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MATHEMATICAL MODELING OF HEAT AND MASS TRANSFER IN MEMBRANE DISTILLATION PROCESS

Summary. *The paper presents the mathematical model of the process contact membrane distillation. The proposed simplified mathematical model of CMD, which takes into account the change in the temperature of the solution and the distillate channel along the membrane and the membrane module height. As well as describing the change in temperature of steam flow in the pores of the membrane. An algorithm for calculating mathematical model of contact membrane distillation.*

Keywords: *mathematical model, contact membrane distillation, heat transfer, mass transfer, distillate channel.*

INTRODUCTION

As a result of active commercial activity in Ukraine sharply reduced the quality of drinking water. Non-point sources, unfortunately, cannot always be considered as promising for solving the supply of water. As deteriorating groundwater quality. In recent years in the world practice widely adopting the technology of desalination of high salinity. In modern conditions the greatest use of received methods of water purification filters in the innovation. From an environmental point of view this technology has several disadvantages in comparison with membrane methods. This is caused, primarily, by dumping large quantities of contaminated water, the weight of which is 3–4 times higher than the mass of salts removed from the water, which is desalinated.

OBJECTIVE OF WORK

The introduction of membrane technology is accompanied by a number of problems arising in the first place, reliability and working resource of the membrane equipment. The installation process contact membrane distillation (CMD) requires the creation of process control system. The aim of the study was to develop a mathematical model of the process of contact membrane distillation.

METHODS

Installation of membrane distillation the membrane module includes, as a core element, the solution heater and the chiller, pumps.

In the process of membrane distillation of the heated mixture is separated (aqueous solution) comes into contact with one side of the hydrophobic membrane. The hydrophobic nature of the membrane prevents the penetration of water into the pores. Driving force CMD is the difference of partial pressures of solvent vapor in the air above menscase fluid on opposite sides of the membrane pores. The partial pressure in turn depends on the temperature of the relevant flow and component composition of the solution. The temperature of solutions in the membrane layer differs from the bulk due to heat transfer through the membrane. This phenomenon is called temperature polarization [1]. Temperature polarization has a negative impact on the performance of the CMD process due to the reduction of the temperature of the solution (saturated vapor pressure) on the evaporation surface and its increase on the condensation surface. It is therefore necessary to consider a temperature field in the channels of the solution and distillate. Depending on the number of factors moving of the substance through the membrane is carried out primarily by the following transfer mechanisms: a free molecule Knudsen diffusion molecular normal diffusion and viscous mass flow. Depending on the change of pore diameter, characteristics of the microstructure, the thickness of the membrane changes the contribution of each mechanism.

Due to the braking action of the solid skeleton of the membrane diffusion of the coefficients in these cases, are significantly lower values for unlimited volume of fluid.

Polymeric membranes used in membrane distillation are heterogeneous systems consisting of two phases — a polymer matrix and aggregate pores. The pores are characterized by heterogeneity of shape, size, orientation in space. Through the work time of the membrane its parameters change. Concentration polarization and salt formation on the membrane surface are one of the major problems in desalination of the mineralized natural water or seawater, the concentration polarization consists in increasing the concentration of solute substance at the membrane surface that contacts with the solution is processed. Consequently, the concentration polarization has an impact to the productivity of the separation process. Due to the preferential migration through the membrane of the solvent, the solute concentration at the surface increases, that is leading to a number of undesirable consequences. The driving force is reduced and performance decreases. With the obtaining the limit of solubility or the formation of a gel on the membrane surface sediments occur, which significantly reduces the partial pressure of the solvent from the giving side of the membrane and this causes a decrease in productivity, which is usually so substantial, the higher the initial permeability of the membrane. High concentration leads to partial or total destruction of the active layer of the membrane, pollution and poisoning, that is hydrophilic-hydrophobic violation of the balance of the surface layer of the membrane and changing its porosity. The above factors lead to significant deterioration of the membranes up to the complete loss of their semi-permeable properties. The process is shown figure:

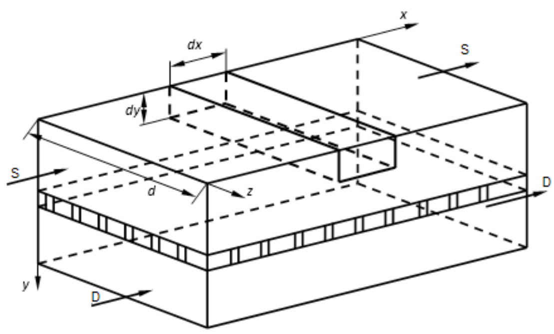

Fig. 1. The scheme of the elementary volume in the membrane module: S — solution, D — distillate

Already the mere appearance of the lateral extent of the membrane module, as an object of management, as well as the thermal polarization of the leads, essentially, to the need to consider it as a system with distributed parameters, only in some special cases in practice constructed with an acceptable rate to the system with lumped parameters. Such simplification of the membrane module while raising the accuracy requirements and the conformity of mathematical model of the real object becomes impossible.

