Computer modeling of the heat exchange process in the calefacient chamber of the evaporator

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Abstract. A system analysis is considered in the construction of a computer model of processes in the heating chamber of a steam heat exchanger, based on the MATLAB application program, by combining blocks of process models of the quasi-apparatus of the regulatory body, the steam zone, the condensate and the wall. According to the computer model of the dynamics of the heating chamber process, depending on the changes in the input parameters (steam pressure in the heating water supply pipeline, changes in the opening coefficient of the heating water supply valve, the temperature of the heating steam in the heating water supply pipeline, the heat sink from the wall), the computer automatically calculates the values of the heating steam pressure, the flow rate of the heating steam passed through the control valve, the condensation temperature of the heating steam, the wall temperature. Calculations show that with an increase in the pressure in the supply line of heating water vapor or the opening of the valve, the steam pressure in the heating chamber increases, along with this, the condensation temperature increases, and the transfer of heat energy through the heat exchange wall increases. For the example under consideration, when the water vapor pressure in the heating chamber increased to 250 kPa, the condensate temperature increased to 1200°C.

1. Introduction

Systemic thinking [1,2] in the study of the current state, the object in particular, the technological line of heat exchange, individual equipment and process, allows you to get the most accurate results and correctly assess the possibility of rational use of raw materials and reduce energy consumption in production.

A four-level hierarchical structure of the system analysis of the process has been developed. At the same time, each level of the hierarchy encompasses certain whole elements of the device, ongoing phenomena, sub-processes, and having interrelationships in them.

The implementation of the system analysis methodology allows obtaining a number of new results in the field of theory and practice of evaporation processes.

A significant number of production processes in the food industry are carried out in tank equipment. These processes are heating, cooling, mixing of liquids, dilution of solutions, dissolution of granular or bulk materials, crystallization, distillation, chemical transformations, additional loading and partial unloading, as well as various combinations of these processes.
As a rule, all these operations take place in non-stationary temperature conditions. In each specific case, the duration-limiting process can be a thermal or heat-mass transfer process. As a rule, the limiting processes are also the most energy consuming. Reducing the duration of limiting processes increases the productivity of equipment, reduces energy consumption and production costs. The intensity of heat and mass transfer processes in liquid products is determined by the hydrodynamic situation in the apparatus.

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To obtain the possibility of rational organization of the process in a heat exchanger, a schematic diagram [1] of a single continuously operating evaporator with natural circulation of the solution is considered using the example of an apparatus with an internal central circulation pipe.

Figure 1. Scheme of a single (one-body) evaporator: 1 – calefacient (heating) chamber; 2 – separator; 3 - boiling pipes; 4 - circulation pipe.

The apparatus has a calefacient chamber 1 and a separator 2. The heat exchanger is a calefacient chamber, which consists of \( \varphi \) quasi-apparatus: a heating chamber, walls of the boiling pipes of the evaporator, a vapor-liquid space - the inner part of the boiling pipes of the evaporator. In turn, the calefacient chamber consists of quasi-apparatus of the steam zone and condensate. The calefacient chamber is usually heated by saturated water vapor entering its space between pipes. Condensate gives off heat through the walls of the heating pipes and is removed from the bottom of the chamber. In the chamber (vapor-liquid space - the inner part of the boiling pipes of the evaporator), the evaporated solution, rising along the heated pipes 3, is concentrated with the formation of secondary vapor. Separation of vapor from liquid takes place in separator 2. Secondary vapor freed from splashes and drops is removed from the upper part of the separator. Part of the liquid descends through the
circulation pipe 4 under the lower tube sheet of the calefacient chamber. Due to the difference in the density of the solution in the pipe 4 and the vapor-liquid emulsion in the pipes 3, the liquid circulates in a closed loop. The one stripped off solution is removed through the fitting in the bottom of the apparatus.

A systematic approach to studying the current state of this industry will allow obtaining the most accurate results and correctly assessing the possibilities of increasing the degree of improving the quality of heat transfer and reducing energy consumption in production [1].

2. About systemic thinking [2-6] and analysis of the heat exchange system

The proposed methodology of systemic thinking [2-5] allows you to analyze the heat exchange system without any particular difficulty. According to the proposed method, the indicators are initially determined - the input, output parameters of the object, in this case a heat exchange apparatus consisting of a system of quasi-apparatus, a quasi-apparatus - a calefacient chamber, a quasi-apparatus - transferring heat through the wall of the apparatus boiling pipes, quasi-apparatus - a vapor-liquid space - the inner part of the boiling pipes of the apparatus and the processes taking place in them. Then, if necessary, the considered system (element) is divided into its constituent elements, the parameters for each selected element and the process in the element are specified. For example, the division of an element (system) into subsequent systems, the calefacient chamber consists of quasi-devices of the vapor zone and condensate. The decomposition was carried out according to the degree of necessity and the possibility of research for making a decision.

