TIME-VARIANT MODEL OF HEAT-AND-MASS EXCHANGE FOR STEAM HUMIDIFIER

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Abstract. The dynamical model of heat-mass exchange for a steam humidifier with lumped parameters, which can be used for synthesis of control systems by inflowing-exhaust ventilation installations, or industrial complexes of artificial microclimate, is considered. A mathematical description that represents the dynamical properties of a steam humidifier concerning the main channels of control and perturbation is presented. Numerical simulation of transient processes for the VEZA KCKP-20 humidification chamber to the influence channels was carried out. The achieved dynamical model of a humidification chamber can be the basis for the synthesis of automatic control systems and simulation of transient states. A significant advantage of the obtained mathematical model in the state space is the possibility of synthesis and analysis of a multidimensional control system.

Keywords: dynamical model, state space, steam humidifier

NIESTACJONARNY MODEL WYMIANY CIEPLA I MASY DLA NAWILŻACZA PAROWEGO

Streszczenie. Rozważono model dynamiczny wymiany ciepła i masy nawilżacza parowego o parametrach skupionych, który można zastosować do syntezy układów sterowania przez instalacje wentylacyjne nadmuchowo-odmuchowe lub przemysłowe kompleksy sztucznego mikroklimatu. Przedstawiono opis matematyczny przedstawiający właściwości dynamiczne nawilżacza parowego dotyczące głównych kanałów regulacji i zaburzeń. Przeprowadzono symulację numeryczną procesów przejściowych dla komory nawilżającej VEZA KCKP-20 z kanałami wpływowymi. Powstał model dynamiczny komory nawilżania może być podstawą do syntezy automatycznych układów sterowania i symulacji stanów nieustalonych. Istotną zaletą uzyskanego modelu matematycznego w przestrzeni stanu jest możliwość syntezy i analizy wielowymiarowego układu sterowania.

Słowa kluczowe: model dynamiczny, przestrzeń stanu, nawilżacz parowy

Introduction

When heating the buildings, water and air systems are most often used. Air heating systems are used recently and have proven themselves as high-speed, with a small specific capital cost. Air heating systems use electric heaters with a distributed automatic control system [11]. For air heating of commercial and business centres, warehouses and industrial buildings, centralized ventilation and conditioning systems are used. The achievement of high performance indicators of industrial conditioning systems involves the development of adequate mathematical models of climatic equipment and their control methods.

Steam humidifying cameras have been widely used in air conditioning. Thanks to technological features, steam humidification is indispensable for creating artificial microclimate: in operating rooms; in the technology of manufacturing drugs, or semiconductor materials of the electronic industry, and so on. In contrast to the spray-type humidification chambers (the process of adiabatic or polytrophic humidification), in the case of steam humidification (the process of isothermal humidification) there is no need for additional heating of air after moisture [1].

In developing a mathematical model, the task is to determine the limits of its detalization. The dynamical model should be simple for its research and synthesis of the control system, and also take into account the features of heat-mass ex-change. Researchers use mathematical models with lumped [4, 12] and distributed [5, 6] parameters to simulate the dynamical processes of heat-mass exchange equipment. Models with lumped parameters are simpler in the calculations and make it possible to obtain an analytical solution. Models with distributed parameters apply for more exact mathematical description. An analytical modelling of equipment with distributed parameters is a rather complicated task, transcendental functions appear in the solution [5]. For such tasks numerical methods of the solution are used in practice.

1. Using dynamic models

Typically, static models of process equipment are used to design and calculate the power of a particular plant. Dynamic models of process equipment are used for the synthesis and analysis of control systems. When designing and optimizing any control system, the structure and parameters of the controller are primarily dependent on the dynamic behaviour of a controlled plant. The choice of whether a different law of control is determined by the dynamic properties of a controlled plant. The choice of a law of control is determined by the dynamic properties of a controlled plant. In automation systems, developers use: classical PI controllers, PID controllers; adaptive controllers [3, 9]; controllers with fuzzy logic [14]; controllers with fractional derivatives [10]; intelligent controllers [8]; controllers based on neural networks and many other types of controllers. In their research, experts compare the operation of control systems with different types of controllers and draw conclusions about the quality of management. In the study of control systems with different types of controllers unchanged in the system there is a controlled plant, which characterizes the dynamic behaviour of the technological apparatus and formalized in the form of differential equations controlled plant. Thus, an adequate mathematical model of a controlled plant is the basis for the synthesis and analysis of a qualitative control system.

