model is its ease of use by existing modeling tools on a personal computer.

**HEAT TRANSFER PROCESS MATHEMATICAL MODELING**

Heat transfer processes are discussed in many publications. To simulate the dynamic processes in heat exchangers, researchers use mathematical models with lumped [8–10] and distributed [11, 12] parameters. Models with lumped parameters provide an analytical solution to the heat transfer task. Models with distributed parameters describe the physical process more accurately, but in the analyti-
cal modeling of such processes, transcendental functions appear in the solution [12], which complicates the calculations. In practice, numerical methods are used to solve distributed heat transfer problems.

The existing dynamic models of air heaters [8–12] are based on the mathematical description of the heat exchange process for devices where the primary heat transfer fluid is steam or water, since these devices have long been used in production as part of automatic control systems. For electric heaters, stationary models are known, which are used to design the equipment. Considering that recently, high-power electric heaters have been used in production as part of cyber-physical systems, we will develop the electric heater dynamic model.

ELECTRIC HEATER MATHEMATICAL MODEL

The modern electric heaters designs are based on blowing the air through a bundle of heating elements, while convective heat exchange is carried out between the moving air and the heater surface. Considering surface heat exchangers used in industrial systems, it is necessary to take into account that the air is intensively mixed by fans. Practical research of unsteady heat transfer characterizes the air heating process as clearly aperiodic [11], which is described with sufficient accuracy by second-order transfer functions. Thus, a lumped-parameter mathematical model for a water cooler would be perfectly acceptable.

When developing a mathematical model, the following simplifications were adopted: there is no heat exchange with the environment; the model contains two dynamic elements with lumped parameters – tubular electric heaters and the air volume of heater. Physical properties of material flows and the heat exchange surface are reduced to the average values of device’s operating range. The electric heater design diagram is shown in Fig. 1.

To heat the air in the heater, electric heaters are used, which are connected to the mains through a triac electrical converter. The electrical converter in proportion to the regulator signal changes the electrical power \( N_E(t) \), due to which the heating elements are heated to the temperature \( \theta_E(t) \). All electrical power is used to heat the air. Air is supplied crosswise to the electric heaters location with a flow rate \( G_A(t) \). The inlet air temperature is \( \theta_A(0) \), the outlet air temperature is \( \theta_A(t) \). The heater geometrical dimensions \( HCL, \) are the depth, width and height, respectively. Let us analyze the heat balance in the dynamics for each dynamic element of the air heater.

The heat balance for heating elements is:

\[
\frac{d}{dt} \Delta \theta_E = N_E - \alpha_0 F_0 (\theta_E - \theta_A) = M_E c_E \frac{d \theta_E}{dt},
\]

where \( c_E \) is the heat capacity of heating elements (heating elements contain metal and dielectric parts, so their heat capacity is averaged in proportion to the mass fraction of each part); \( M_E \) is the total mass of heating elements; \( \alpha_0 \) is the heat transfer coefficient between the air in the heater and the heating elements outer surface; \( F_0 \) is the heating elements surface ribbing total area. Let us present equation (1) in canonical form:

\[
T_E \frac{d}{dt} \Delta \theta_E + \Delta \theta_E = k_0 \Delta N_E + k_1 \Delta \theta_A,
\]
where $K_E = \alpha_0 F_0$; $T_E = \frac{c_E M_E}{K_E}$; $k_0 = \frac{1}{K_E}$; $k_1 = 1$.

Electric heaters are often used in air conditioning systems. For such systems, in addition to the temperature regime, it is also important to simulate the heated air humidity characteristics. It is known from the physical properties of air that with an increase in the vapor-air mixture temperature, its relative humidity decreases.

