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Energy saving in distillation by combining vortex contact device and thermal effects

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ABSTRACT

Thermal effects are proposed to improve the efficiency of heat and mass transfer phenomena in distillation columns. The new design of the vortex contact device is developed. The paper investigates a combined use of the vortex devices that act as the contact stages of the distillation column and heat removal from the upper contact stage. Theoretical results on the distribution of vapor and liquid flows on each tray of the vortex device are obtained. The mass flow rate of the liquid phase as a result of the partial condensation of vapors is determined based on the amount of heat removed and the location of the tray with additional heat removal. A reduction in the mass flow rate of reflux during thermal distillation is experimentally established. The dependence of the average Murphree tray efficiency of the vortex contact stage is obtained depending on the reflux ratio at thermal distillation, which is confirmed experimentally. Experimental study shows an increase in the average efficiency of the stage by 10.6% compared to the adiabatic column without heat removal. A distillate mass fraction of 0.884 in the liquid phase is achieved at the outlet of the column when using 10 vortex contact stages and the working reflux ratio of 1.83. The comparative analysis of the use of the developed vortex contact devices in the thermal distillation process is performed in terms of the separation quality of the ethanol–water mixture, energy costs for the supply, and removal of heat.

Introduction

Distillation is the most common method of separating liquid mixtures. The energy consumption during the distillation in columns is significant and is associated with the high heat of evaporation of the mixture components and the continuous consumption of heating steam. In this regard, there is a growing interest in finding new engineering solutions to increase the efficiency of liquid separation processes. Various methods have been developed to achieve savings in both energy and capital costs to date, including replacement of contact devices and liquid distribution devices [1–6].

Marin-Gallego et al. [7] studied the conceptual object of a heat-integrated distillation column (HIDiC), known since 1970 [8], in which the vapor that leaves the stripping section is compressed before being fed to the distillation section, allowing the distillation column to operate at higher temperatures and pressure. Combining the principle of heat pump and nonadiabatic distillation, the HIDiC concept with reversible flow mixing provides a maximum reduction of separation energy costs. Earlier, Bruinsma et al. [9] proposed the configuration of a structured tray contact device (s-HIDiC). It was experimentally found that the efficiency of both heat and mass transfer of the tray-packing configuration using structured packing increases significantly with increasing throughput compared to HIDiC, but involves a rise in pressure drop per stage. However, such schemes have not been widely used because of the complexity of design and system management.

Implementation of distillation schemes with reversible flow mixing is possible due to the use of heat pumps (VRC steam recompression columns) by compression of low-pressure steam [10]. The increase in vapor pressure is accompanied by an increase in the condensation temperature, and it becomes possible to use the heat of their condensation to evaporate the same working medium with a light-volatile point [11,12]. The maximum temperature difference between the top and bottom of the column is 30 °C [13] as the main criterion that limits the use of such schemes.

The divided wall column (DWC) [14] has great potential for significant both energy and capital costs compared to adiabatic columns. The use of DWC due to internal heat integration has been proven to lead to a decrease in steam consumption by 10 to 50 % compared to conventional

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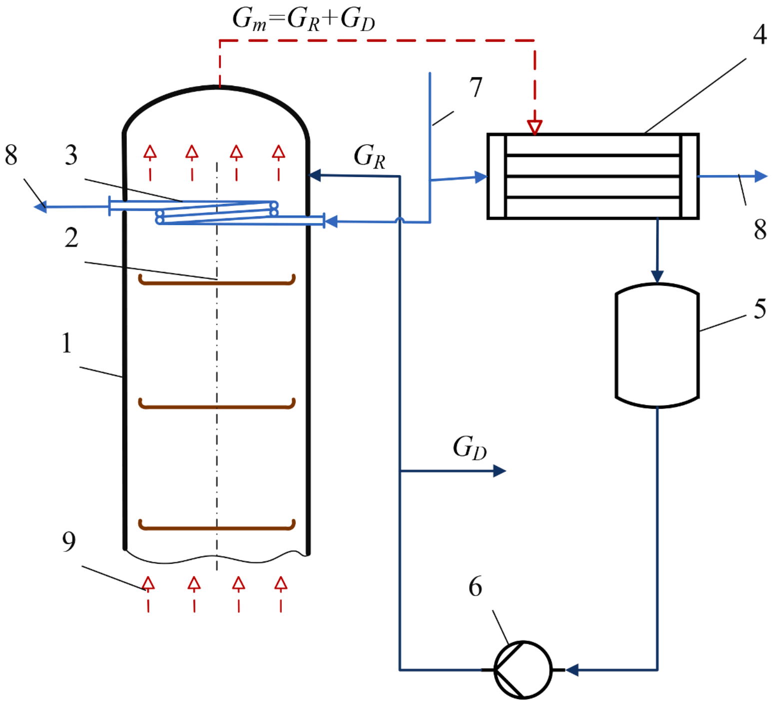


Fig. 1. Diagram of the tray column with a built-in dephlegmator: 1 – body; 2 – tray; 3 – coil dephlegmator; 4 – condenser; 5 – drum; 6 – pump; 7 – coolant water supply line; 8 – water outlet; 9 – vapor supply.

column configurations. At the same time, the number of equipment is reduced compared to columns with thermally coupled schemes [15]. On the other hand, the application of DWC requires an increase in the number of separation stages, which leads to an increase in capital costs and requires an economic assessment of the proposed engineering solutions.

Energy efficiency of the separation process can be improved by thermal distillation based on cooling the components at a temperature higher than the condenser temperature and heating at a temperature lower than the boiler temperature by installing heat exchangers at all stages of the column. In other words, the required amount of heat is supplied to each tray of the stripping section and a certain amount of heat is removed from each tray of the rectifying section. Voinov et al. [16] investigated the process of heat transfer in the diabatic column during the distillation of the ethanol–water mixture. Partial condensation of ascending vapors occurs on the surface of heat exchange pipes installed vertically along the column height, and evaporation of intermediate condensate occurs on the surface of horizontal trays.

Based on Fonyo’s work [17,18] on reversible distillation and Rivero’s work [19] on thermal distillation, Koeijer et al. [20] revealed the laws of optimal design of the thermal distillation column, in particular that intermediate heat exchangers are only required in the upper and lower parts of the column. Moreover, the greater the driving force, the fewer heat exchangers are required. If heat exchangers are located farther away than the boiler and condenser, the lower the throughput and heat transfer area. The redistribution of vapor and liquid flow across trays is required to maintain optimal column resistance and prevent column flooding. The column diameter at the top and bottom should also be reduced. At the same time, although diabatization of the distillation process can effectively reduce the entropy production rate, as confirmed by the results of exergy analysis [21,22], diabatization can lead to an increase in both the cost of both the equipment itself and its operation, since the total heat load supplied or removed in the diabatic column is higher than in the adiabatic one. The evaluation of economic characteristics provides more information on the feasibility of diabatization of stages in the distillation column [23].

Werle et al. [24] proposed the use of distributed heating applied along a distillation column with the sieve trays. Based on experimental results, they concluded that this heating system reduces the transient operating time by 40 % and the energy required for the startup of the pilot column by 33 %, compared to the conventional approach. However, their CFD study revealed [25] that a distributed control strategy using electrical resistances in intermediate trays of a distillation column negatively affected the hydrodynamics of the trays.

Marangoni et al. [26] proposed the introduction of heat tray distributed sources in combination with a boiler to control a distillation column. The experimental results showed that the use of the combined heat supply reduced the hydraulic delay in the column and, consequently, the transition time. In a later study, the authors [27] developed a control strategy with distributed corrective action for the distillation column. It consisted of a dual temperature control combined with additional heating in a tray of the column. They found that the shortest transition time is achieved when the inner loop is close to the feed (disturbance).

Mello et al. [28] estimated the application of a control strategy with distributed cooling action applied to one tray of the rectifying section of a distillation column. The results showed that distributed control provides better performance compared with conventional control for the analysis of the distributed action either in stripping or rectifying section of the column. Further in the work [29] the authors studied the use of distributed-action control with simultaneous heating and cooling in trays of a diabatic distillation column integrated with conventional control on boiler and condenser. They found that the distributed control strategy allows a significant reduction in transition time, improving quality and productivity for the distillate.

Thus, the energy costs of separation in systems with partially coupled heat flows are averaged between conventional distillation schemes and systems with fully coupled heat flows. In general, systems with reversible flow mixing and coupled heat flow can significantly reduce the energy costs for the separation of various mixtures. In each case, this positive effect depends on the composition of the mixture and the relative volatility ratio of the components to be separated.

The technical and economic parameters of the distillation apparatus depend on the efficiency of the contact devices [30]. As the stage

