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DYNAMIC PROCESS MODELING AND SIMULATION OF SHELL-AND-TUBE HEAT EXCHANGER

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ABSTRACT

Heat exchangers are commonly used to exchange heat in industrial production. According to the law of energy conservation, the characteristics of shell-and-tube heat exchanger were analyzed and the dynamic model was established. The dynamic model can effectively simulate the change of outlet temperature of cold stream with the change of flowrate and inlet temperature of hot stream. The relationship curves of the dynamic model between temperature, flowrate and time were obtained through simulation experiments. By using the simulation results the heat transfer process of heat exchanger can be analyzed comprehensively, which provides a theoretical basis for the control and optimization of heat transfer process in engineering practice.

KEYWORDS

Shell-and-tube heat exchanger, dynamic models, simulation.

1. INTRODUCTION

Heat exchangers are devices used to transfer heat between materials, which are commonly used in many industrial sectors such as petrochemicals, atomic energy, light industry, power, pharmaceuticals, and aviation. At present, the shell-and-tube heat exchanger is the most widely used heat exchanger, which has many advantages such as a large operating temperature and pressure range, low manufacturing cost, convenient cleaning, large processing volume, and high reliability [1-4]. In industrial production, it is necessary to control the outlet temperature of the heat exchanger to ensure the smooth progress of the production process. Therefore, the study of the automatic control process of the heat exchanger has great practical significance for industrial production. In the paper, based on the analysis the dynamic characteristics of the shell-and-tube heat exchanger, a dynamic model of the exchanger is established and the control effect of the dynamic model is verified by the simulation experiment.

2. INTRODUCTION TO HEAT EXCHANGER PROCESSES

The main purpose of a heat exchanger is to transfer heat from a stream with a higher temperature to a stream with a lower temperature to perform heat exchange so that the temperature of the stream reaches the temperature required for the process. When the outlet temperature of cold stream deviates from the set target value, the flowrate of the hot stream is adjusted by regulator valve. Take the shell-and-tube heat exchanger as an example to research the automatic control system [5,6]. The process flow diagram of shell-and-tube is shown in Figure 1.

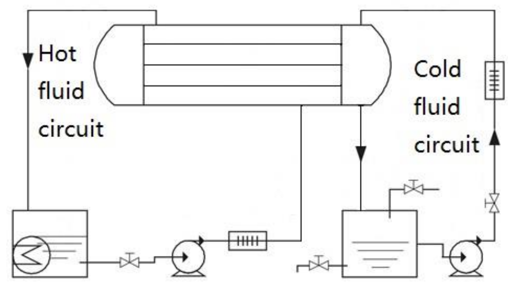

Figure 1: Process flow diagram of shell-and-tube heat exchanger

As shown in Figure 1, heat exchanger has a hot stream and a cold stream. The two streams exchange heat countercurrent inside the heat exchanger, the hot stream temperature decreases, while the cold stream temperature rises, so as to achieve the process requirements.

3. HEAT EXCHANGER DYNAMIC MATHEMATICAL MODEL

Taking the shell-and-tube heat exchanger as an example, we assume that the physical properties of the streams do not change with temperature, there is no heat loss in the heat transfer process, and the cold and hot streams are completely counter-current. The cold and hot streams all use water as the research objects. The phase change does not occur during heat transfer and heat exchange starts when the distance to inlet of the cold stream is zero. During the dynamic process of heat exchange the heat balance equation can be expressed as follow [7-9].

$$H_h + H_c - h_h - h_c = 0 \qquad (1)$$

In the equations: H_h is the heat input of hot stream, J; H_c is the heat input of cold stream, J; h_h is the heat output of hot stream, h_c is the heat output of cold stream.

The mathematical expression of the heat exchanger in steady state is:

$$\frac{dT_c}{dt} = \frac{K\upsilon_h}{C_{pc}\upsilon_c S}(T_h - T_c) \qquad (2)$$

$$\frac{dT_h}{dt} = \frac{K\upsilon_h}{C_{ph}\upsilon_c S}(T_h - T_c) \qquad (3)$$

In the equations: T_c is cold stream temperature,℃;T_h is hot stream temperature,℃; K is total heat transfer coefficient, W/(m²·K); υ_c is cold stream velocity, Kg/(m²·s); υ_h is hot stream velocity, Kg/(m²·s);C_{pc} is cold stream heat capacity flowrate, J/(Kg·℃); C_{ph} is hot stream heat capacity flowrate, J/(Kg·℃); S is shell section area, m²; t is time, s。