In general, systemic thinking and multistage analysis of the system, analysis and synthesis of the heat exchange device is performed in the following sequence:

First stage. (Systemic thinking and analysis)
- preliminary consideration was given to the technological line for juice evaporation, which has a number of elements, including the heat exchanger itself;
- in the installation of heat exchange, an object is selected - a heat exchanger, quasi-apparatus of heat exchange are studied. This is a quasi-apparatus - a calefacient chamber, a quasi-apparatus - which transfers heat through the wall of the boiler's pipes of the apparatus, a quasi-apparatus - a liquid space - the inner part of the pipes of the apparatus. In each subsystem - in quasi-apparatus (element of the apparatus), many processes take place. From the set of processes, those processes are selected that are necessary for the correct decision-making of a given problem; the investigated process in the system is preliminarily studied;
- input and output parameters of both the apparatus and the investigated process are determined. Determining the relationship of parameters requires a deeper study of the apparatus system;
- elements are defined - quasi-apparatus - subsystems or subobjects. The considered system of a subobject (element) is divided into its constituent elements, the process and its parameters are specified for each selected element, etc. It is carried out according to the degree of necessity and the possibility of research to make an optimal decision. In this case, it is limited by the fact that the calefacient chamber consists of quasi-apparatus of the steam zone and the condensate zone

Second stage. (Determination of the relationship of parameters)
Determining the quantitative ratio of parameters requires the use of mathematical expressions, which leads to the use of mathematical or computer models.

Third stage. (Choosing the optimal solution)
Here, the requirements for quasi-apparatus are specified on the basis of systemic thinking and analysis. Optimization criteria are selected both for the primary object of the apparatus and for the quasi-apparatus of each hierarchical level. A way of finding the optimal solution is selected. The optimal solution is determined.

Mathematical modeling and calculation of the apparatus have their own specific features. On the basis of systemic thinking, the evaporator unit is decomposed and the heat exchanger under consideration is also decomposed into quasi-apparatus of heat exchange units, such as a quasi-steam zone and condensate unit (Figure 2).
The process in the calefacient chamber of the heat exchanger by heating with water vapor during its condensation is divided into the following elementary processes:
- the process of throttling of water vapor;
- the process of steam accumulation;
- cooling it down to the condensation temperature;
- the formation of condensation;
- thermal conductivity through the walls of the heat exchanger.

For a more detailed study, let us consider the process of heating with water vapor in an evaporator. Steam is transferred to the steam space through a valve - a restriction device.

![Technological line of juice evaporation](image)

**Figure 2.** Decomposition of the heat exchange apparatus into quasi-apparatus based on systemic thinking.

The calefacient chamber is a hydrodynamic capacity, the structure of flows, which can be expressed by the structure of ideal mixing, where the temperature of condensation of the heating steam in it throughout the total volume is usually the same. Therefore, in the mathematical description of the heating steam supply channel, the pressure in the quasi-apparatus – calefacient chamber can be considered as a model of ideal mixing.

For a mathematical description of the steam flow through the orifice, the following equation can be used:

\[ D = k \sqrt{P_L - P_s} \]  \hspace{1cm} (1)

where: \( k \) is the proportionality coefficient, \( (k = K \times F) \) is characterized by the flow area of the restricting device (regulating body).

Or in a computer display of a MATLAB application (Figure 3)

![Computer model of steam flow through the orifice](image)

**Figure 3.** Computer model of steam flow through the orifice.
In this case, the coefficient \( k = K \times F \) is characterized by the flow area of the restricting device (regulating body) and steam parameters (density, compressibility coefficient, etc.).

The elementary processes of apparatus, where the temperatures of the liquid throughout the volume will be close, can be attributed to heat transfer with ideal mixing. The process is described by a mathematical model with lumped parameters. From the heat balance equation we get:

\[
\frac{dt_k}{d\tau} = \frac{1}{m_k c_k} (Q_0 - Q - \Delta Q)
\]

where:
- \( t_k \) is the condensate temperature;
- \( m_k \) is the condensate mass;
- \( c_k \) is the heat capacity of the condensate;
- \( Q_0 \) is the amount of heat during steam accumulation;
- \( \Delta Q \) is the amount of heat by the leaving steam condensate;
- \( Q \) - the amount of heat transferred by the condensate by heat transfer to the outer surface of the wall of the heat-conducting pipe.

The amount of heat in the accumulation of steam:

\[
Q_0 = Di
\]  
(3)

where \( Di \) - vapor enthalpy.

The enthalpy of steam depends on its temperature \( T \) and according to the MATLAB (1) application program is the condensation temperature, it can be expressed in a computer display as:

\[
2514 + 1.53 \times u(1)
\]

\( T_l \) \( T_b \)

\( 2514+1.53*u(1) \)

**Figure 4.** Computer model of the enthalpy of water vapor in the computer display of the MATLAB application program.

The amount of heat by the leaving steam condensate:

\[
Q = D_k c_k t_k
\]

where:
- \( D_k \) - condensate consumption;
- \( c_k \) is the heat capacity of the condensate;
- \( t_k \) - condensate temperature.