**Fig. 1.** Design diagram for modelling an electric air heater.

The heat balance for the air heater air space is:

$$G_A c_A (\theta_{A0} - \theta_A) + \alpha_0 F_0 (\theta_E - \theta_A) = M_A c_A \frac{d\theta_A}{dt},$$  

where $c_A$ is the air heat capacity; $M_A$ is the air mass in the heater volume $L \times C \times H$. After linearization, let us transform equations (3) to the canonical form:

$$T_A \frac{d \Delta \theta_A}{dt} + \Delta \theta_A = k_2 \Delta \theta_E + k_3 \Delta \theta_{A0} + k_4 \Delta G_A,$$

where $K_A = c_A G_A + \alpha_0 F_0$; $T_A = \frac{c_A M_A}{K_A}$; $k_2 = \frac{\alpha_0 F_0}{K_A}$; $k_3 = 1 - k_2$;

$$k_4 = \frac{c_A (\theta_{A0} - \theta_A)}{K_A}.$$
creases (an increase in temperature by 1 °C leads to a decrease in moisture by about 3%), while the air moisture content remains constant [6]. In addition, atmospheric pressure affects humidity. For these reasons, we write the material balance for the air space of the heater in air moisture content terms:

$$\frac{dA}{1000} = \frac{dA_0}{dt} - \frac{dA}{dt},$$  \hspace{1cm} (5)

where $dA_0(t)$ and $dA(t)$ are the air moisture content at the air inlet and outlet, respectively; $\rho_A$ is the air density; $V_A$ is the heater air space volume. The humid air density is determined from the equation [13]:

$$\rho_A = \rho_0 \left(1 + \frac{dA}{1000}\right),$$  \hspace{1cm} (6)

where $\rho_0$ is the dry air density under normal conditions. Taking into account (6), equation (5) after mathematical transformations will take the form:

$$T_d \frac{dA}{dt} + A_0 = k_5 A_0 + k_6 A,$$  \hspace{1cm} (7)

where $T_d = \frac{\rho A}{G_A}$; $k_5 = 1$; $k_6 = \frac{dA_0 - dA}{G_A}$.

Equations (2), (4) and (7) represent a dynamic model of heat and mass transfer processes when humid air is heated by an electric heater:

$$
\begin{align*}
T_E \frac{d\theta_E}{dt} + \theta_E &= k_0 \theta_E + k_1 \theta_A; \\
T_A \frac{d\theta_A}{dt} + \theta_A &= k_2 \theta_E + k_3 \theta_A + k_4 A; \\
T_d \frac{dA}{dt} + A_0 &= k_5 A_0 + k_6 A. 
\end{align*}
$$  \hspace{1cm} (8)

Mathematical model (8) in the state space has the form:

$$X' = AX + BU,$$  \hspace{1cm} (9)

where

$$X' = \begin{bmatrix} \Delta \theta_A \\ \Delta d_A \\ \Delta \theta_E \end{bmatrix}; \quad A = \begin{bmatrix} -1/T_A & 0 & k_2/T_A \\ 0 & -1/T_d & 0 \\ k_1/T_E & 0 & -1/T_E \end{bmatrix}; \quad X = \begin{bmatrix} \Delta \theta_A \\ \Delta d_A \\ \Delta \theta_E \end{bmatrix}; \quad \theta = \begin{bmatrix} \Delta \theta_A \\ \Delta d_A \\ \Delta \theta_E \end{bmatrix}.$$

$$B = \begin{bmatrix} k_3/T_A & 0 & k_4/T_A \\ 0 & k_5/T_d & k_6/T_d \\ 0 & 0 & k_0/T_E \end{bmatrix}; \quad U = \begin{bmatrix} \Delta \theta_A \\ \Delta d_A \\ \Delta \theta_E \end{bmatrix}.$$

