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Hydraulic calculation unit in the mathematical model of air separation plant evaporator-condenser

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Abstract. The hydraulic calculation, which is part of a mathematical model of a condenser-evaporator of a cryogenic air separation plant, based on the multi-step (iterative) method of equation of the hydrodynamic balance of a circuit with natural circulation.

To simulate complex systems, which include air separation plants (ASU), the method of separate analysis is applied, the basic unit of which is the calculation of the hydraulic situation [1], in the case of ASU used to determine the circulation rate in the natural convection contour.

Approximate calculation of the condenser-evaporator can be performed by the method without determining the circulation rate w_0 . This is done using a graph-analytical solution of the heat transfer task based on three equations that correspond to the processes of heat transfer from the condensing vapor to the outer surface of the pipe, through the pipe wall of a given thickness and from the inner surface of the pipe to evaporating liquid. However, the use of equations that determine the circulation rate in the contour of natural convection, allows us to obtain a more rigorous solution of the task.

The circulation rate when the process is stationary is determined from the condition of dynamic equilibrium of the driving head and the sum of hydraulic resistances of the lifting and lowering branches of the contour

$$\Delta p_{dh} = \Delta p_{lift} + \Delta p_{low}. \quad (1)$$

Using the designations shown in figure 1, the driving circulation head can be written as

$$\Delta p_{dh} = g[\rho'(H - l_{ec}) + \bar{\varphi}(\rho' - \rho'')(l_w - l_{ec})], \quad (2)$$

where ρ' – liquid density in the lowering system; ρ'' – vapor density at medium pressure in the pipe; $\bar{\varphi}$ – average true volumetric vapor content along the evaporating zone; $H = l_{low} - l + l_w$.

The true volumetric vapor content of the two-phase flow in the vertical channels is related to the circulation rate by the ratio

$$\varphi = \frac{w_0''}{w_0'' + w_0} \left(1 + \frac{w^*}{\frac{w_0''}{2} + w_0} \right)^{-1}, \quad (3)$$



where $w^* = 2,1 \left(\frac{\rho'}{\rho''} \right)^{0,2} \left(1 - \frac{\rho''}{\rho'} \right)^5 \sqrt{g \sigma \frac{\rho' - \rho''}{(\rho')^2}}$ – relative ascent rate of vapor bubbles;

$w_0'' = \frac{Q_1}{r \rho'' 0,785 d_{inn}^2}$ – reduced vapor velocity at pipe outlet; σ – surface tension; d_{inn} – pipe inner diameter; r – latent evaporating heat of oxygen; Q_1 – heat flow in one pipe.

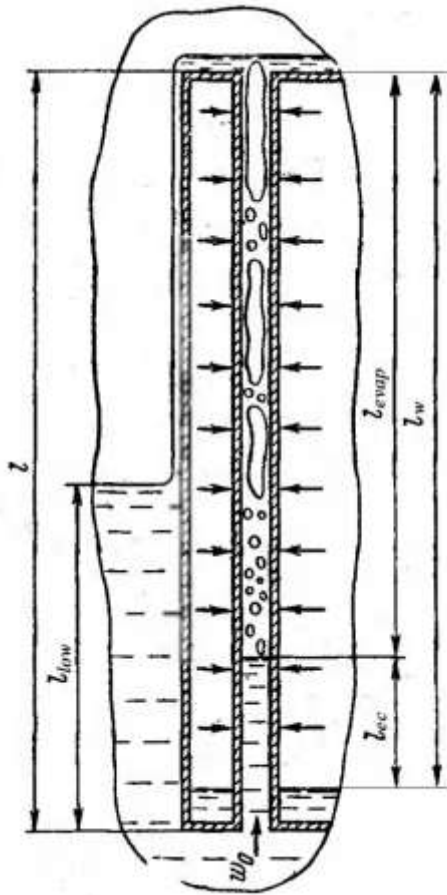


Figure1. Circuit scheme with natural circulation of evaporating liquid:

l – pipe length; l_w – working zone length;

l_{evap} – evaporating zone length; l_{ec} – economizer zone length;

l_{low} – length of the lowering part; w_0 – circulation rate.