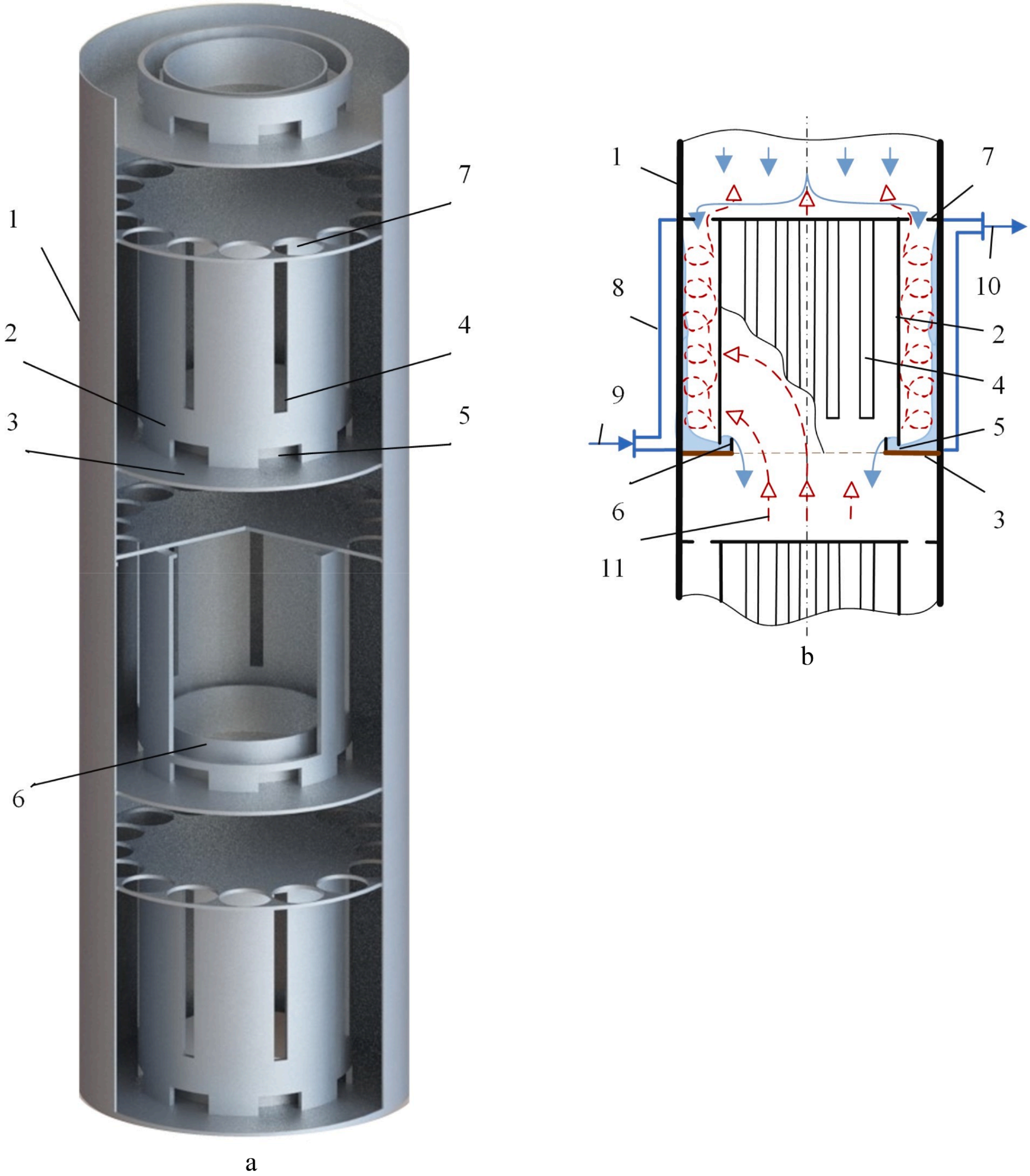


Fig. 2. Diagram of the column apparatus with vortex contact stages: a – 3D model of the column (without cooling jacket); b – flow layout; 1 – body; 2 – internal pipe; 3 – base; 4 – slots; 5 – liquid passage openings; 6 – water seal; 7 – vapor passage openings; 8 – cooling jacket; 9 – coolant water inlet pipe; 10 – water outlet pipe; 11 – vapor supply.

efficiency becomes higher, the reflux ratio decreases, which for adiabatic distillation determines the energy consumption for supplying heat to the column boiler and the discharge into the dephlegmator and condenser. However, in thermal distillation processes, the term reflux ratio determines only the flow rate of liquid supplied for irrigation to the upper part of the distillation column. In this case, reflux (phlegm) is generated in the column independently due to external sources of cooling the vapor–liquid mixture, resulting in condensation of excess vapors in the column.

Implementing the thermal distillation process as the multistage tray column is shown in Fig. 1. When the vapor flow 9 reaches a dephlegmator 3, that built-in at the top of the column (over the first tray 2), it partially condenses to form a reflux. The reflux flows down to the bottom trays, where it mixes with the main fluid flow and partially evaporates. Thus, by partial condensation of the vapors rising in the column, it is possible to achieve a decrease in their mass flow rate. Then the vapors enter the inter-pipe space of a condenser 4, where they are completely condensed by the coolant water circulating inside pipes. In very tall industrial columns, to reduce the height of the distillation units, the condenser is installed below the top of the column. Therefore, in the problem under study, a pump 6 is used to supply distillate and flux. Circulating water works as a coolant agent, which enters both the condenser 4 and the other into the dephlegmator 3. So, the total mass flow rate of water entering both the condenser and the dephlegmator remains constant. Moreover, it is possible to reduce the required heat transfer surface of the condenser. Therefore, when the built-in the dephlegmators in distillation columns, no additional energy consumption is required to supply the coolant.

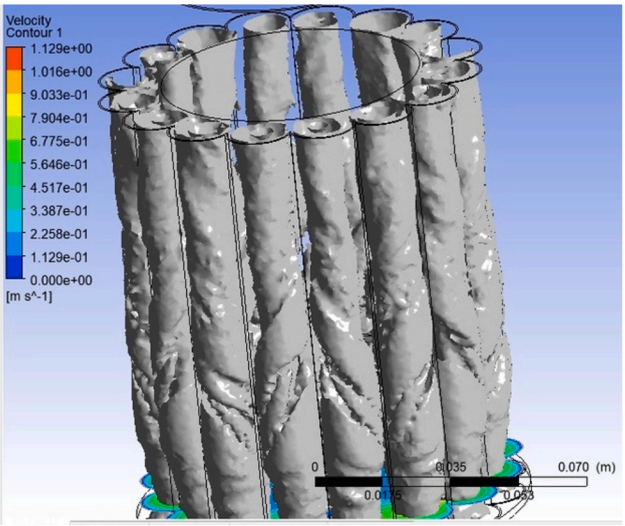


Fig. 3. Vortex formation in the annular space of the contact device.

The estimation of the operating parameters of the coil dephlegmator built in the column of 0.6 m in diameter shows that the heat flow with a heat exchange surface of 0.44 m^2 can reach 41.84 kW with a water flow rate of 0.6675 kg/s and an initial temperature of 20 °C. The temperature of the coolant (water) at the dephlegmator outlet was 35 °C. The temperature of the vapor entering the tray was assumed to 79 °C. In addition, note that the amount of heat removed from the trays can be controlled by the flow rate of water in the dephlegmator.

Thus, the installation of dephlegmators built into the column provides additional condensation of heavy-volatile components, while evaporating light-volatile fractions of the mixture. Such organization of thermal effects along column height makes it possible to control and optimize the hydrodynamic pattern inside the apparatus in terms of selecting the ratio of the liquid and vapor loads to reach the maximum possible efficiency of the contact devices.

However, the greatest benefit of thermal distillation lies in the combined use of new contact devices to enhance heat and mass transfer processes [31–33]. Thus, the authors of the article developed vortex devices that provide intensive interaction of the vapor–liquid phases.

Fig. 2a shows the realization of the thermal distillation process on the column apparatus, in which the developed vortex contact devices are used as a contact stages. Each vortex contact device represents two coaxial pipes (external and internal) that form an annular space between them, in which a vortex dispersion-annular vapor–liquid flow in the vertical channel occurs. This is achieved because the internal pipe 2 that has slots 4 designed to pass vapor into the annular gap. The vapor passing through the slots (without the need to create high radial velocities, i.e., starting from a relatively low vapor velocity), swirls, forming two annular vortex flows. It should be noted that at the operating gas velocities from 1 to 25 m/s (on the full cross section of the device), a vortex structure is formed in the annular space of the device for the water–air system [34].

The liquid, passing through the openings 5 of above the contact device installed on the basis 3, flowing through the water seal 6, flows down to the cover of the cylindrical pipe 2. Then, the liquid breaks up into droplets, which are thrown to the wall of the vortex device under the action of centrifugal forces, where a film flow is formed.

The following flow pattern is observed along the entire height of the internal pipe 2 in the annular space of the device (Fig. 2b). The liquid flowing along the inner wall of body 1, under the action of a swirled flow of vapor, breaks into single droplets of liquid, forming a swirling vapor–liquid flow, as shown in Fig. 3. The vortex interaction of vapor and liquid phases in the annular space of the device is characterized by a developed and constantly renewing phase contact surface, high heat and mass transfer coefficients, which leads to an increase in the efficiency of the heat and mass exchange device. This provides high values of the specific heat flow through the wall of the contact stage to the coolant agent during thermal distillation.

After intensive phase contact, the vapor–liquid mixture enters the separation zone, where a flat disc with openings 7 is installed for vapor outlet. The liquid, which is mostly in the outer swirled layer, hits the flat disc and flows down the inner wall of body 1. The separated gas is directed upwards into the internal pipe of the upper installed vortex device of the column. The liquid is drawn out of the contact device through openings 5 and a water seal 6. To implement the process of thermal distillation using the vortex contact stage developed, a cooling jacket 8 is mounted, where the coolant (water) is supplied through the inlet pipe 9. The coolant is discharged through the outlet pipe 10 (Fig. 2b).

The main feature of the vortex device is the formation of a stable vortex structure in the annular space of the device; therefore, there is no need to use special structural elements to swirl the gas–liquid flow. Flow swirling occurs due to the division of the flow into two equal vortices rotated in opposite directions, providing support for the neighboring vortices. The geometric dimensions of the contact device are selected taking into account equal flow conditions for the gas passage.

The formation of a swirling two-phase flow in the vertical channel of the proposed device makes it possible to achieve almost perfect mixing in the cross section of the device, which makes it possible to increase the efficiency of heat and mass transfer. In this case, numerical studies show that the heat transfer coefficient of 14747 W/(m^2·K) is achieved on the inner wall of the device at an average liquid flow rate of 1 m/s. High specific heat flows through the wall of the contact device and constant renewal of the heat transfer surface allow the most efficient transfer of heat to the cooling agent in the jacket during vapor condensation in the annular space.

According to previous numerical and experimental studies of thermal distillation processes with heat removal in the column rectifying section, an increase in the efficiency of separation processes in the contact stage was observed, starting from 10 % [35] and up to 3–4 times [36] compared to adiabatic distillation. It has been found that the Murphree tray efficiency can be higher than one [16]. Following [37], the equilibrium of the contacting phases for the water–air system is reached at the vortex contact stage with a height of 400 mm. In addition, many authors note that the use of thermal effects in the heat and mass transfer apparatus can reduce energy costs. Therefore, the performance evaluation of the column with various contact devices for thermal distillation processes is relevant.

The present paper aims to study thermal distillation processes to improve the energy efficiency of heat and mass transfer phenomena in the column apparatus with the additional dephlegmator. Two tasks had to be performed to achieve the objective of this study.

1. To evaluate the influence of the amount of additional heat removed from the upper tray on the process parameters of the distillation column operation.
2. To perform theoretical and experimental studies of the efficiency of the developed vortex contact devices in the thermal distillation process with additional heat removal.