Let us solve the system of differential equations (8) with respect to the sought variables using the Laplace transform:

$$
\begin{align*}
\Delta \theta_E(T_E p + 1) &= k_0 \Delta N_E + k_1 \Delta \theta_A; \\
\Delta \theta_A(T_A p + 1) &= k_2 \Delta \theta_E + k_3 \Delta \theta_A + k_4 \Delta A; \\
\Delta d_A(T_d p + 1) &= k_5 \Delta d_A + k_6 \Delta A. 
\end{align*}
$$  \hspace{1cm} (10)
From (11) we find \( \Delta \theta_E(p) \), then we substitute it in (12), and after grouping similar ones we obtain:

\[
\Delta \theta_A = \frac{1}{a_2 p^2 + a_1 p + 1} [(b_1 p + b_0) \Delta \theta_{A0} + (b_3 p + b_2) \Delta G_A + b_4 \Delta N_E],
\]

(14)

where

\[
a_2 = \frac{T_E T_A}{1 - k_1 k_2}; \quad a_1 = \frac{T_E + T_A}{1 - k_1 k_2}; \quad b_0 = \frac{k_3}{1 - k_1 k_2}; \quad b_1 = \frac{k_5 T_E}{1 - k_1 k_2};
\]

\[
b_2 = \frac{k_4}{1 - k_1 k_2}; \quad b_3 = \frac{k_4 T_E}{1 - k_1 k_2}; \quad b_4 = \frac{k_0 k_2}{1 - k_1 k_2}.
\]

From (13) we obtain a solution for the variable \( \Delta d_A \):

\[
\Delta d_A = \frac{1}{T_d p + 1} [k_6 \Delta d_{A0} + k_7 \Delta G_A].
\]

(15)

Applying the inverse Laplace transform, it is possible to find an analytical solution for (14) and (15) by the influence channels. We represent (14) and (15) by a multidimensional model in the Laplace domain

\[
Y = WZ,
\]

(16)

where

\[
Y = \begin{bmatrix} \Delta \theta_A \\ \Delta d_A \end{bmatrix}; \quad W = \begin{bmatrix} W_{11} & 0 & W_{13} & W_{14} \\ 0 & W_{22} & W_{23} & 0 \end{bmatrix};
\]

(17)

\[
Z^T = [\Delta \theta_{A0} \Delta d_{A0} \Delta G_A \Delta N_E];
\]

\[
W_{11} = \frac{b_1 p + b_0}{a_2 p^2 + a_1 p + 1}; \quad W_{13} = \frac{b_3 p + b_2}{a_2 p^2 + a_1 p + 1};
\]

\[
W_{14} = \frac{b_4}{a_2 p^2 + a_1 p + 1}; \quad W_{22} = \frac{k_6}{T_d p + 1}; \quad W_{23} = \frac{k_7}{T_d p + 1}.
\]

The proposed electric heater dynamic model in the differential equations system form (8), in the state space (9), or in the Laplace region (16)–(17), when modelling mass transfer processes, uses the air moisture content, which by definition is expressed as:

\[
d_A = \frac{M_W}{M_A},
\]

(18)

where \( M_W \) is the water steam mass in the air mixture; \( M_A \) is the dry air mass in the air mixture. Often, when synthesizing and analysing industrial air conditioners control systems, it is necessary to use the relative humidity of air, which is defined as:

\[
\varphi_A = \frac{P_p}{P_S},
\]

(19)

where \( P_S \) is the saturated steam pressure; \( P_p \) is the water steam partial pressure. The water steam partial pressure of humid air is uniquely determined by the moisture content and does not depend on the steam temperature [14].
Electric heater mathematical model for cyber-physical systems

\[ P_p = \frac{P_B d_A}{623 + d_A}, \quad (20) \]

where \( P_B \) is the barometric air pressure. The saturated steam pressure can be determined by the approximating dependence of N.I. Filnem [15]

\[ P_S = 133.3 \cdot 10^{\frac{156+8.12 \theta_A}{236+\theta_A}}. \quad (21) \]

If the air temperature \( \theta_A \) and its relative humidity \( \varphi \) are known, using dependencies (18)–(21), it is possible to determine the air mixture moisture content \( d_A \)

\[ d_A = \frac{83045.9 \varphi_A 10^{\frac{156+8.12 \theta_A}{236+\theta_A}}}{133.3 (623+d_A) 10^{\frac{156+8.12 \theta_A}{236+\theta_A}}}. \quad (22) \]