The purpose of the publication is to develop a mathematical model of the heat-mass exchange process for a steam humidifier in the state space, which will allow the analysis of dynamic characteristics of steam generator of industrial air conditioners. An additional requirement is the convenience of using the resulting model in the MatLAB environment.

2. Dynamical model of steam humidifier

When developing a mathematical model of a steam humidifier, the model [13] was used as the base model, where the humidification chamber without a steam generator is analysed. In [13], the differential equation of the humidifier chamber material balance is considered in characteristic of relative humidity, which is linearized. Relative humidity is determined by a significant nonlinear dependence on the temperature of air [2]. As a consequence, the temperature range of the use of the linear model is small. Therefore, the material balance equations of the steam humidification chamber will be considered in characteristic of the air moisture content.

The following simplifications were made during the development of a dynamic model of a steam humidifier: heat exchange with the environment is absent, since the thermal losses of modern heaters do not exceed 5%; the model contains two main dynamic elements with lumped parameters (air space humidifying chamber and steam generator with water); the physical properties of the material flows and the heat transfer surface are brought to the averaged values of the working range. The calculation scheme of the steam humidifier is shown in Fig. 1.
where $c_A$ is heat capacity of the air mixture; $r$ is heat of vaporization; $M_A$ is mass of moist air in volume $V_A$. Consider the material balance for airspace of the humidification chamber. The moisture content accumulated in the humidifier air space is defined as the difference between the mass input and output pairs

$$
\frac{G_A}{1000}(d_{A0} - d_A) + G_p = V_A \frac{d\rho_A}{dt}
$$

(2)

The heat and material balance for the steam generator are represented by the corresponding equations:

$$
G_w c_w \theta_{W0} + N_E - r G_p = c_w \frac{dM_w \theta_w}{dt}
$$

(3)

$$
G_w - G_p = \frac{dM_w}{dt}
$$

(4)

where $\theta_{W0}$ is temperature of feed water; $\theta_w$ is water temperature in the steam generator (in operating mode $\theta_w = 100^\circ C$); $G_p$, $G_w$ is mass flows of steam and water; $c_w$ is heat capacity of water; $N_E$ is power of the steam generator; $M_w$ is mass of water in the steam generator. Equations (1)–(4) represent a dynamic model of heat-mass exchange for the steam humidifier of an air conditioner:

$$
\begin{align*}
G_A \left[ c_A (\theta_{A0} - \theta_A) + \frac{r}{1000} (d_{A0} - d_A) \right] + \\
+ r G_p = c_A M_A \frac{d\theta_A}{dt},
\end{align*}
$$

(1)

The design of the steam generator includes a system for stabilizing the water level. For these reasons $\frac{dM_w}{dt} \approx 0$ and the differential equation (4) becomes algebraic $G_w - G_p \approx 0$. Also, let’s take into account the constant temperature of water in the steam generator $\theta_w \approx 100^\circ C$, from where for equation (3) $\frac{dM_w \theta_w}{dt} \approx 0$, from which it is easy to determine $G_p$:

$$
G_p = \frac{1}{r - c_w \theta_{W0}} N_E
$$

(6)

Thus, the system of equations (5) is simplified. After grouping similar terms for (1), (2) with regard to (6) and $G_A = \text{const}$, we obtain a dynamic model of the steam humidifier:

$$
\begin{align*}
T_A \frac{d\theta_A}{dt} + \theta_A &= k_0 d_{A0} + k_1 d_{A0} + k_2 d_A + k_3 N_E \\
T_d \frac{dA}{dt} + d_A &= k_4 d_{A0} + k_5 N_E
\end{align*}
$$

(7)

where $T_A = \frac{M_A}{G_A}$; $T_d = \frac{\alpha V_A}{G_A}$:

$$
k_0 = 1; \quad k_1 = \frac{r}{1000 c_w G_A}; \quad k_2 = -k_1
$$

$$
k_3 = \frac{r}{c_A G_A (r - c_w \theta_{W0})}; \quad k_4 = 1; \quad k_5 = \frac{1000}{r - c_w \theta_{W0}}
$$

