Mathematical model of evaporator-condenser

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Abstract. The basic provisions of the mathematical model of a condenser-evaporator in relation to air separation units are considered. All influencing quantities are shown, the main component blocks are highlighted, and the sequence of their solution is given. The model is based on a joint solution of the equations of hydrodynamics and heat transfer for tubular apparatuses using iterative calculations to clarify the initial values of the determining parameters both within individual blocks and between blocks. Application of the model is possible for both design and verification calculations with minimal changes. The development of the considered model is associated with the adaptation of its algorithm to machine calculation. One of the main directions is the inclusion of a database of parameters of working substances in the field of vapor-liquid states with the ability to automatically search and transfer the required thermophysical parameters on the evaporation and condensation lines in the model.

Condensers-evaporators have found application in many thermal engineering installations. They are especially widely used in cryogenic technology and are one of the essential elements that ensure the operation of almost any air separation and other gas mixture separation plant.

Condensers-evaporators in air separation plants are used to condense nitrogen by evaporating oxygen, i.e. represent heat exchangers with a change in the phase state of both substances involved in the heat transfer process.

The efficiency of the condenser-evaporator largely determines the efficiency of the entire plant. For example, an increase in the temperature difference between the working substances by 1°K leads to an increase in energy consumption for air compression up to 5% of the total energy costs [1]. On the other hand, a decrease in the temperature difference below the optimum value necessitates a significant increase in the heat transfer surface. Given the high-energy consumption and metal consumption of the air separation plants, it becomes obvious the need to optimize each of their elements, including the condenser-evaporator.

The most appropriate method of research and optimization of such large and expensive objects is mathematical modeling, because it allows you to objectively consider and compare many different options and choose the most suitable. In addition, the mathematical model limits the scope of a physical experiment to only checking the correctness of the model and determining the numerical values of the coefficients, which cannot be obtained analytically.

Condensers-evaporators of air separation plants operate in natural circulation mode, respectively, they have a complex relationship of thermal and hydraulic characteristics of the process of vaporization. The heat transfer from the side of the boiling liquid is determined by the circulation rate, which, in turn, can be found from hydraulic calculation with known values of heat fluxes and geometric dimensions of
the heat transfer surface, which are the target function of the optimization task. In addition, the boiling process is implemented simultaneously with the condensation process, which imposes restrictions on the ratio of heat fluxes and temperature differences in both processes. Thus, the model should be based on a system of equations describing the circulation of boiling liquid and heat transfer processes on both sides of the heat transfer surface.

The mathematical model, the scheme of which is shown in figure 1, includes five blocks: a block of input parameters, a block of pre-selected parameters, a block of hydraulic calculation, a block of thermal calculation and a block of output parameters. The calculation method is based on the principle of successive approximations.

![Figure 1. Scheme of the evaporator-condenser mathematical model.](image)
The input parameters block is similar for both design and verification calculations. As input parameters are used:

- \( Q \) – total heat load;
- \( p_{evap} \) – pressure on evaporation side;
- \( p_{cond} \) – pressure on condensation side;
- \( l \) – pipe length;
- \( d_{out} \) – pipe outer diameter;
- \( d_{inn} \) – pipe inner diameter;
- \( S \) – pipes pitch.

The block of pre-selectable parameters includes the determination of the physical parameters of the working media from the evaporation and condensation pressures, as well as the selection of parameters necessary to start iterations.

The group of physical parameters includes the temperatures of evaporation \( T_{evap} \) and condensation \( T_{cond} \) of the working flows, taking into account impurities, as well as the densities of the liquid \( \rho' \) and vapor \( \rho^* \), the coefficients of thermal conductivity \( \lambda \), the coefficients of dynamic viscosity \( \mu \) and heat of vaporization \( r \) on the sides of evaporation and condensation [2].

The parameters necessary to start iterations include:

- Average heat flow density on the evaporation side \( \bar{q}_2 \);
- Temperature depression on the evaporation side

\[
\delta t = \frac{0.5T_{evap}H\rho'_{evap}}{0.102r\rho^*_{evap}}
\]  

(1)

where \( H \) – relative liquid level, selected according to the conditions of explosion safety and value of \( \bar{q}_2 \);

- Average temperature driving force between heat exchanging flow

\[
\Delta T = T_{cond} - T_{evap} - \delta t
\]  

(2)

- Circulation rate \( w_0 \);
- Heat flow in a single channel

\[
Q_1 = w_0 f \rho'_{evap} f x
\]  

(3)

where \( f \) – channel cross-sectional area; \( x \) – vapor content at the exit of the evaporation channel.

The purpose of the hydraulic calculation unit is to clarify the circulation rate, the length of the economizer zone, pressures and temperatures in the characteristic cross sections of the channel. The calculation is based on the solution of the equation of the circuit hydrodynamic balance with natural circulation using the multistep (iterative) method. The hydraulic calculation unit is described in detail in [3].

The task of the heat calculation unit is to clarify the value of the heat flow density in the active pipe section according to the results of hydraulic calculation, as well as to clarify the available temperature driving force taking into account hydrostatic temperature depression. Thermal calculation is based on solving the criteria equations of heat transfer during condensation between pipes and evaporation inside pipes. When calculating the condensation, the heat transfer model with the condensation of a single-component steam on a vertical wall with a laminar flow of the condensate film is used. The calculation
of evaporation is based on the model of heat-exchange to a two-phase flow in a pipe [4]. The solution is carried out by a multistep (iterative) method. The heat flow density on the evaporation side is used as a criterion for the convergence of iterations. The heat calculation unit is described in detail in [5].

Hydraulic and thermal calculations are repeated in the same sequence if the preliminary and calculated values of the heat flow density differ by more than 5%. The accuracy of the calculation, as a rule, is sufficient after the second approximation.

The block of output parameters is final and includes the calculation of the basic geometric characteristics of the apparatus. As output parameters are considered [6]:

- Heat exchange surface area on the evaporation side

\[ F_{\text{evap}} = \frac{Q}{q_2} \]  

(4)

- Number of pipes in the pipe lattice

\[ n = \frac{F_{\text{evap}}}{\pi d_{\text{evap}} l} \]  

(5)

where \( d_{\text{evap}} \) – pipe diameter on the evaporation side;

- Diameter of the central circulation pipe

\[ d_{c.p} = \left( \frac{4 f_{c.p}}{\pi} \right)^{1/2} \]  

(6)

where \( f_{c.p} = \frac{V_{c.p}}{w_{c.p}} \) – cross-sectional area of the circulation pipe, \( V_{c.p} = \frac{\pi d_{\text{evap}}^2 n w_0}{4} - \frac{\pi d_{\text{evap}} n l q_2}{\rho'_{\text{evap}} r} \) – liquid volumetric flow rate in vapor flow, \( w_{c.p} = 0.97u \) – liquid velocity in the circulation pipe,

\[ u = 1.5 \left( \frac{g \sigma (\rho' - \rho^*)}{\rho^2} \right)^{1/4} \]  

– relative single bubble ascent rate.

In the verification calculation, the number of pipes in the pipe lattice is known, and the pressure on the condensation side is determined [7].

References
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