Hydraulic resistance to the movement of the medium in the lifting part of the circulation loop is defined as the sum of the resistances of its constituent parts

$$\Delta p_{lift} = \Delta p_{in} + \Delta p_k + \Delta p_{ec} + \Delta p_{fr} + \Delta p_{acc} + \Delta p_{out}, \quad (4)$$

each of which is also associated with the circulation rate.

Resistance of liquid entry into the vapor generating pipe

$$\Delta p_{in} = \zeta_{in} \frac{\rho' w_0^2}{2}, \quad (5)$$

where ζ_{in} – input resistance coefficient.

Single-phase flow friction resistance in the zone $H_k = l - l_w$

$$\Delta p_k = \xi_k \frac{\rho' w_0^2}{2} \frac{H_k}{d_{inn}}, \quad (6)$$

where ξ_k – coefficient of friction resistance on the H_k zone.

Friction resistance of a single-phase liquid in an economizer zone of length l_{ec}

$$\Delta p_{ec} = \xi_{ec} \frac{\rho' w_0^2}{2} \frac{l_{ec}}{d_{inn}}, \quad (7)$$

where ξ_{ec} – economizer friction coefficient.

The friction resistance of a two-phase mixture at the evaporating zone of length l_{evap}

$$\Delta p_{fr} = \xi l_{evap} \frac{\rho' w_0^2}{2} \left[1 + \psi \frac{w_0''}{2w_0} \left(1 - \frac{\rho''}{\rho'} \right) \right], \quad (8)$$

where ξ – coefficient of friction of the evaporating zone; ψ – flow structure ratio.

Head loss due to two-phase flow acceleration

$$\Delta p_{acc} = \rho' w_0^2 (y_2 - y_1), \quad (9)$$

where complex $y = \frac{x^2}{\rho'' \varphi} - \frac{(1-x)^2}{\rho'(1-\varphi)}$ determined in the input and output sections of the pipe; x – vapor content.

Two-phase flow resistance to exit from the pipe

$$\Delta p_{out} = \zeta_{out} \frac{\rho' w_0^2}{2} \left[1 + \frac{w_0''}{w_0} \left(1 - \frac{\rho''}{\rho'} \right) \right], \quad (10)$$

where ζ_{out} – output resistance coefficient.

The pressure loss in the descending part of the circuit is determined by the speed of the descending movement of the liquid, the value of which should not exceed the speed of ascent of vapor bubbles formed during the heating of the walls of the lowering pipe. When this condition is met, the hydraulic resistance of the lowering system does not exceed 1% of the hydraulic resistance of the lifting circuit, therefore, in expression (1) we can assume $\Delta p_{low} = 0$ [2]. Also, due to the smallness, it is possible to neglect the components of the pressure loss Δp_k and Δp_{ec} in the lifting part of the circuit.

Thus, after conversion, equation (1) takes the form

$$g[\rho'(H - l_{ec}) + \bar{\varphi}(\rho' - \rho'')(l_w - l_{ec})] = \Delta p_{in} + \Delta p_{fr} + \Delta p_{acc} + \Delta p_{out}. \quad (11)$$

The calculation is carried out by a multi-step (iterative) method with the specification of the circulation rate and includes three steps (figure 2).

In the first step, the thermophysical and hydraulic quantities involved in equation (11) are determined. To start the calculation, it is necessary to set the preliminary values of the one pipe heat flow Q_1 and the circulation rate w_0 . To reduce the number of iterations a value of circulation rate can be approximately determined from the graphs [3]. Next, for the selected speed, we determine the values of the resistance coefficients according to the data [4]. The lengths of the contour zones are selected on the basis of the experience of designing devices of this type and subsequently also specified.