In particular, the first task includes determining the degree of influence of different amounts of heat additionally removed from the upper part of the tray column on the mass flow rate of vapor and liquid and concentration of the light-volatile component in the liquid and vapor phases on each tray at a constant reflux ratio. In addition, the process parameters of the thermal distillation process are determined by the change of the heat power of the dephlegmator built into the column, taking into account the constant amount of heat supplied to the column boiler. Besides, the effect of additional heat removal from trays is assessed on their efficiency with change of ratio of mass flow rates of

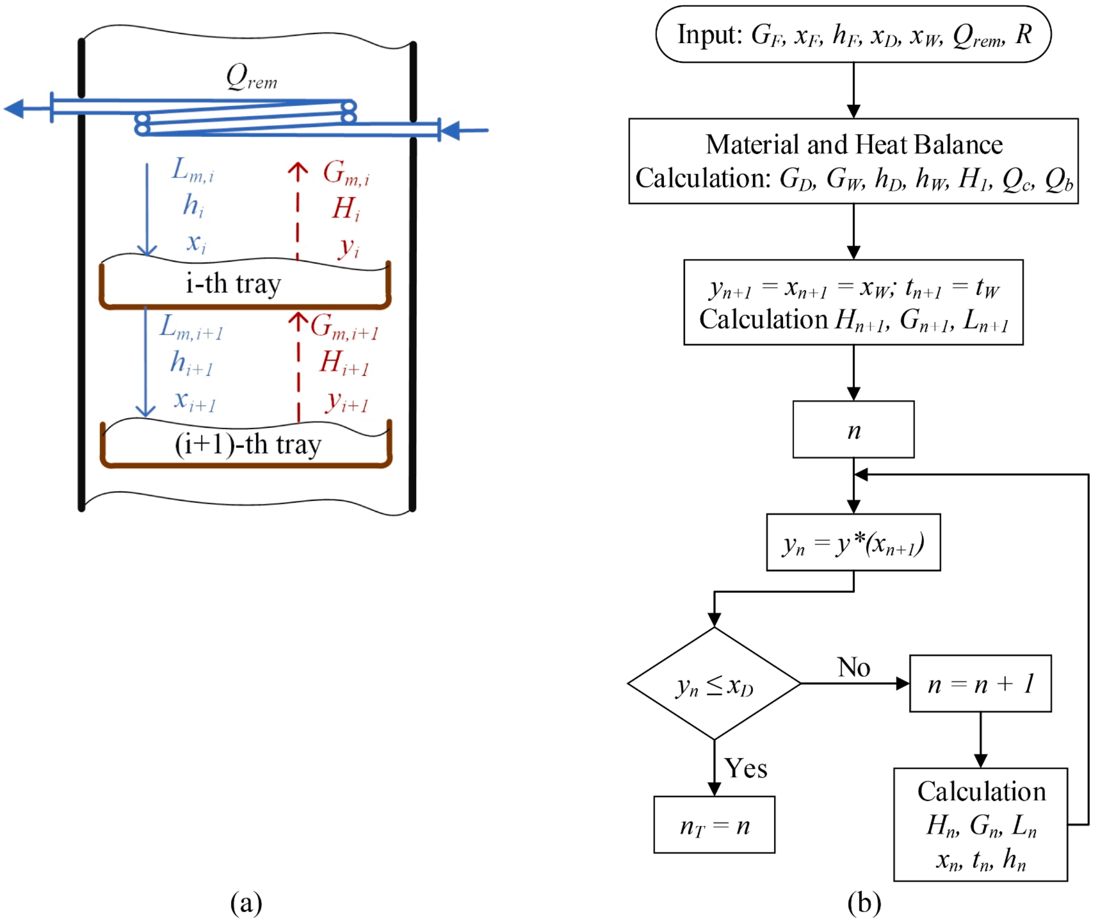


Fig. 4. Calculation algorithm: a – diagram for balance calculations; b – computation scheme.

liquid and vapor.

The second task is to test the efficiency of the developed vortex contact devices used in the column during the thermal distillation process. In addition, the influence of the amount of heat removed from the upper vortex stage of the column on the process parameters of the setup, including the heat consumption for evaporation and condensation of working fluids, and the reflux ratio, is studied.

Methodology

Calculation algorithm

The studies were carried out on a distillation column with 11 trays. The initial mixture for separation by distillation is ethanol–water. The mixture with a temperature of 80 °C enters the distillation column on the sixth tray with a mass flow rate of 1000 kg/h. The mass fraction of ethanol in the initial mixture was taken equal to 0.4 based on the data of the industrial column for distillation and recovery of reflux ethanol from the epoxidate fraction with a capacity of 1000 kg/h. The top of the column (in the first tray) has a temperature of 79.2–79.7 °C and an atmospheric pressure. The pressure drop in the column was taken to be 30 kPa. Under these conditions, the temperature of the column bottom was 106.7 to 106.8 °C. Requirements for the quality of separation products: the concentration of ethanol at the bottom of the column is not over 0.0034 wt%. The liquid temperature on the 8th tray of the column, equal to 98 °C, was taken as a control for the process parameters of the column distillation calculation.

The calculation of the composition of the liquid and vapor phases and their mass flow rate on each tray of the distillation column is based on the tray-by-tray distillation method. The calculation diagram is given in Fig. 4a. The trays are numbered from top to bottom, starting from the upper 1st tray of the column. The subscripts for the liquid flow rate L_m, specific enthalpy of ethanol–water mixture in a liquid form h_i, and the concentration of the light-volatile component in the liquid phase x_i correspond to the inlet at the i-th tray, but for the vapor flow rate G_m, specific enthalpy of ethanol–water mixture in a vapor form H_i, and the concentration of the light-volatile component in the vapor phase y_i correspond to the outlet.

For the rectifying section of the distillation column, the equations of material and heat balances, taking into account the additional removed heat, can be written as follows.

$$\begin{gathered} G_i - L_i = G_D \\ G_iY_i - L_iX_i = G_DX_D \\ G_iH_i - L_ih_i = G_Dh_D + Q_c + Q_{rem} \end{gathered} \tag{1}$$

where G_i is the mass flow rate of the vapor at the outlet of the i-th tray, kg/s; L_i is the mass flow rate of liquid at the inlet to the i-th tray, kg/s; G_D is the mass flow rate of distillate, kg/s; Y_i is the mass fraction of light-volatile component in the vapor phase at the outlet of the i-th tray; X_i is the mass fraction of light-volatile component in the liquid phase at the inlet to the i-th tray; X_D is the mass fraction of light-volatile component in the distillate; H_i is a specific enthalpy of a ethanol–water mixture in a vapor form at the outlet of the i-th tray, J/kg; h_i is a specific enthalpy of ethanol–water mixture in a liquid form at the inlet to the i-tray, J/kg; h_D is a specific enthalpy of ethanol–water mixture in a liquid form in distillate, J/kg; Q_c is heat flow in the condenser, W; Q_{rem} is heat flow of the built-in dephlegmator (additional removed heat), W.

For the stripping section of the column, equations of material and heat balance can be written in the classical form:

$$\begin{gathered} L_i - G_i = G_W \\ L_i X_i - G_i Y_i = G_W X_W \\ L_i h_i - G_i H_i = G_W h_W - Q_b \end{gathered} \tag{2}$$

where G_W is the mass flow rate of bottom product, kg/s; X_W is the mass fraction of light-volatile component in bottom product; h_W is a specific enthalpy of ethanol–water mixture in a liquid form in bottom product, J/kg; Q_b is heat flow in the boiler of the column, W.

The composition of the liquid that leaves the bottom tray of the column is equal to the composition of the bottom product, and the temperature of this liquid is equal to the boiling temperature of the bottom product. By determining the enthalpy of the vapor coming from the boiler of the column on the bottom (n-th) tray, calculated at the temperature and composition identical to the temperature and composition of bottom product, it is possible to find the mass flow rate of vapor flowing to the bottom tray according to the following equation:

$$G_{n+1} = \frac{Q_b}{H_{n+1} - h_{n+1}} \tag{3}$$

where H_{n+1} is a specific enthalpy of ethanol–water mixture in a vapor form at the outlet of the boiler, J/kg; h_{n+1} is a specific enthalpy of ethanol–water mixture in a liquid form at the inlet of $(n+1)$ tray, J/kg,$h_{n+1} = h_W$; n is the number of trays.

From the first equation of the Eq. (2), the mass flow rate of liquid flowing down from the n-th tray can be determined as:

$$L_{n+1} = G_{n+1} + G_W \tag{4}$$

Then, from the equilibrium data for the ethanol–water mixture, the composition of the vapor coming out of the bottom n-th tray can be found be the formula:

$$y_n = y^*(x_{n+1}) \tag{5}$$

where $y^*(x_{n+1})$ is the equilibrium mole fraction of the light-volatile component in the vapor phase at$x_{n+1} = x_W$; x_{n+1} is the mole fraction of the light-volatile component at the inlet to the $(n+1)$-tray or at the outlet of the n-th tray in the liquid phase.

Next, it is possible to determine a specific enthalpy of vapor of the composition found on the bottom tray at the temperature $t_{n+1} = t_W$. The mass flow rate of vapor, as well as the mass flow rate, composition, and temperature of the liquid flowing from the $(n-1)$-tray to the n-th can be found from the Eq. (2) by simple iterations. As a first approximation, it is possible to accept the mass flow rate of vapor coming out of the n-th tray equal to the mass flow rate of vapor coming from the boiler to the n-th tray. Then, the mass flow rate of the liquid entering the n-th stage from the above tray can be determined by the equation:

$$L_n = G_W + G_n \tag{6}$$

From the second equation of the Eq. (2), it is possible to determine the composition of the liquid at the inlet to the n-th tray:

$$x_n = \frac{G_w x_w + G_n y_n}{L_n} \tag{7}$$

Next, it is required to check the previously accepted mass flow rate of vapor coming out of the n-th tray by the equation:

$$G_n = \frac{Q_b + G_W(h_n - h_W)}{H_n - h_n} \tag{8}$$

Thus, the Eqs. (4)–(8) are repeated until the mole fraction of the light-volatile component in the liquid phase of the feed mixture composition is reached, as shown in Fig. 4b.