Moisture content recalculation into relative humidity can be carried out according to the inverse relationship

\[ \varphi_A = \frac{P_B d_A 10^{\frac{156+8.12 \theta_A}{236+\theta_A}}}{133.3 (623+d_A) 10^{\frac{156+8.12 \theta_A}{236+\theta_A}}}. \quad (23) \]

It is worth noting that the moisture content (22) and relative humidity (23) are calculated in absolute values, and in models (8), (9), and (16), variables increments are considered, and this feature must be taken into account during modelling.

AIR HEATER DYNAMIC MODE SIMULATION

As an example, let us carry out dynamic processes’ simulation modelling for the eclectic heater HE 36/2 of the central air conditioner CV-P 2L N-63B/F-N manufactured by VTS CLIMA. In Table the thermal and physical parameters for modelling the air heater HE 36/2 are shown.

<table>
<thead>
<tr>
<th>N</th>
<th>Parameter name</th>
<th>Symbol</th>
<th>Numerical value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electric heater dimensions</td>
<td>( H \times C \times L )</td>
<td>0.38 \times 1 \times 0.4</td>
<td>m</td>
</tr>
<tr>
<td>2</td>
<td>Heating element material density</td>
<td>( \rho_E )</td>
<td>9900</td>
<td>kg/m³</td>
</tr>
<tr>
<td>3</td>
<td>Heating element material heat capacity</td>
<td>( c_E )</td>
<td>460</td>
<td>J/(kg ºC)</td>
</tr>
<tr>
<td>4</td>
<td>Heating element material mass</td>
<td>( M_E )</td>
<td>0.6</td>
<td>kg</td>
</tr>
<tr>
<td>5</td>
<td>Air flow through the electric heater</td>
<td>( G_A )</td>
<td>0.43</td>
<td>kg/s</td>
</tr>
<tr>
<td>6</td>
<td>Dry air density</td>
<td>( \omega )</td>
<td>1.2</td>
<td>kg/m³</td>
</tr>
<tr>
<td>7</td>
<td>Air heat capacity</td>
<td>( c_A )</td>
<td>1010</td>
<td>J/(kg ºC)</td>
</tr>
<tr>
<td>8</td>
<td>Air mass in the heater</td>
<td>( M_A )</td>
<td>0.182</td>
<td>kg</td>
</tr>
<tr>
<td>9</td>
<td>Heat exchange area between heating elements and air</td>
<td>( F_0 )</td>
<td>0.306</td>
<td>m²</td>
</tr>
<tr>
<td>10</td>
<td>Heat transfer coefficient between heating elements and air</td>
<td>( \alpha_0 )</td>
<td>161</td>
<td>W/(m²ºC)</td>
</tr>
<tr>
<td>11</td>
<td>Input air temperature</td>
<td>( \theta_{AI} )</td>
<td>11</td>
<td>ºC</td>
</tr>
<tr>
<td>12</td>
<td>Output air temperature</td>
<td>( \theta_A )</td>
<td>15</td>
<td>ºC</td>
</tr>
<tr>
<td>13</td>
<td>Input air moisture content</td>
<td>( d_{AI} )</td>
<td>9</td>
<td>g/kg</td>
</tr>
<tr>
<td>14</td>
<td>Output air moisture content</td>
<td>( d_A )</td>
<td>9</td>
<td>g/kg</td>
</tr>
<tr>
<td>15</td>
<td>Heater power</td>
<td>( N_E )</td>
<td>3300</td>
<td>W</td>
</tr>
</tbody>
</table>
The elements for the matrices $A$ and $B$ of the electric heater model (9) were calculated according to the dependencies (10) in the MatLab environment using the program module:

$$
H=0.38; \quad C=1; \quad L=0.4;
$$

$$
A_0=161; \quad F_0=0.306; \quad G_a=0.43; \quad w=1.2;
$$

$$
M_a=0.182; \quad c_a=1010; \quad M_e=0.6; \quad c_e=460;
$$

$$
T_{etA}=11; \quad d_{etA}=15; \quad dA=9; \quad dA_0=11;
$$

$$
K_a=c_a*G_a+A_0*F_0; \quad T_a=c_a*M_a/K_a; \quad k_2=A_0*F_0/K_a; \quad k_3=1-k_2;
$$

$$
T_d=w*H*L*C/G_a; \quad k_5=1; \quad k_6=(dA_0-dA)/G_a;
$$

$$
A=[-1/T_t, 0, k_2/T_t; 0, -1/T_d, 0; k_1/T_e, 0, -1/T_e];
$$

$$
B=[k_3/T_t, 0, k_4/T_t, 0; 0, k_5/T_d, k_6/T_d, 0, 0, 0, k_0/T_e];
$$

According to the calculations, the following numerical values were obtained for the matrices:

$$
A = \begin{bmatrix} -2.631 & 0 & 0.268 \\ 0 & -2.357 & 0 \\ 0.179 & 0 & -0.178 \end{bmatrix}; \quad B = \begin{bmatrix} 2.362 & 0 & -21.98 & 0 \\ 0 & 2.358 & 0 & 0 \\ 0 & 0 & 0 & 0.0036 \end{bmatrix}.
$$

The dynamic mode simulation for the HE 36/2 electric heater was carried out in the Simulink MatLab environment using the State Space function block. Fig. 2, a–c show the research results for transient processes in the electric heater for the perturbation channels, and Fig. 2, d – shows such results for the control channel.

From the conducted research, it can be concluded that a change in the inlet temperature $\Delta \theta_{40}$ does not affect the air moisture content at the electric heater outlet $\Delta d_A$ (Fig. 2, a). A change in the air moisture content at the inlet $\Delta d_{40}$ does not affect the outlet temperature (Fig. 2, b). A change in the steam-air mixture flow rate $\Delta G_{40}$ affects the heated air temperature $\Delta \theta_A$ (Fig. 2, c). Control actions $\Delta N_E$ do not affect the heated air moisture content $\Delta d_A$ (Fig. 2, d). The considered effect of heating the steam-air mixture on air heaters is recommended to be used in the artificial microclimate control systems development. The air moisture content use as a control variable (relative humidity instead) can significantly reduce the mutual influences of the temperature and humidity control loops in the air conditioner and improve the control system dynamic properties.

The resulting transients are aperiodic without delay. The control channel inertia is greater than the disturbance channels inertia. This dynamic is explained by the small heater airspace volume $V_A=0.152 m^3$ with a relatively large flow rate of heated air $G_A=0.43 kg/s$. For this reason, if necessary, it is recommended to calculate the relative humidity at the output of the electric heater according to dependence (23). The transient processes inertia in the electric heater is comparable to the temperature sensor inertia, therefore, the dynamic sensor properties must be taken into account when developing a control system. From practical recommendations in control systems with electric heaters, it is sufficient to use control PI-law. Using the more complex control law is not justified for these devices.
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CONCLUSIONS

The article proposes a mathematical description of heating the steam-air mixture by an electric heater. The mathematical model is obtained in the equivalent dependencies form: the system of differential equations (8); in the state space (9); in the Laplace domain (16). The mathematical model can be used as a digital twin for a digital controller with a reference model. In addition, the proposed model is recommended to be used for the synthesis and analysis of control systems for balanced ventilation systems or industrial artificial microclimate systems. The mathematical description makes it possible to obtain the air heater dynamic characteristics for the main channels of control and disturbance. An example for the transient processes simulation for an electric heater HE 36/2 is given.