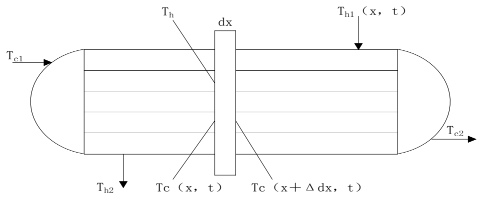

Figure 2: Temperature distribution of the micro segment dx

As shown in Figure 2, heat balance for a certain micro segment in the heat exchanger tube is made. When the temperature and flowrate of the inlet and outlet of cold and hot streams fluctuate, the temperature distribution function of any section in the tube at any time can be obtained, so the dynamic relationship between temperature and time and position is derived. According to thermal balance based on dynamic thermal equilibrium equation, the heat exchanger dynamic expression is expressed as follow.

$$\frac{\partial}{\partial t}\left(A\rho C_P T dx\right) = A\, \upsilon_c \rho\, C_P T_c - A\, \upsilon_c \rho\, C_P\left(T_c + \Delta T\right) + \frac{K\pi D\, \upsilon_h\left(T_h - T_c\right)}{\rho} \quad (4)$$

Because the cold and hot streams are the same material water, C_{pc} and C_{ph} are equal and both are represented by C_p.

In the equation: A is tube section area, m^2; ρ is fluid density, Kg / m^3; D is outside diameter， m; T_s is fluid temperature outside the tube,°C.

because of $A, S, dx, C_p, \upsilon_c, \upsilon_h$ and ρ can be regarded as constants, formula (4) can be simplified as:

$$\frac{\partial T_c}{\partial t} = \frac{\upsilon_c}{A\rho}\,\frac{T_c - \left(T_c + \Delta T\right)}{dx} + \frac{K\, \upsilon_h (T_h - T_c)}{\rho^2 A C_p dx} \quad (5)$$

When $dx \to 0$, there were:

$$\frac{\partial T_c}{\partial t} = -\frac{\upsilon_c}{A\rho}\,\frac{\partial T_c}{\partial x} + \frac{K\, \upsilon_h\left(T_h - T_c\right)}{\rho^2 A C_p} \quad (6)$$

Equation (6) is the relationship between the temperature inside the pipe T_c and the time and the length of the pipe. Because it contains the shell temperature T_h, T_h also changes with time and the length of the pipe, a mathematical model of the temperature of the shell T_h is also required. Using the same method can get a mathematical model of the shell temperature:

$$\frac{\partial T_h}{\partial t} = \frac{\upsilon_h}{S\rho}\,\frac{\partial T_h}{\partial x} - \frac{K\, \upsilon_h\left(T_h - T_c\right)}{\rho^2 S C_p} \quad (7)$$

Equation (6) and (7) constitutes a dynamic mathematical model of the heat exchanger.

4. SOLUTION OF THE DYNAMIC MODEL

4.1 The total heat transfer coefficient

Total heat transfer coefficient is expressed as follow.

$$\frac{1}{K} = \frac{d_o}{a_i d_i} + R_{si}\frac{d_o}{d_i} + \frac{b d_o}{\lambda\, d_m} + R_{so} + \frac{1}{a_o} \quad (8)$$

K is based on the outer wall of the tube. Because water is a low viscosity fluid, Dittus-Boelter correlation can be used, which is

$$a = 0.23\,\frac{\lambda}{d_i}\left(\frac{d_i \upsilon \rho}{\mu}\right)^{0.8}\left(\frac{C_p \mu}{\lambda}\right)^n \quad (9)$$

In the equation, α_o and α_i are the heat transfer coefficients of shell-side and tube-side fluids, respectively, W/(m^2·K); R_{so} and R_{si} are the thermal resistance of the shell and the tube, m^2,K/W; d_o and d_i are the outer diameter and inner diameter of the heat transfer tube, respectively, m; d_m is the average value of the inner diameter and outer diameter of the heat transfer tube, m; b is the heat transfer tube wall thickness, m;λ is the thermal conductivity of the pipe wall, W/(m·K);μ is fluid viscosity, Pa·S.

4.2 Basic equation solving

Simplify the equation (4) for energy balance of the heat exchanger micro segment,

$$\begin{cases} \dfrac{\partial T_c}{\partial t} = -\upsilon_c \dfrac{\partial T_c}{\partial x} + \dfrac{K\, \upsilon_h}{\rho^2 A C_p}\left(T_h - T_c\right) \\ \dfrac{\partial T_h}{\partial t} = -\upsilon_h \dfrac{\partial T_h}{\partial x} + \dfrac{K\, \upsilon_h}{\rho^2 S C_p}\left(T_h - T_c\right) \end{cases} \quad (10)$$

Set the intermediate variables α_1, α_2, let

$$a_1 = \frac{K\, \upsilon_h}{\rho^2 A C_p}, \quad a_2 = \frac{K\, \upsilon_h}{\rho^2 S C_p} \quad (11)$$