To calculate the subsequent stages in the rectifying section of the column, the Eq. (1) is solved by successive iterations, similar to the solution of Eq. (2). To do this, it is necessary to set the flow rate of vapor G_{i+1} and find the flow rate of liquid from the equation:

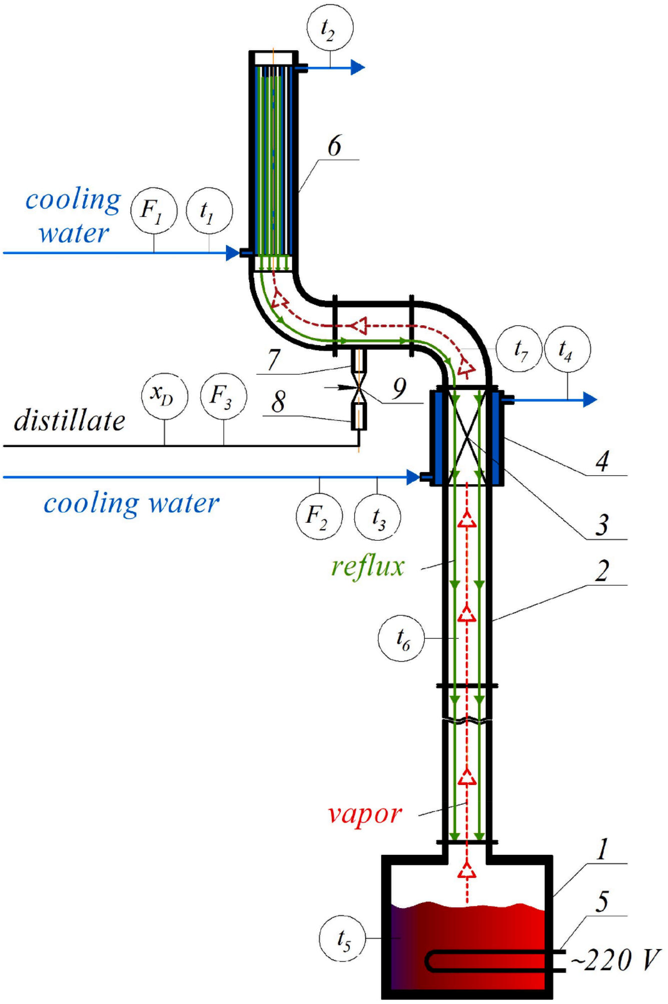


Fig. 5. Experimental setup: 1 – boiler; 2 – body; 3 – vortex contact stage; 4 – cooling jacket (dephlegmator); 5 – electric heater; 6 – condenser; 7 – pipe; 8 – probe for distillate; 9 – needle valve.

$$L_{i+1} = G_{i+1} - G_D \tag{9}$$

Then, it is possible to determine the composition of the liquid from the second equation of the Eq. (1):

$$x_{i+1} = \frac{G_{i+1} y_{i+1} - G_D x_D}{L_{i+1}} \tag{10}$$

After determining the boiling temperature and enthalpy of the liquid of this composition, a new approximation for the mass flow rate of vapor can be found according to the equation:

$$G_{i+1} = \frac{Q_c + G_D(h_D - h_{i+1})}{H_{i+1} - h_{i+1}} \tag{11}$$

If there is a built-in dephlegmator located on the i-th tray in the rectifying section of the column, the mass flow rate of vapor can be determined:

$$G_i = \frac{Q_c + Q_{rem} + G_D(h_D - h_i)}{H_i - h_i} - \frac{Q_{rem}}{r_i} \tag{12}$$

where r_i is the specific heat of vapor condensation of the mixture on the i-th tray, J/kg.

The specific condensation heat of vapors r depends on the position of the tray with additional removed heat and on the composition of the mixture on this tray:

Fig. 6. Photo of the vortex contact device.

$$r = r_{light}X + r_{heavy}(1 - X) \tag{13}$$

where r_{light} and r_{heavy} are the specific heat of condensation for the light- and heavy-volatile components of the mixture, respectively, J/kg; X is the mass fraction of the light-volatile component of the mixture.

The amount of liquid phase resulting from the condensation of ascending vapors in the distillation column can be determined by the equation:

$$\Delta L_m = \frac{Q_{rem}}{r} \tag{14}$$

where ΔL_m is the mass flow rate of the liquid produced by condensation of vapors on the tray, kg/s.

Trial calculations showed that the mass flow rate of the reflux could be reduced by the amount of additional reflux formed in the column due to partial condensation of the rising vapors.

Experimental procedure

Experimental studies of thermal distillation with vortex contact stages were performed on the ethanol–water mixture using an experimental setup (Fig. 5), which consists of boiler 1 with a 3 kW tubular electric heater 5, a distillation column and a condenser 6. The setup operates in a periodic mode.

The body of column 2 includes two shell sections with a height of 500 mm and an inner diameter of 47.3 mm. The upper (rectifying) section of the column has a cooling jacket that acts as a dephlegmator 4 with a height of 100 mm. Heat transfer from the cooling water occurs through the wall of the body, the heat transfer surface is 0.0307 m^2. The outer diameter of the cooling jacket is 76 mm. To condense the remaining part of the rising vapors, the tube condenser 6 is used 275 mm in length, consisting of 8 tubes with a 12 mm in diameter. The distillate product is collected through a pipe 7 and a probe 8. The distillate flow rate, and hence the reflux ratio, is regulated by a needle valve 9.

Inside the shell column, ten developed vortex contact devices 3 with a height of 100 mm were installed (Fig. 6). The height of the contact zone of vapor–liquid phases in the annular gap of the device was 90 mm. The internal pipe was 32 mm in diameter. Six slots were made with 4 mm wide and 45 mm high along the height of the internal pipe to form a vortex structure. In the annular space, there is a flat disk with 12 openings for the vapor outlet with a diameter of 6 mm. The outer surface of body 2 of the column was insulated.

The flow rate of the cooling water entering the condenser varied from 14.0 to 36.1 kg/h, and in the dephlegmator jacket from 4.41 to 35.90 kg/h. The water temperature at the inlet and outlet of the condenser and the jacket of the dephlegmator was measured by a two-channel meter regulator OWEN 2TRM1. Fig. 5 shows the actual location of the sensors for measuring vapor and liquid temperatures, distillate concentration, and liquid phase flow rate.

The experiments were carried out at the initial volume fraction of ethanol in a column boiler of 15–25 %. The composition of the test mixture was determined using a Megeon 72014 alcohol refractometer with a relative error within 1 % at 0–60 % and 2 % at 60–80 %, and an ASP-3 70–100 hydrometer with an error of ± 0.5 %. Ethanol concentration was measured in the liquid phase after complete vapor condensation.

In the course of experimental studies, the heat flow of the vapor mixture entering the column from the boiler was changed from 628.1 to 1277.5 W. When heat is removed from the upper contact stage, the average heat flow ranges between 246.3 and 255 W, that is, 32.1–34.6 % of the total heat in the condenser and the dephlegmator. In experimental studies, the reflux ratio varied between 1.60 and 2.81.

The amount of heat supplied to the apparatus can be determined based on the heat balance:

$$Q = Q_c + Q_{rem} + Q_l \tag{15}$$

where Q_c is the heat flow in the condenser, W; Q_{rem} is the additionally removed heat (heat flow in the dephlegmator), W; Q_l is heat loss (taken at 3 % of total heat), W.

The heat flow removed in the condenser is determined by the formula:

$$Q_c = L_m c_p (t_2 - t_1) \tag{16}$$

where L_m is the mass flow rate of water in the condenser, kg/s; c_p is the specific mass heat capacity of water, J/(kg·K); t_1 is the condenser inlet water temperature, K; t_2 is the condenser outlet water temperature, K.

The heat flow removed in the dephlegmator can be estimated as:

$$Q_{rem} = L_m c_p (t_4 - t_3) \tag{17}$$

where t_3 is the dephlegmator inlet water temperature, K; t_4 is the dephlegmator outlet water temperature, K.

The mass vapor rate of the mixture (kg/s) can be determined by the formula:

$$G_m = \frac{Q}{r} \tag{18}$$

The reflux ratio can be found by the formula:

$$R = \frac{G_m - G_D}{G_D} \tag{19}$$

where G_D is the mass flow rate of the distillate, kg/s.

Thus, the Murphree tray efficiency can be determined by:

$$\eta = \frac{n_T}{n_A} \tag{20}$$

where n_T is the number of theoretical trays; n_A is the number of actual trays.

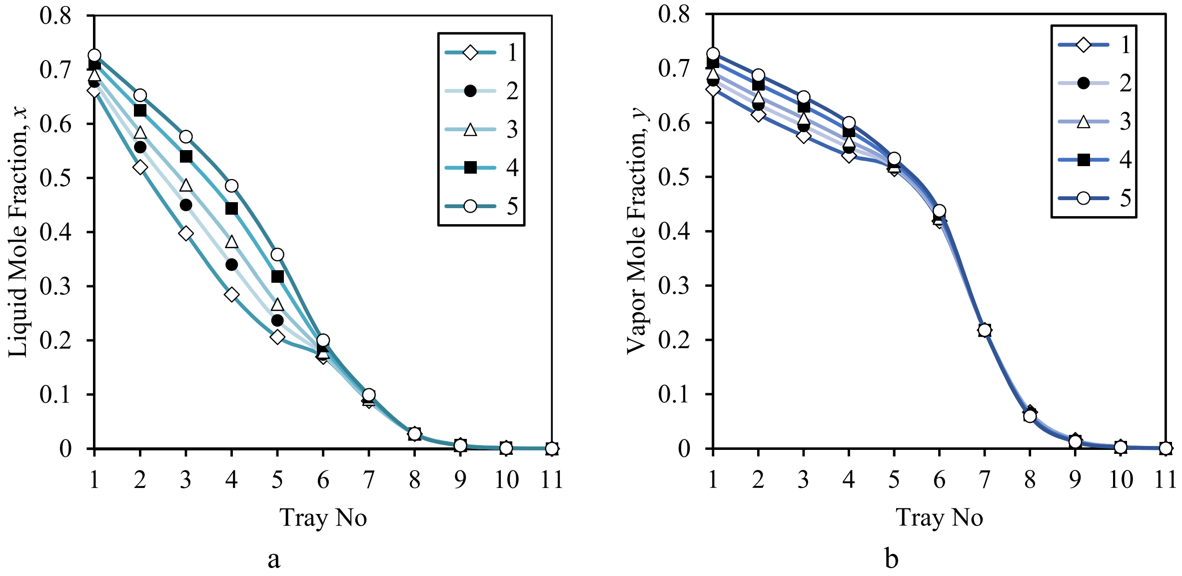


Fig. 7. Mole fraction of the light-volatile component versus the number of trays in the liquid (a) and vapor (b) phases at different amounts of additional heat removed from the 1st tray of the column Q_{rem}, kW: 1 – 0; 2 – 13.89; 3 – 27.78; 4 – 55.56; 5 – 83.33.

Table 1
Increase in the mole fraction in the light-volatile component (in %) in liquid and vapor phases *x*/*y* during thermal distillation relative to the column without additional heat exchange.

Tray No	The ratio of additional heat removed to the total heat flow in the condenser and dephlegmator (Q_{rem} /Q_{Σ})							
	0.0616		0.1182		0.2165		0.2977	
	x	*y*	*x*	*y*	*x*	*y*	*x*	*y*
1	2.46	2.46	4.46	4.46	7.62	7.62	9.82	9.82
2	7.12	2.95	12.47	5.32	20.24	9.09	25.51	11.80
3	13.09	3.20	22.49	5.69	35.71	9.57	44.78	12.46
4	19.39	2.74	34.54	4.99	55.68	8.49	70.45	11.15
5	14.81	0.54	29.37	1.15	54.05	2.46	73.73	3.72
6	2.24	0.67	4.99	1.37	11.22	2.98	17.85	4.51

Results and discussions

Study of thermal and adiabatic distillation in the tray column

Study of thermal distillation processes at constant reflux ratio

First, the influence of heat additionally removed from the column on the process parameters was studied at the constant reflux ratio of 0.5.