The task of managing the process membrane distillation cannot be resolved at the appropriate level without regard to the quality of the specifics of the membrane module, as an object with distributed parameters. The mathematical model of heat — mass transfer in the process of contact membrane distillation [2], which includes the equations of continuity, motion, concentration (salt solution) and heat-mass transfer to the solution and the distillate. The transfer mechanism of the steam flow through the membrane is accounted for in the system of equations of hydrodynamics and heat-mass transfer for flow of vapor in the membrane.

RESULTS

The implementation of the calculation of this mathematical model requires a lot of time, which makes its application in control system is not very real. Therefore, a simplified mathematical model of the process CMD, which takes into account the temperature change of the solution and distillate channels along the membranes and the height of the membrane module. As well as describes the temperature change of the steam flow in the pores of the membrane. The feature of mathematical models is that the mathematical model of the process CMD takes into account the processes occurring in the membrane, namely, the dynamics of the temperature distribution of steam in the pores of the membrane, which has the form. The identification problem is formulated as a problem of minimization of the residual functional, which looks like this:

$$\gamma\frac{\partial T}{\partial t}+kV\frac{\partial T}{\partial y}=\alpha_M k\frac{\partial^2 T}{\partial y^2}; \quad (1)$$

γ — volumetric coefficient of porosity of the membrane;

k — the surface porosity of the membrane;

α_M — the diffusivity of vapor, m^2/s ;

V — the velocity of vapor in the pores of the membrane, m^2/s .

For the elementary volume of the solution (Fig. 1) taking into account the convection and thermal conductivity in the transverse direction of the channels is composed of equations of dynamics:

$$\frac{\partial\theta_s}{\partial t}+U_s\frac{\partial\theta_s}{\partial x}+V_s\frac{\partial\theta_s}{\partial y}=a_s\frac{\partial^2\theta_s}{\partial y^2}, \quad (2)$$

θ_s — the temperature of the solution, K;

U_s, V_s — accordingly, the speed of the solution in longitudinal and transverse directions, m/s;

a_s — the thermal diffusivity of the solution, m^2/s.

Taking into account heat transfer across the membrane boundary conditions on the membrane surface from the hot solution can be written:

$$-\lambda_s \frac{\partial \theta_s}{\partial y}\bigg|_{y=l_s} = \alpha_s\left[\theta_s - \theta_1\right], \qquad (3)$$

α_s — the coefficient of heat transfer from the hot solution to the surface of the membrane, $W/(m^2 K)$;

λ_s — the conductivity of the solution, $W/(m K)$;

θ_1 — the surface temperature of the membrane from the solution, K;

l_S — the height of the solution channel, m.

By analogy with equation (1) taking into account the distribution of the distillate temperature along the channel and at the channel height of the membrane amounted to the dynamic equation:

$$\frac{\partial \theta_D}{\partial t} + U_D \frac{\partial \theta_D}{\partial x} + V_D \frac{\partial \theta_D}{\partial y} = a_D \frac{\partial^2 \theta_D}{\partial y^2}, \qquad (4)$$

$$\theta_D(0,t) = \theta_{D0},\ \theta_D(x,0) = \theta_{Din},$$

$$-\lambda_D \frac{\partial \theta_D}{\partial y}\bigg|_{y=l_s+\delta} = \alpha_D\left[\theta_2 - \theta_D\right], \qquad (5)$$

θ_s — the temperature of the distillate, K;

θ_2 — the temperature of the membrane surface by the distillate, K;

U_D, V_D — accordingly, the velocity of distillate in the longitudinal and transverse directions, m/s;

a_D — the thermal diffusivity of the distillate, m^2/s;

δ — the thickness of the membrane, m.

Provided that the outer walls of the channels of solvent and distillate insulated debating for impermeable boundaries, the boundary conditions on the membrane surface:

$$\frac{\partial \theta_S}{\partial y}\bigg|_{y=0} = 0,\ \frac{\partial \theta_S}{\partial y}\bigg|_{y=l_s+\delta+l_D} = 0, \qquad (6)$$

The process of membrane distillation is accompanied by phase transition and is determined by the heat transfer and mass transfer in a membrane system. Heat transfer through the membrane occurs in two ways: thermal conductivity through the polymer structure and steamair mixture in the pores of the membrane [3]; the integral mass flow of solvent vapor. Thus, for the total heat flux through the membrane can be written:

$$\alpha_S(\theta_S - \theta_1) = -\bar{\lambda}_M \frac{\partial \theta_M}{\partial y}\bigg|_{y=l_s} + J_n r(\bar{\theta}), \qquad (7)$$

$$-\bar{\lambda}_M \frac{\partial \theta_M}{\partial y}\bigg|_{y=l_s+\delta} + J_n r(\bar{\theta}) = \alpha_D(\theta_2 - \theta_D), \qquad (8)$$

The calculation algorithm of mathematical model of the contact membrane distillation. The calculation has three phases, between which change the equations of calculation as changing the physical structure of installation: the area of flow of hot fluid; the diaphragm; the region of the cooling flow.