So, equation (10) can be simplified as:

$$\begin{cases} \dfrac{\partial T_c}{\upsilon_c} = -\dfrac{\partial T_c}{\partial x} + a_1\left(T_h - T_c\right) \\ \dfrac{\partial T_h}{\upsilon_h} = -\dfrac{\partial T_h}{\partial x} + a_2\left(T_h - T_c\right) \end{cases} \quad (12)$$

$$\begin{cases} \dfrac{A}{\upsilon_h} T_c = \dfrac{dT_c}{dx} + a_1\left[\dfrac{a_2}{A - a_2} - \dfrac{\upsilon_h C_p}{A\, a_2}\left(T_h - T_h - T_c\right)\right] \\ -\dfrac{dT_c}{dx} = \left[\dfrac{a_2}{S\, a_2} T_c - \dfrac{\upsilon_h C_p}{S - a_2}\left(T_h - T_c\right)\right] - \dfrac{S}{\upsilon_h} T_c - \left(a_1 + \dfrac{S}{\upsilon_h}\right) T_c \end{cases} \quad (13)$$

Let

$$\theta = a_2 - \left(a_1 + \frac{A}{\upsilon_h}\right), \quad \beta = \frac{a_1 a_2 T_c - \upsilon_h C_p a_1\left(T_h - T_C\right)}{A - a_2} \quad (14)$$

The simplification solution is finally obtained:

$$T_h\left(H, s\right) = \frac{a_1 a_2 \upsilon_c\left(1 - e^{-aH}\right) T_c + \upsilon_h C_p \theta\ \upsilon_c\left(1 - e^{-aH}\right) T_h}{\left(a_1 \upsilon_h + s\right)\left(s - a_2\right) - \upsilon_h C_p \theta\ \upsilon_c\left(1 - e^{aH}\right)} + \frac{T_h e^{-aH}\left(a_1 \upsilon_c + s\right)\left(s - a_2\right)}{\left(a_1 V_1 + s\right)\left(s - a_2\right) - \upsilon_h C_p \theta\ \upsilon_c\left(1 - e^{-aH}\right)} \quad (15)$$

4.3 Simulation curves

The model is based on equation (16) simulate by the configuration software. The relationships between cold stream outlet temperature and hot stream temperature and flowrate is obtained, and the simulation curves of this dynamic model are shown in Figures 3.

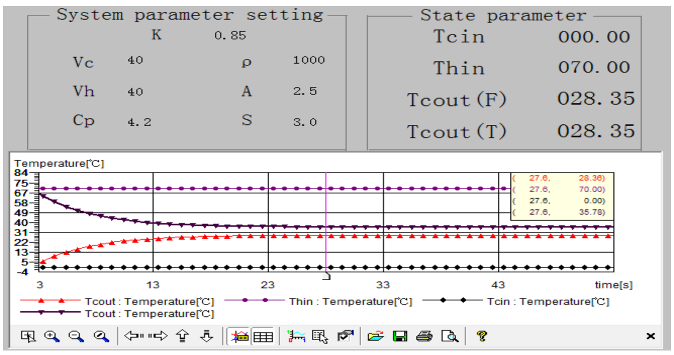

Figure 3: Simulation interface

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As shown in Figure 3, the simulation operation interface includes the two parts that are the real-time trend and the parameters display setting. The fluids in the shell side and in the tube are hot water and cold water respectively. The two fluid flows at 40kg/(m³·s) without disturbance.

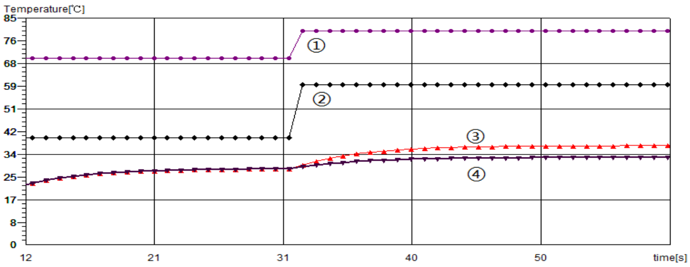

Figure 4: Simulation curve

As shown in Figure 4, the curve ① is the inlet temperature of hot stream. The curve ② is the flowrate of hot steam. The curve ③ is the dynamic response of the outlet temperature of cold stream to inlet temperature of hot stream; The curve ④ is the dynamic response of the outlet temperature of cold stream to the flowrate of the hot stream. The curves show that the outlet temperature of the cold stream is affected by the inlet temperature and flowrate of the hot stream during the disturbance, and the inlet temperature of hot stream has a great influence. The simulation results of the model are in agreement with the actual production process.

5. CONCLUSION

The shell-and-tube heat exchanger is used as the research object. The dynamic model of the heat exchanger is established through the dynamic analysis of the micro segment of the heat exchange process. The model is simulated by the configuration software to verify the relationship between the temperature, flow and time of the heat exchanger. The obtained curves show that the established heat exchanger model can reasonably reflect the dynamic response of the heat exchanger, which is basically consistent with the actual situation. The model obtained in this paper can also be used for other similar equipment and has been applied in heat exchanger networks, which plays a better control and optimization role.

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