The results showed that with an increase in the amount of heat removed from the 1st tray of the column, there is an enrichment of the mixture associated with an increase in the concentration of the volatile component in both the liquid and vapor phases (Fig. 7a, b). Moreover, the increase in concentration of ethanol occurs not only on the tray, where an additional dephlegmator is installed but also on the following ones, up to the feeding tray (6th tray). At the same time, the growth rate of the mole fraction of the light-volatile component is significant,

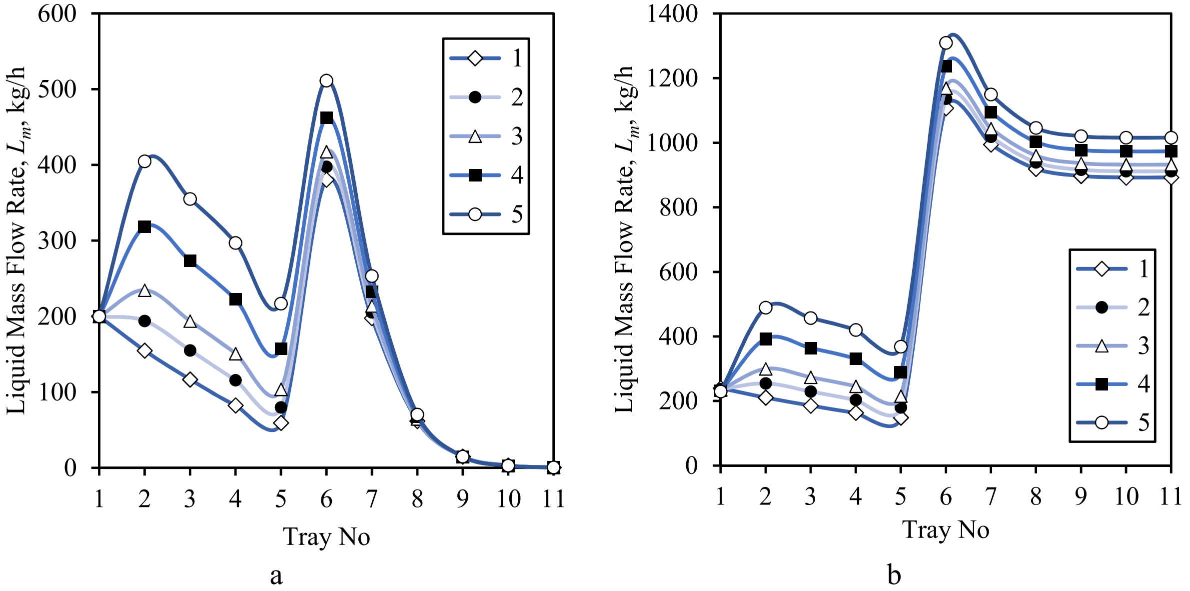


Fig. 8. Mass flow rate of the liquid phase of ethanol (a) and the mixture (b) versus the number of trays at different amounts of additional heat removed from the 1st tray of the column Q_{rem}, kW: 1 – 0; 2 – 13.89; 3 – 27.78; 4 – 55.56; 5 – 83.33.

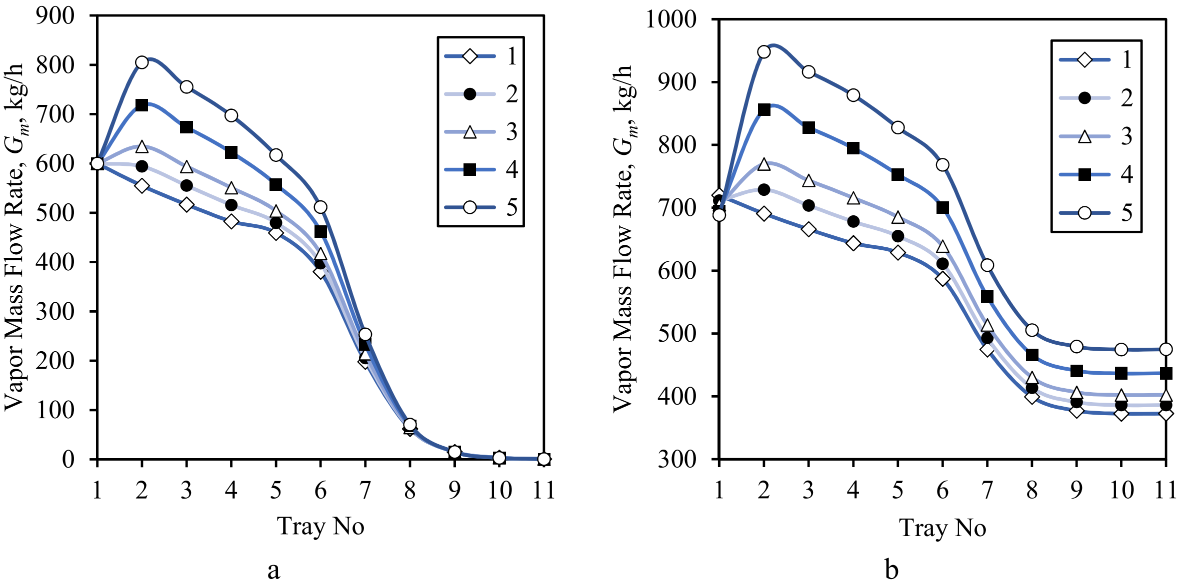


Fig. 9. Mass flow rate of the vapor phase of ethanol (a) and the mixture (b) versus the number of trays with different amounts of additional heat removed from the 1st tray of the column Q_{rem}, kW: 1 – 0; 2 – 13.89; 3 – 27.78; 4 – 55.56; 5 – 83.33.

especially in the liquid phase (Table 1). For example, with additional heat removal from the 1st tray of the column in the amount of 27.78 kW, an increase in the concentration of ethanol in the liquid phase is observed by 22.49 %, and in the vapor phase – by 5.69 % on the 3rd tray of the column.

The increase in the concentration of the light-volatile component in the distillate reaches 9.82 % with an additional removal from the 1st tray of the column of heat power equal to 83.33 kW.

In addition, note that the maximum increase in the concentration of the light-volatile component in the liquid phase is observed, typically, on the 4th or 5th trays. The maximum value of an increase of mole fraction of ethanol in the liquid relative to the column with adiabatic distillation reached 73.73 % with the ratio $Q_{rem} / Q_{\Sigma} = 0.2977$. In the vapor phase, the maximum increase in the concentration of ethanol occurs in the 3rd tray. Thus, it can be concluded that the greatest growth in the concentrations of the volatile component is observed in the 3rd tray of the test column. This is due to the feature of presenting the obtained data, since the liquid entering the 4th tray comes out with the largest increase in concentrations as a result of heat and mass transfer processes from the 3rd tray of the distillation column.

Figs. 8 and 9 show the distribution of vapor–liquid flows on each tray in the distillation column with additional heat removal. It can be seen from Fig. 8 that at the reflux ratio $R = 0.5$, the amount of liquid inside the column increases with a rise in the heat power of the built-in dephlegmator. It is typical for trays following the tray with additional heat removal. For example, the mass flow rate of ethanol obtained because of condensation of ascending vapors during thermal distillation at the outlet of the 1st tray increases by 2.055 times with an additional removed heat power of 55.56 kW. At the same time, the amount of liquid returned to the column as the reflux decreased slightly (to 4.61 %). This is due to the fact that, when additional heat removal because of condensation of a part of the vapor on the surface of the dephlegmator built into the column, reflux consumption is significantly reduced.

However, in terms of the statement of this work, the decrease in the reflux flow rate is covered by the growth of the liquid flow rate (Fig. 8b) because of an increase in the thermal flow in the distillation column with additional heat removal to increase the concentration of the light-volatile component.

The principle of changing the mass flow rate of the vapor phase of ethanol and the mixture when using additional heat removal in the column is similar to liquid flow. Therefore, the amount of vapor of the light-volatile component formed at the outlet of the column, regardless of the heat power of the additional dephlegmator, remains unchanged, for this case 600 kg/h (Fig. 9a). At the same time, it is clearly seen that the total amount of mixture vapor at the outlet of the 1st tray of the column decreases (Fig. 9b), which leads to the enriching of the remaining part of the non-condensed vapors. This is in good agreement with the results obtained in Fig. 7a, b.

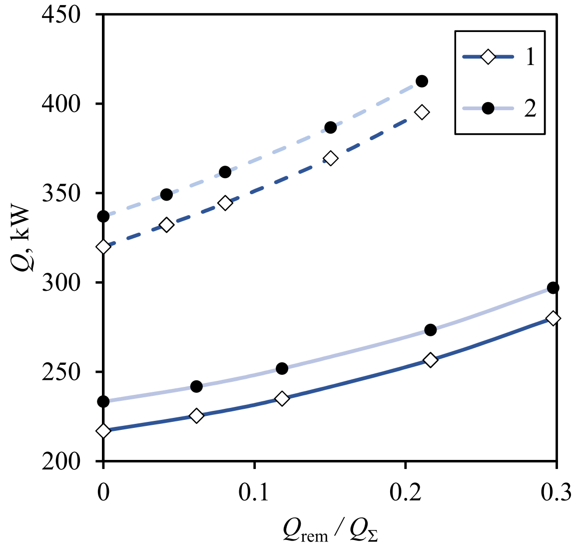


Fig. 10. Heat flow in the condenser (1) and boiler of column (2) during thermal distillation depending on the ratio of heat removed from the 1st tray of the column to total heat flow in the condenser and dephlegmator at different reflux ratio R: 0.5 – solid line; 1.5 – dashed line.

It is worth noting that in the statement under study with the constant reflux ratio, the heat flow will increase with an increase in the amount of heat additional removed from the 1st tray of the column (Fig. 10). For example, at reflux number $R = 0.5$, the increase in the required heat flow power in the column boiler was 40.08 kW, and in the condenser 39.61 kW with additional heat removal from the 1st column tray of 55.56 kW

Table 2
Comparison of process parameters of distillation column in adiabatic mode at different efficiency of contact devices according to Murphree.