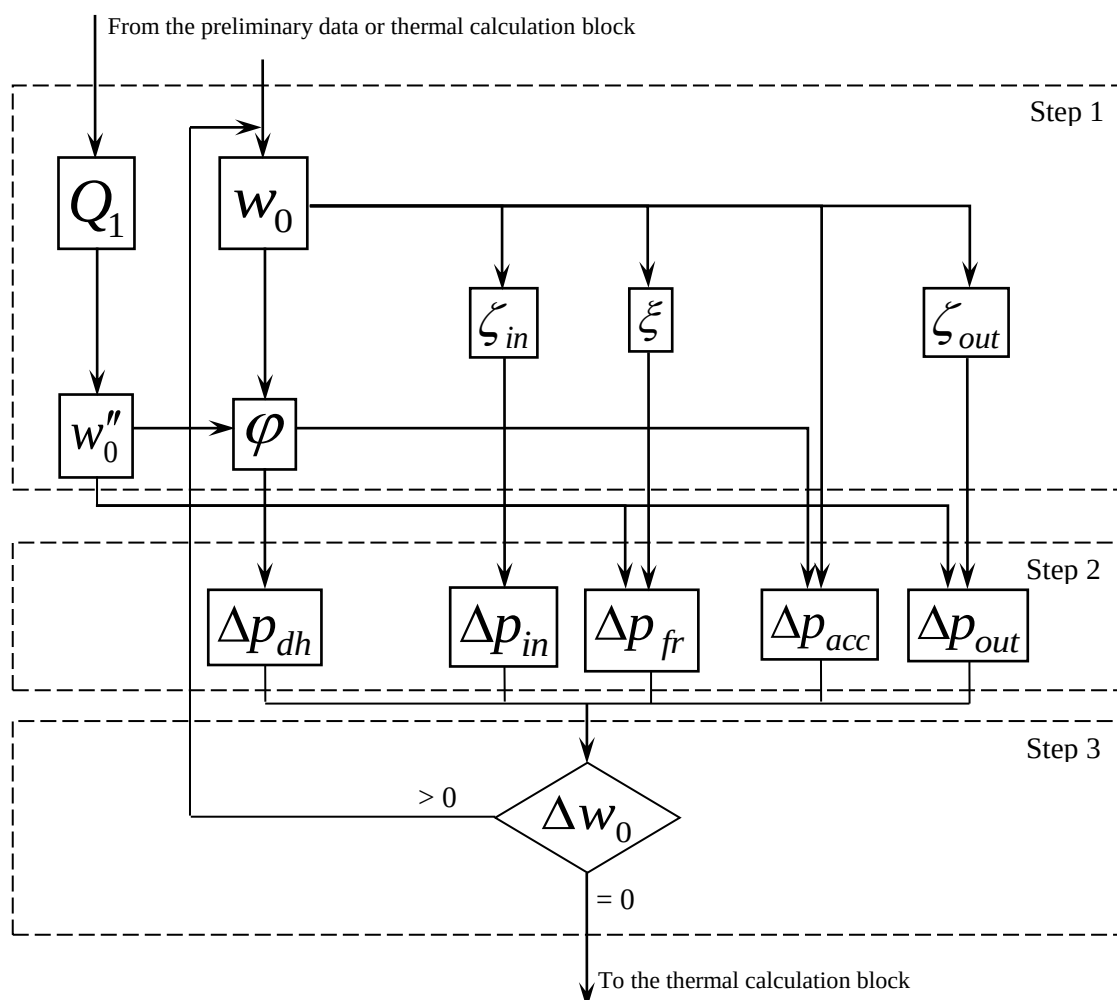


Figure 2. Scheme of the hydraulic unit calculation sequence.

In the second step, all the components of equation (11) are determined and the proximity to the balance of its left and right sides is estimated.

In the third step, a circulation velocity increment is selected (relative to the previous value) and the transition to the first step is performed. Iterations are performed until a given level of equation convergence is reached.

Upon completion of the iteration cycle, the results are transferred to the thermal calculation module. The results of the thermal module calculation are used to clarify the input parameters of the hydraulic module.

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