The amount of heat with the leaving condensate is determined by multiplying the temperature \( t_k \) (or \( u(1) \), flow rate \( u(2) \) in the MATLAB application program) and \( c_k \) the heat capacity of the condensate (Figure 5.).

\[
\text{\{u(2)*c_k*u(1)\}}
\]

**Figure 5.** Computer model of the amount of heat by the outgoing condensate.

The amount of heat transferred by the condensate by heat transfer to the outer surface of the wall of the heat-conducting pipe:
\[ \Delta Q = \alpha_1 F_1 (t_k - t_c) \]  \hspace{1cm} (5)

where:
\( \alpha_1 \) is the coefficient of thermal conductivity;
\( F_1 \) - surface area of the heat exchanger wall;
\( t_c \) - wall temperature.

Or it is in the computer display of the MATLAB application program \((u(1), u(2))\) (Figure 6).

**Figure 6.** Computer model of the amount of heat transferred by condensate by heat transfer to the outer surface of the wall of the heat-conducting pipe.

The mass of condensate in the calefacient chamber is determined by multiplying the density \( Ro \) \((u(1))\) in the calefacient chamber by the volume of condensate, which consists of multiplying the outer surface of the pipe by the thickness of the condensate (Figure 7).

\[ F_1 * u(1) * (L) \]

**Figure 7.** Computer model of the mass of condensate in the calefacient chamber.

The condensation temperature of water vapor depends on the vapor pressure in the calefacient chamber and is described as a non-linear dependence:
\[ t_k = f(P) \]  \hspace{1cm} (6)

From the operating conditions of heat exchangers in the food and related industries, the condensation temperature of water vapor can be analytically determined by the equation [5]:
\[ t = 86 + 0.15P, \ ^\circ C \]  \hspace{1cm} (7)

where \( P \) is the pressure in MPa.

Or, for the pressure of water vapor in the calefacient chamber, the equation \( P = f(t_k) \) determines it from the condensation \( t_k \), temperature can be transformed in the MATLAB application program, by the model (Figure 8).

\[ 100 + 6.8*(u(1)-99) \]

**Figure 8.** Computer model of water vapor pressure in the calefacient chamber.

Thus, the process in the vapor space is represented by the following system of equations:
Based on the mathematical description in the steam space of the calefacient chamber, a computer model of hydrodynamic processes and heat changes in the heating chamber was compiled in accordance with the MATLAB application program (Figure 9).

\[
\begin{align*}
D &= \kappa \sqrt{P_L - P_k} \\
\frac{dt_k}{d\tau} &= \frac{1}{m_k c_k} (Q_0 - Q - \Delta Q) \\
Q_0 &= Di \\
Q &= D_k c_k t_k \\
\Delta Q &= \alpha_1 T_1 (t_k - t_c) \\
P &= f(t_k)
\end{align*}
\]  

(8)

As can be seen, the description of the dynamics of the vapor condensation process, including a first-order differential equation, indicates the time dependence of the transient process. In the case of a small mass of condensate, in the study of the dynamics of the apparatus process, this process can be described by the model of the amplifying link and included in the mathematical model of more inertial links. Then the mathematical model can be used to calculate the statics of the calefacient chamber process.

Thus, on the basis of the mathematical descriptions given in the equations, a computer model of the dynamics of the calefacient chamber process in the MATLAB application program was formalized, where the following parameters were introduced as output parameters: heating steam condensation temperature, wall temperature, heating steam pressure, heating steam flow through the regulating body. And at the inlet of the computer model of the calefacient chamber, the input parameters are indicated: steam pressure in the pipeline, heating water supply, change in the opening ratio of the heating water supply valve, heating steam temperature in the pipeline and wall temperature.

In the computer model of the quasi-apparatus of the calefacient chamber, the block with the regulating body equation shows that with an increase in the pressure in the heating water vapor supply line or a change in the valve-opening ratio, an increase in the steam pressure in the calefacient chamber occurs, and the condensation temperature also increases. The generalized computer model of the calefacient chamber in the MATLAB application program is shown in Figure 10.
At the inlet of the computer model of the calefacient chamber, the following input parameters are indicated: steam pressure in the heating steam supply pipeline, change in the valve-opening factor, heating steam temperature in the pipeline, and wall temperature.

Computer studies of the process in the calefacient chamber using the MATLAB program are shown in (Figure 11).

**Figure 10.** General view of the computer model of the processes in the calefacient chamber in the MATLAB application program.

**Figure 11.** Changing the heating steam pressure over time.

**Figure 12.** Change in the heating steam condensation temperature over time.
3. Conclusion

The technological unit and the pectin evaporation apparatus were analyzed by means of systemic thinking. A method has been developed for constructing a computer model of processes in the calefacient chamber of a heat exchanger using the MATLAB application program, based on the combination of models of the processes of the quasi-apparatus of the throttle, the steam zone, the steam condensate and the wall. Calculations on a computer model show stable changes in the calefacient steam pressure, wall temperature, condensation temperature of the heating steam and the wall, heating steam flow through the valve - the regulating body. A computer model of the process in the calefacient chamber will be used in the design of a steam-heated evaporator.

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