The Murphree tray efficiency, η	Reflux ratio, R	Heat flow in the boiler, Q_b, kW	Heat flow in the condenser, Q_c, kW
0.5	3.89	723.06	706.94
0.6	1.35	355.56	339.17
0.7	0.90	291.11	274.92
0.8	0.69	261.31	245.11
0.9	0.58	244.58	228.39
1	0.51	234.17	218.00

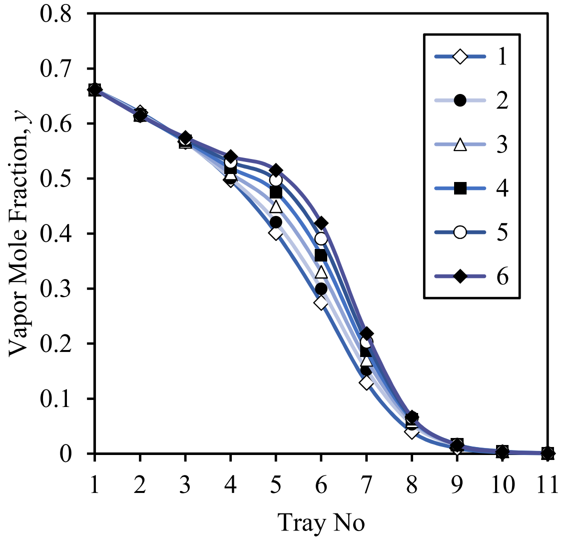


Fig. 11. Change in the mole fraction of the light-volatile component in the vapor phase depending on the tray number in the distillation column without heat removal at different efficiency of the trays according to Murphree η: 1 – 0.5; 2 – 0.6; 3 – 0.7; 4 – 0.8; 5 – 0.9; 6 – 1.0.

compared to adiabatic distillation.

Data shown in Figs. 7–10 were obtained at a Murphree tray efficiency of 100 %.

Study of adiabatic distillation at different efficiency of contact devices

An analysis of data from the adiabatic distillation process in the column under study shows that the efficiency of the contact devices significantly affects the reflux ratio and heat flow in the boiler and condenser. Thus, the most significant reduction in flow rate is observed when the efficiency of the Murphree trays increases from 0.5 to 0.6. Here, the reflux ratio can be reduced by 2.89 times and the heat consumption in the column boiler and condenser by 2.03 times (Table 2).

Figs. 11–13 show changes in the concentration of the light-volatile component, the mass flow rates of the liquid and vapor phases on the trays during adiabatic distillation at different efficiency of the trays used. It is apparent that an increase in the Murphree tray efficiency leads to an increase in the mole fraction of the light-volatile component in the vapor phase for trays in the middle of the column with numbers from 8 to 4 (Fig. 11). Here, in the calculation, the conditions of the constant mass flow rate of the distillate and its final concentration are set. Therefore, to reach the required concentration at the same number of actual trays, more energy should be consumed for evaporation and condensation of vapor–liquid media, which leads to an increase in the energy and mass consumption of the working fluids in the column. These data are confirmed by the plots shown in Figs. 12–14. As illustrated, the column with trays that have low efficiency values (0.5–0.6) has unreasonably high liquid and vapor flow rates. Therefore, the higher the efficiency of the contact devices used in the distillation columns, the lower the liquid and vapor flow rates are required, which consequently results in lower operating costs.

It confirms the practicability of using thermal effects in columns to reduce energy consumption and excessive high mass flow rates of the vapor phase on the trays by partially condensing the ascending vapors. In this case, a reflux of the same composition is formed inside the column, and partially (mainly a light-volatile component) is reevaporated as a result of the heat generated by the condensation of vapors.

Previously in [16], it was found that, because of partial condensation during thermal distillation processes in mass exchange columns, the separation efficiency of liquid mixtures increases by more than 10–15 %. Similar results were obtained in the study of valve trays with heat removal from one upper tray, while the increase in the Murphree tray efficiency was 13.3 % at a ratio of $Q_{rem}/Q_{\Sigma} = 0.51$.

Thus, given the values of increase in efficiency of contact devices within the range of 10 to 15 %, the decrease in the amount of heat consumed in the column boiler and condenser can be calculated. For

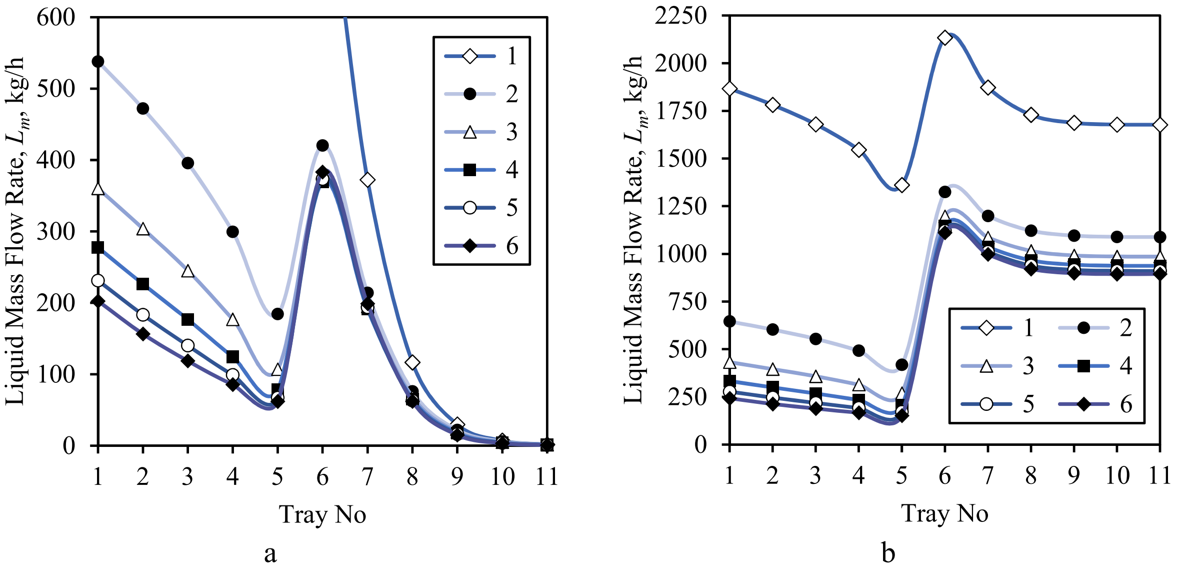


Fig. 12. Change in the mass flow rate of the liquid phase of ethanol (a) and mixture (b) depending on the tray number in the distillation column without heat removal at different efficiency of the trays according to Murphree η: 1 – 0.5; 2 – 0.6; 3 – 0.7; 4 – 0.8; 5 – 0.9; 6 – 1.0.

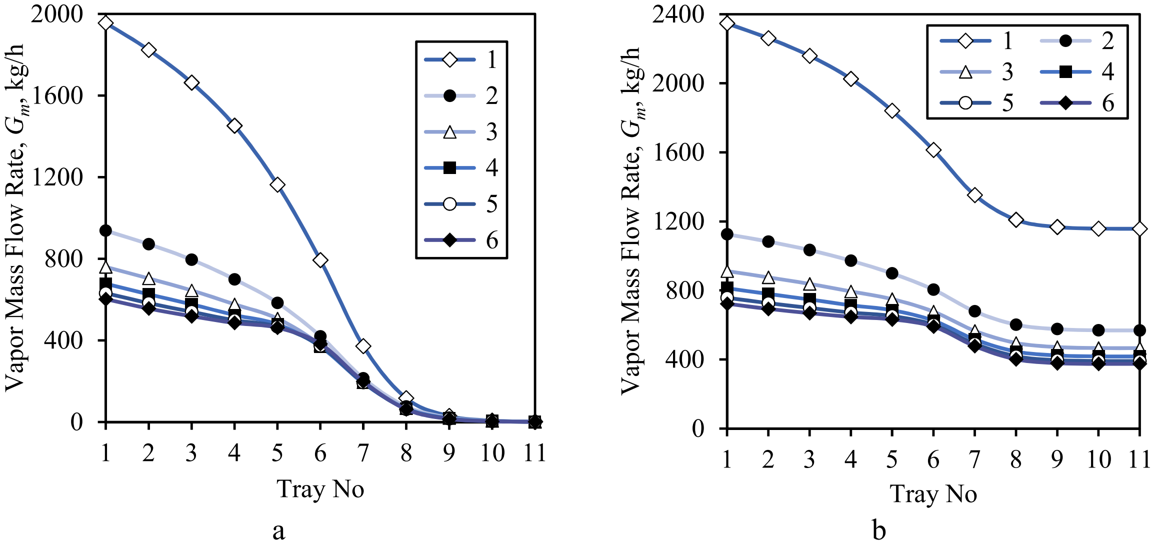


Fig. 13. Change in the mass flow rate of the vapor of ethanol (a) and mixture (b) depending on the tray number in the distillation column without heat removal at different efficiency of the trays according to Murphree η: 1 – 0.5; 2 – 0.6; 3 – 0.7; 4 – 0.8; 5 – 0.9; 6 – 1.0.

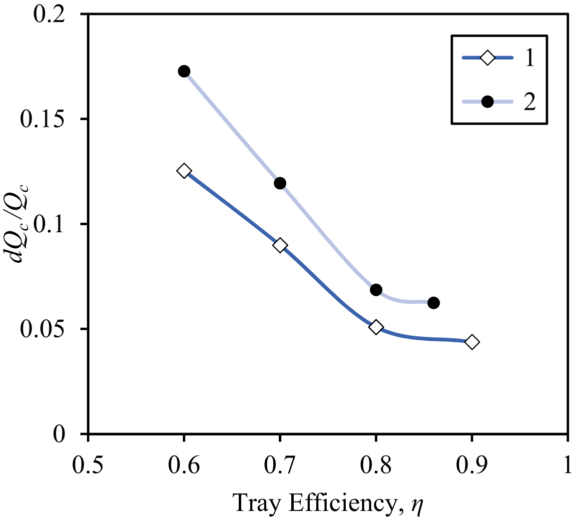


Fig. 14. The ratio of the change in heat flow in the column condenser to the total heat flow depending on the Murphree tray efficiency at different levels of increase in efficiency during thermal distillation $\Delta\eta$: 1 – 0.10; 2 – 0.15.

this, the dependence of the heat flow function in the condenser Q_c, kW, on the Murphree efficiency of trays is determined as:

$$Q_c = -2342.6\eta^3 + 6485.1\eta^2 - 6087.6\eta + 2162.9 \tag{21}$$

where η is the Murphree tray efficiency.

The coefficient of variation for Eq. (21) was 0.9997.

Fig. 14 indicates that using thermal distillation processes can reduce the energy consumption in the column condenser by 12.5–17.3 % at the initial tray efficiency $\eta = 0.6$ only by increasing the efficiency of used contact devices. The area between the two lines in the plot helps to estimate the reduction of heat consumption in the column's condenser. Similar results were obtained on the reduction of heat flow power in the boiler of the column under study.

Study of thermal distillation at constant heat power in column boiler

For evaluation of efficiency of contact devices during thermal distillation valve circular trays we used, which differ in the efficiency of rectifying and stripping sections of the column. For example, the efficiency of the valve trays above the feed tray is assumed to be 0.7, at the bottom of the column – 0.6. The heat power in the column boiler was assumed to be constant and equal to 666.67 kW. Under these conditions, with different amounts of heat removal from the 1st tray of the column, the total heat power in the condenser and dephlegmator remained unchanged (650 kW).