The choice of a mathematical model (8), (9) or (16) is determined by the approach to designing a cyber-physical system. The model in the state space (9) has a number of advantages over the notation in the transfer functions form (16). For example, it allows to describe the internal model structures using a minimum number of parameters. An additional argument in favor of vector models is a large number of software packages for the computer analysis of technical systems in the state space, which allow complex mathematical research to be carried out with little time.

Fig. 2. Transient processes modelling in the heater HE 36/2 for the action main channels: a — $\Delta \theta_{a_0} \rightarrow X$, $\Delta \theta_{a_0} = 1^\circ C$; b — $\Delta d_{a_0} \rightarrow X$, $\Delta d_{a_0} = 1 \text{ g/kg}$; c — $\Delta G_{a_0} \rightarrow X$, $\Delta G_{a_0} = 0,1 \text{ kg/s}$; d — $\Delta N_E \rightarrow X$, $\Delta N_E = 1000 W$
A separate direction in the technical systems modeling is the identification of dynamic model coefficients and the resulting model adequacy assessment. The electric heater model coefficients were calculated according to the parameters given in Table. Thermal and physical parameters for the considered model are determined with a high accuracy from reference books, except for the heat transfer coefficient $\alpha_0$. This coefficient depends on many factors [16]. Therefore, the heat transfer coefficient should be attributed to the proposed model parametric uncertainty, which affects almost all elements in matrices $\mathbf{A}$ and $\mathbf{B}$ of model (9). The heat transfer coefficient can be determined with a high accuracy based on experimental studies. Thus, there is a need for the proposed model parametric adaptation to the specific conditions of air preparation on the experiment basis. This research will be the topic for the next publication, where the model coefficients will be identified based on an active experiment using computer technology.

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МАТЕМАТИЧНА МОДЕЛЬ ЕЛЕКТРИЧНОГО КАЛОРИФЕРА ДЛЯ КІБЕРФІЗИЧНИХ СИСТЕМ / Н.Д. Панкратова, І.М. Голінко

Анотація. Розглянуто динамічну модель тепло- і масообміну для електричного калорифера із зосередженнями параметрами, яка дозволяє проводити імітаційне моделювання переходних процесів за основними каналами впливу. Запропоновану модель рекомендується використовувати в кіберфізичних системах для прогнозування та оцінювання ефективності систем управління, інтегрованих в єдину інформаційну систему управління. Розроблену модель можуть використовувати фахівці для аналізу та синтезу систем управління припливно-витяжної вентиляції або промислових кондиціонерів. Як приклад виконано числове моделювання переходних процесів за основними каналами впливу для електрокалорифера HE 36/2 виробництва VTS CLIMA. Суттєвим перевагою запропонованої моделі є можливість використання її для синтезу та аналізу багатовимірних систем управління.

Ключові слова: кіберфізична система, цифровий двійник, математична модель, простір станів, електричний калорифер.

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ЭЛЕКТРИЧЕСКОГО КАЛОРИФЕРА ДЛЯ КИБЕРФИЗИЧЕСКИХ СИСТЕМ / Н.Д. Панкратова, И.М. Голинко

Аннотация. Рассмотрена динамическая модель темнопротча обмена для электрического калорифера с сосредоточенными параметрами, которая позволяет проводить имитационное моделирование переходных процессов по основным каналам воздействия. Предложенную модель рекомендуется использовать в киберфизических системах для прогнозирования и оценки эффективности систем управления, интегрированных в единую информационную систему управления. Разработанную модель можно использовать специалисты для анализа и синтеза систем регулирования приточно-вытяжной вентиляции или промышленных кондиционеров. В качестве примера проведено численное моделирование переходных процессов по основным каналам воздействия для электрического калорифера HE 36/2 производства фирмы VTS CLIMA. Существенным преимуществом предложенной модели является возможность её использования для синтеза и анализа многомерных систем управления.

Ключевые слова: киберфизическая система, цифровой двойник, математическая модель, пространство состояний, электрический калорифер.