Limits switch program define the limiting conditions, when you go through them there is a change of payment in accordance with the nature of the apparatus which is responsible for the equation to describe this field.

The system of equations was solved numerical layer-by-layer method. The procedure for calculating the equations like this:

1. The temperature distribution of the solvent and the distillate to the input section specified. Taking into account the heat transfer through the membrane find the temperature at its surfaces θ_1, θ_2.

2. Was solving the system of equations (2), (1), (4) with different boundary conditions were the temperature distribution θ_s, T, θ_D on the next layer.

Table

Initial data for calculation of the mathematical model

Option	Symbol parameter	Unit of measure	The value
Module length	l	m	0,5
Channel width	d	m	0,3
The height of the channel	h	m	0,08
The time of observation	t_f	c	45
Step time discretization	d_t	c	0,01
The feed rate of solution	U_s	m/c	0,1
The feed rate of the distillate	U_D	m/c	0,1
The initial concentration of the solution	B_{S0}	kg/kg	0,1
The density of the solution at the inlet in MM	P_{S0}	kg/m^3	1114
The dynamic viscosity of the fluid	μ_S	Pa*c	1,7·10–3
The conductivity of the solution	λ_S	W/m*K	0,528
The thermal conductivity of the distillate	λ_D	W/m*K	0,5995
The porosity of the membrane	ε	-	0,8

The obtained temperature distribution along the height of the membrane module.

The graph shows the distribution of temperature field along the height of the membrane module at different distances from the entrance (Fig. 2) when the membrane layer from the hot solution there is a decrease in the temperature and cold side temperature rise, i.e. temperature polarization. The character of change of steam temperature in the membrane is different from linear.

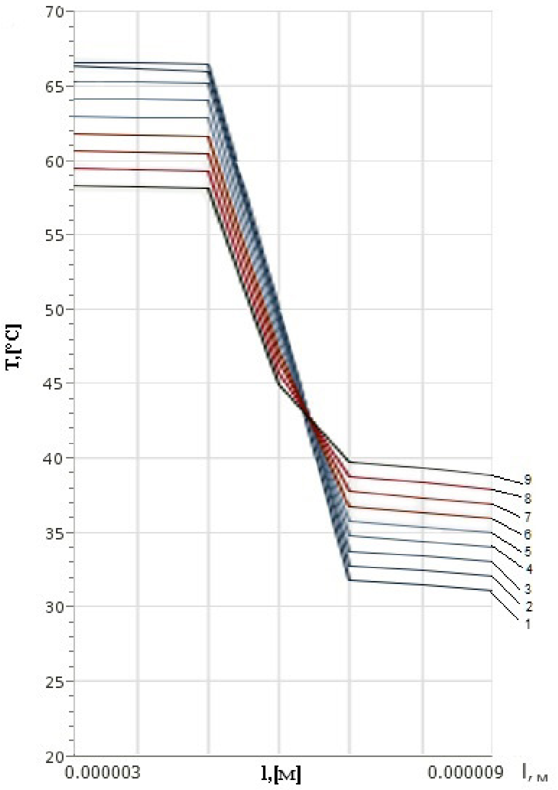

Fig. 2. The temperature distribution along the height of the membrane module:

1-x=0.005m, 2-x=0.03m, 3-x=0.055m, 4-x=0.08m, 5-x=0.105m, 6-x=0.13m, 7-x=0.155 m, 8-x=0.18 m, 9-x=0.205 m.

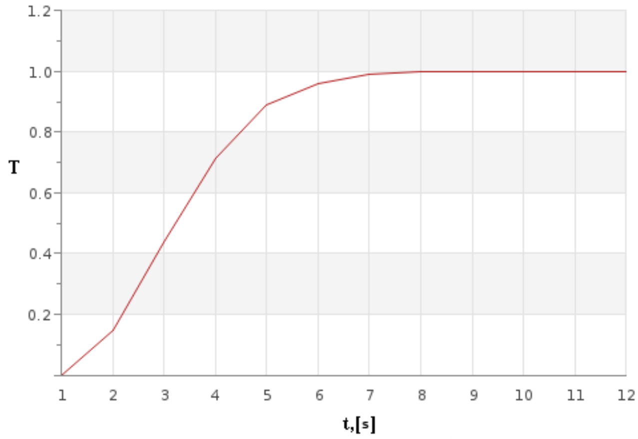

Fig. 3. Transient response by the channel "the flow speed of the solution inlet, the solution temperature at the outlet of the membrane module"

Also obtained transient response by the channel "the flow speed of the solution inlet, the solution temperature at the outlet of the membrane module" (Fig. 3).

CONCLUSIONS

The mathematical model of membrane distillation process, which takes into account the temperature distribution of steam in the membrane and the presence of temperature polarization. Reducing the influence of the temperature polarization is also greater feed rate of solution at inlet to the membrane module.

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