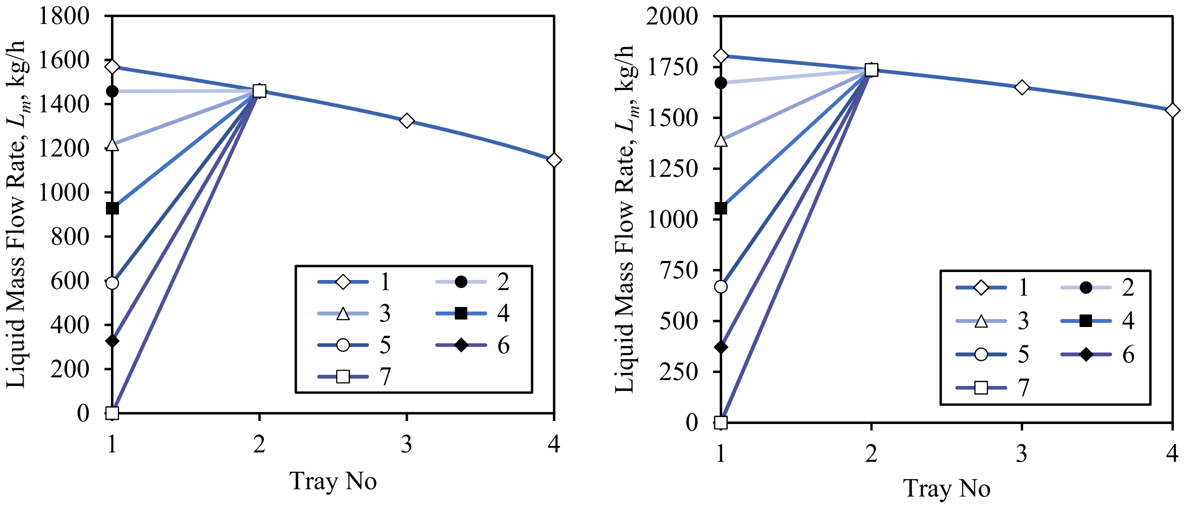
The results show that with an increase in the amount of additional heat removed from the 1st tray of the column, a decrease in the mass flow rates of the liquid and vapor is observed. Figs. 15 and 16 demonstrate that the mass flow rate of liquid entering the 1st tray of the column as reflux and the mass flow rate of vapor leaving the 1st tray and coming further to the condenser are simultaneously reduced. Moreover, the greater the heat power of the built-in dephlegmator, the lower the mass flow rates of the vapor–liquid phases occur on the 1st tray in the column.

At the same time, it is possible to diminish the reflux ratio close to zero, making it possible to cancel irrigation of the column due to internal reflux formation on the 1st tray of the distillation column. Note that the mass flow rate of the vapor–liquid phase to the subsequent trays remains constant regardless of the amount of heat removed.

The results of assessing the effect of additional heat removal on the product quality show that the use of partial condensation of vapors only on one upper tray of the column allows increasing the mole fraction of the light-volatile component at the outlet of the column by 3 % at saving the heat power of the boiler (Table 3). Here, it is possible to increase the efficiency of the valve tray by up to 14.1 %.

Theoretical and experimental studies of the efficiency of the developed vortex contact devices in the thermal distillation process

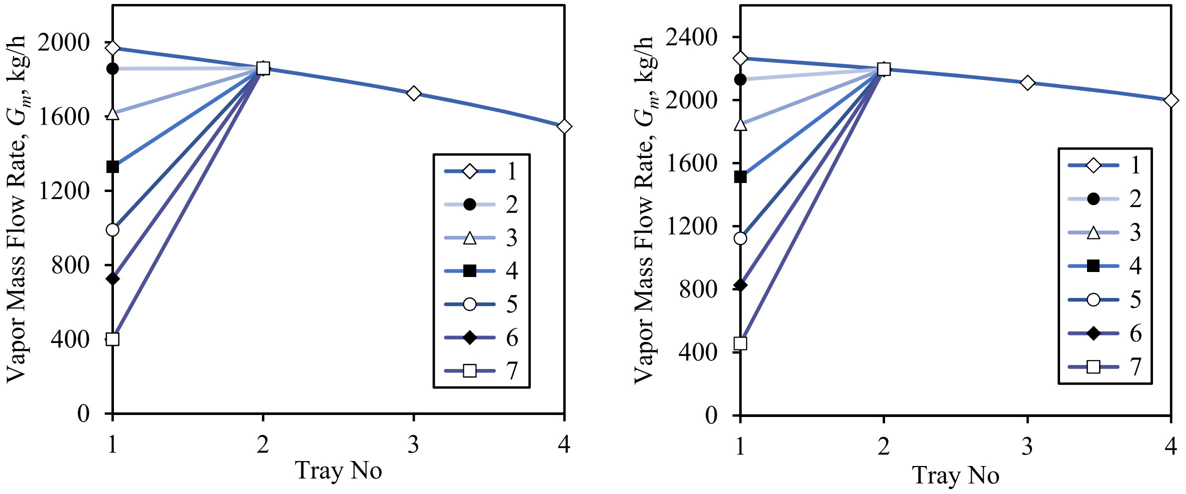
Calculations of the process parameters of the column with the proposed vortex contact devices based on the developed calculation algorithm of the thermal distillation with heat removal are made. Thus, in the calculation of the heat flow from the 1st (upper) vortex stage was 222.22 kW. The heat outlet of the column boiler was assumed to be 666.67 kW. The working reflux ratio ranges from 2.353 to 2.464. The results presented in Fig. 17, show that using the proposed vortex device, it is possible to achieve a mole fraction of ethanol at the outlet of the column $x_D = 0.7625$ at the initial efficiency of the device $\eta_0 = 0.85$. Therefore, the total increase in the final mole fraction of the light-volatile component in the liquid phase can reach 5.61 % with the



a

b

Fig. 15. Change in the mass flow rate of the liquid phase of ethanol (a) and mixture (b) depending on the tray number with different ratio of heat removed from the 1st tray of the column to the total heat flow in the condenser and dephlegmator Q_{rem}/Q_{Σ}: 1 – 0; 2 – 0.0641; 3 – 0.192; 4 – 0.342; 5 – 0.513; 6 – 0.641; 7 – 0.803.



a

b

Fig. 16. Change in the mass flow rate of the vapor phase of ethanol (a) and total mixture (b) depending on the tray number with different ratio of heat removed from the 1st tray of the column to the total heat flow in the condenser and dephlegmator Q_{rem}/Q_{Σ}: 1 – 0; 2 – 0.0641; 3 – 0.1920; 4 – 0.3420; 5 – 0.5130; 6 – 0.6410; 7 – 0.8030.

Table 3
Characteristics of the column operation during adiabatic and thermal distillation (heat removal on the 1st tray).

Heat removed from the 1st tray, Q_{rem}, kW	Ratio, Q_{rem}/Q_{Σ}	The Murphree efficiency of the 1st tray, η_1	Reflux ratio, R	Mole fraction of ethanol at column outlet x_D
0	0	0.710	3.923	0.722
41.67	0.064	0.728	3.646	0.727
125.00	0.192	0.755	3.044	0.734
222.22	0.342	0.785	2.321	0.739
333.33	0.513	0.810	1.474	0.744
416.67	0.641	0.800	0.818	0.742
522.22	0.803	0.770	0	0.736

same amount of heat supplied to the column boiler.

Under these conditions, the decrease in the mass flow rate of reflux reaches 64.05 %, and the mass flow rate of vapor at the outlet of the column is 46.4 % compared to adiabatic distillation (Figs. 18 and 19). In the first case, the pump capacity for reflux and distillate can be reduced by 46.4 %, i.e. by the amount of excess phase flow, which can be condensed in the column by thermal distillation. In addition, this leads to a decrease in the required heat transfer surface area in the condenser and the use of smaller temperature differences in the cooling carrier.

To validate the obtained calculation results, experimental studies of thermal distillation (with heat removal) on the column with developed vortex contact stages are performed. Fig. 20 shows good agreement between calculations of heat removal from the contact stages in the column and experimental data. The deviation from the experimental data of the average efficiency of the vortex stage in the reflux ratios is on average 4.58 %.

During the processing of experimental data, it was found that the increased heat flow in the cooling jacket leads to a significant reduction in the reflux ratio and a slight increase in the efficiency of the vortex stage. Therefore, if the heat flow of the dephlegmator increases from

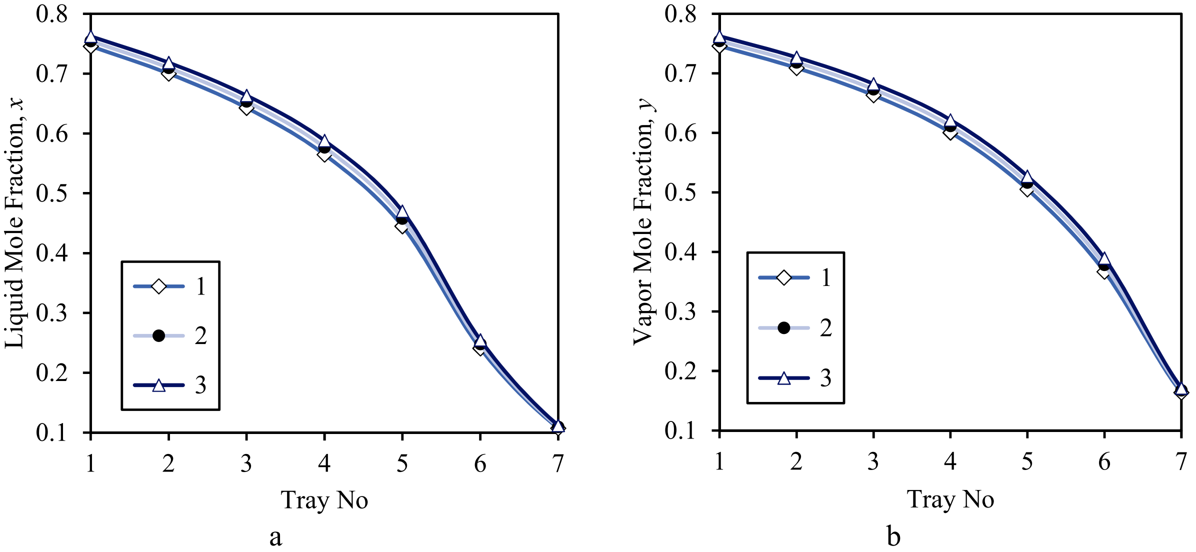


Fig. 17. Change in the mole fraction of the light-volatile component in the liquid (a) and vapor (b) phases depending on the tray number at different initial efficiency of the vortex contact stage according to the Murphree η_0: 1 – 0.75; 2 – 0.80; 3 – 0.85.