The mathematical model (7) is representable in the states space:

$$
X' = AX + BU
$$

(8)
where

\[
\mathbf{X} = \begin{bmatrix} \theta_A \\ d_A \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} -\frac{1}{T_A} - \frac{k_2}{T_d} \\ 0 & -\frac{1}{T_d} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \frac{k_2}{T_d} & \frac{k_1}{T_A} & \frac{k_3}{T_A} \\ \frac{1}{T_A} & \frac{k_1}{T_A} & \frac{k_2}{T_A} \end{bmatrix}, \quad \mathbf{U} = \begin{bmatrix} \theta_A \\ d_A \end{bmatrix}.
\]

Applying the Laplace transform to the system (7), we obtain:

\[
d_A = \frac{1}{T_d} p + 1 \left[ k_4 d_{A0} + k_3 N_E \right]
\]

\[
\theta_A = \frac{1}{a_2 p^2 + a_1 p + 1} \left[ (b_1 p + b_0) \theta_{A0} + (b_2 p + b_1) N_E \right]
\]

where \( a_1 = T_A + T_d; \quad a_2 = T_A T_d; \quad b_0 = k_0; \quad b_1 = k_0 T_d; \quad b_2 = k_1 + k_2 k_4; \quad b_3 = k_1 T_d; \quad b_4 = k_3 + k_2 k_5; \quad b_5 = k_3 T_d. \)

Using the inverse Laplace transform, one can find the analytic solution (9) and (10) by the channels of control and disturbance.

Thus, a dynamic model of the steam humidifier, which can be represented as one of the equivalent dependences (7), (8), (9) or (10), is obtained.

### 3. An example of dynamic mode simulation for a steam humidifier

Consider the simulation of dynamic processes for the steam humidifying chamber KCKP-20 of the company "VEZA" in the complete set with the steam generator SMU-233 [2]. Tab. 1 shows the thermal physic parameters for the VEZA KCKP-20 steam humidifying chamber.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Marking</th>
<th>Numerical value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions of the water heater</td>
<td>H × L × C</td>
<td>1×1×1.9 m</td>
<td></td>
</tr>
<tr>
<td>Flow of air mixture</td>
<td>G_A</td>
<td>6.7 kg/sec</td>
<td></td>
</tr>
<tr>
<td>Power of the steam humidifier</td>
<td>N_E</td>
<td>16000 Watt</td>
<td></td>
</tr>
<tr>
<td>Moist air density</td>
<td>( \rho_A )</td>
<td>1.2 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Dry air density</td>
<td>( \omega )</td>
<td>1.2 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Air heat capacity</td>
<td>( c_A )</td>
<td>1010 J/(kg°C)</td>
<td></td>
</tr>
<tr>
<td>Water heat capacity</td>
<td>( c_W )</td>
<td>4185 J/(kg°C)</td>
<td></td>
</tr>
<tr>
<td>Heat of vaporization</td>
<td>( r )</td>
<td>2256000 J/kg</td>
<td></td>
</tr>
<tr>
<td>Input air temperature</td>
<td>( \theta_{A0} )</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>Output air temperature</td>
<td>( \theta_A )</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>Input water temperature</td>
<td>( \theta_{W0} )</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>Input moisture content of air</td>
<td>( d_{A0} )</td>
<td>2 g/kg</td>
<td></td>
</tr>
<tr>
<td>Output moisture content of air</td>
<td>( d_A )</td>
<td>6 g/kg</td>
<td></td>
</tr>
</tbody>
</table>

Coefficients for models (8)–(10) of the steam generator were calculated in the MatLAB software environment using the `coef_SMU233.m` program:

- \( H=1; \quad L=1.4; \quad C=1.9; \)
- \( V_a=H+L+C; \quad G_A=0.43; \quad p_a=1.2; \)
- \( w=1.2; \quad c_a=1010; \quad c_w=4182; \quad r=2256000; \)
- \( \text{TetA}_0=20; \quad \text{TetA}=20; \quad \text{TetW}_0=20; \quad \text{da}=2; \quad \text{da}=6; \)
- \( \text{Ta}=\text{pa}^*\text{Va}/\text{Ga}; \)

Simulation modelling of the dynamic mode for the steam humidifier was carried out in the Simulink MatLAB environment using the State Space functional block. The simulation results of transients along the control channel are presented in Fig. 2.

![Fig. 2: Graphs of the transient processes for the control channel \( N_E \rightarrow \mathbf{X}(t) \)](image-url)
The proposed dynamic model is recommended to be used in the support and decision-making system at the middle level of enterprise management [7]. This will integrate the air conditioning control system into the enterprise management system. Such an approach will allow the company to transfer to a qualitatively new level of management and allow the efficient use of energy resources.

References


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