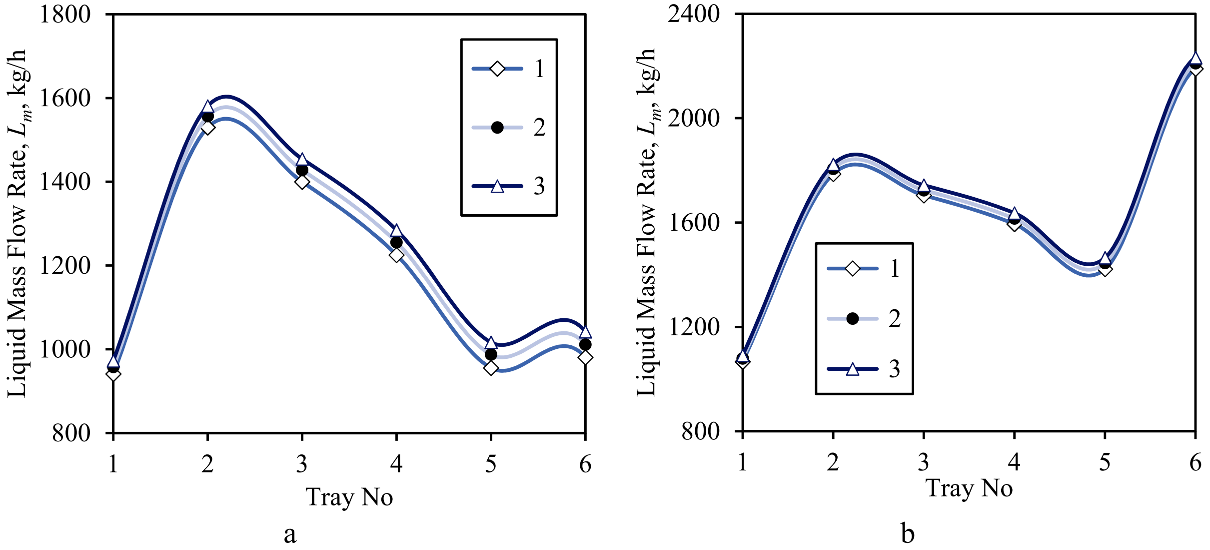


Fig. 18. Change in the mass flow rate of the liquid phase of ethanol (a) and mixture (b) depending on the tray number at different initial efficiency of the vortex contact stage according to Murphree η_0: 1 – 0.75; 2 – 0.80; 3 – 0.85.

48.3 to 254.7 W, the reflux ratio is reduced by 76.87 %. The average efficiency of the stage increases by 10.6 % compared to the column without heat removal (adiabatic distillation). Note that the data are obtained at a constant mass flow rate of distillate equal to 0.618 kg/h. Under these conditions, the use of thermal effects also reduces the energy cost of the process. Thus, when the heat removal is 254.7 W in the cooling jacket of the column with vortex devices, the heat flow in the boiler is reduced by 6.9 % compared to the column without heat removal.

Note that similar results for the thermal distillation using other design of vortex devices are obtained by Voinov N.A. et al. [38], Nikolaev N.A. et al. [39] and others. Therefore, the increase in the efficiency of the contact stage during the supply of cooling water to the jacket of the vortex device was no greater than 10 % [38,40]. At 21 vortex stages, the concentration of ethanol was reached at 96.2 % vol, while for adiabatic distillation it is less than 92 % vol. Studies were performed with reflux ratio $R = 0.8–2.5$ [38].

In addition, during the experiments, the mass fraction of distillate product at the outlet of the column is 0.884 in the liquid phase ($R = 1.83$) when using 10 vortex contact stages, and additional heat removal from the jacket in the upper stage of 254.7 W. For adiabatic distillation, the value of x_D was 0.878 with the reflux ratio of 3.56. In this case, the heat flow in the boiler of the column was 831.94 W, in the condenser – 729.4 W. For thermal distillation with vortex contact devices, the heat flow in the boiler column was 778.25 W, in the condenser 474.7 W. Thus, when the heat removal is 254.7 W in a jacket with vortex devices, the heat flow in the boiler of the column is reduced by 6.9 % compared to the column without heat removal. At the same time, in the condenser and the dephlegmator, the total heat flow remains unchanged (as in the case of adiabatic distillation).

Conclusions

The performed studies allow evaluating the thermal effects both in

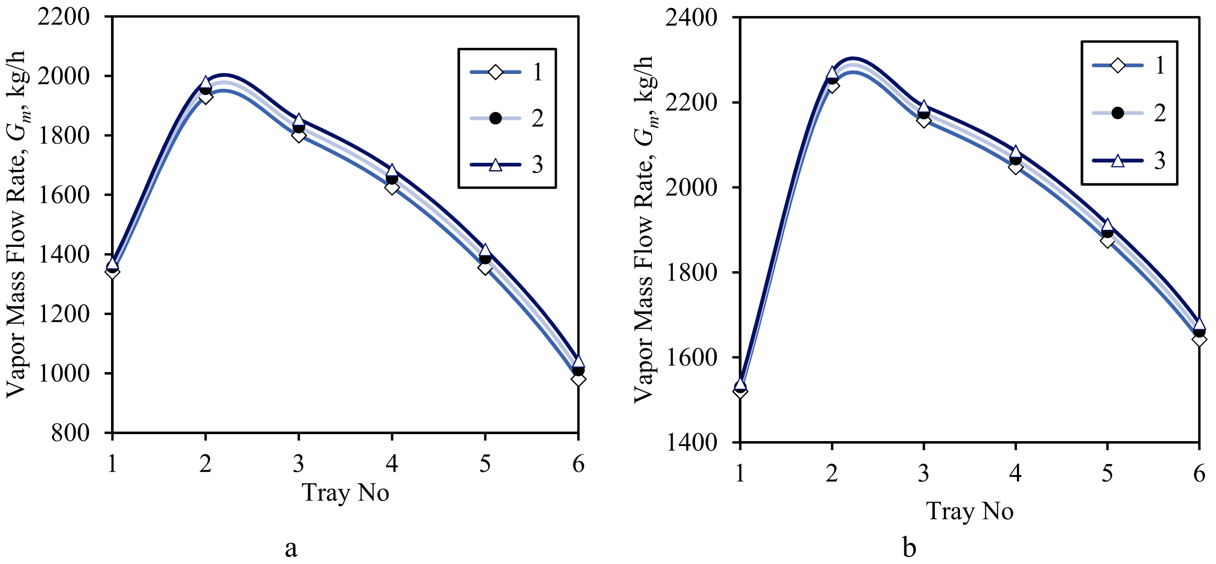


Fig. 19. Change in the mass flow rate of the vapor phase of ethanol (a) and mixture (b) depending on the tray number at different initial efficiency of the vortex contact stage according to the Murphree η_0: 1 – 0.75; 2 – 0.80; 3 – 0.85.

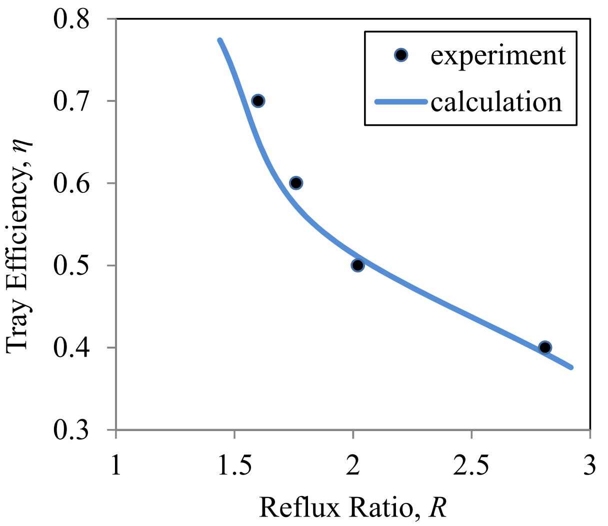


Fig. 20. Changing the average efficiency of the vortex contact stage depending on the reflux ratio during the thermal distillation.

classical design and in the developed design of the contact device of the distillation column. The obtained results on the distribution of the mole fraction of the light-volatile component on each tray of the column with implementing the thermal distillation process at the constant reflux ratio provide selecting the most optimal tray for product outlet from the fractionation distillation column with stripping sections. Additionally, product separation in the rectifying section of the column is substantially improved by using a single reflux dephlegmator installed on the upper 1st tray of the column.

Using additional heat removal from the upper 1st tray of the distillation column allows to reduce the total heat flow in the condenser and dephlegmator by 8.985–11.94 % when using contact devices with the initial efficiency of the tray according to Murphree $\eta = 0.7$. Similar results were obtained for the column boiler.

Studies of thermal distillation processes using an ethanol–water mixture show that, by using additional heat removal from the rectifying section of the column, it is possible to reduce the mass flow rate of vapors to almost the minimum required, i.e., the required flow rate determined by the amount of the distillate. Therefore, it is possible to significantly decrease reflux, while the useful power of the pump for reflux and distillate can be reduced by 46.4 % at $Q_{rem} / Q_\Sigma = 0.342$. In addition, the working surface of the condenser is decreased with a simultaneous reduction in the temperature difference of the supplied heat carrier.

Due to the thermal distillation method implemented on one upper tray of the column, it is possible to increase the Murphree efficiency of the valve tray from 71.5 % without additional heat removal to 81 % with the built-in dephlegmator at $Q_{rem} / Q_\Sigma = 0.51$ and column diameter of 0.6 m.

Using vortex contact devices developed by the authors, with additional heat removal, increases the mole fraction of the light-volatile component in the liquid phase at the outlet of the column by 5.61 % with the same number of actual trays.

As a result of the performed study with combining use of the vortex contact devices and heat removal from the upper stage of the distillation column, it has been found that the increased heat flow in the jacket leads to a significant reduction in the reflux ratio and an insignificant increase in the efficiency of the vortex stage. Thus, if the heat power of the dephlegmator is increased from 48.3 to 254.7 W, the reflux ratio is reduced by 76.87 %. It has also been found that the average efficiency of the stage is 10.6 % higher than that of the column without heat removal (adiabatic distillation). Moreover, thermal distillation with vortex contact stages reduces the heat flow in the boiler of the column in comparison to the adiabatic column without heat removal. At the same time, in the condenser and the dephlegmator, the total heat flow remains unchanged.

CRediT authorship contribution statement

I.N. Madyshev: Supervision, Resources, Conceptualization, Data curation, Investigation. **V.V. Kharkov:** Methodology, Validation, Writing – original draft, Investigation, Writing – review & editing. **O.S. Dmitrieva:** Writing – review & editing, Software, Project administration. **V.E. Zinurov:** Methodology, Formal analysis, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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