Обґрунтована необхідність пошуку рішень проблем ефективного використання енергетичних ресурсів за умови забезпечення вимог до екологічності виробництв під час виконання таких технологічних операцій як випарювання та ректифікація. Відзначено перспективність пошуку та застосування індукованих процесів, які характеризуються високою енергоефективністю і екологічністю.

Досліджено кінетику температури під час ефекту індукованого тепломасообміну складових внутрішнього об'єму термостата за умови використання різних рідин у його внутрішньому середовищі.

Дослідженнями встановлена неможливість досягнення рідиною у внутрішньому виділеному об'ємі термостата температури кипіння за умови протікання ефекту індукованого тепломасообміну, що доведено візуальним спостереженням та значенням її температури. Впродовж експерименту за атмосферного тиску температура термостата дорівнювала 115…116 °С, а температура об'ємної води не перевищувала 97 °С. Встановлено для температури термостата 105…106 °С та атмосферного тиску температура етилового спирту не перевищувала 72…73 °С, а для води – 83…85 °С за умови протікання ефекту індукованого тепломасообміну.

Встановлено, що етиловий спирт та вода переходять до газового стану під час ефекту індукованого тепломасообміну окремо. Фіксувати видалення рідкої фази компонентів суміші можливо за стрибкоподібним переходом кінетики температури рідини. Встановлено, що для суміші етилового спирту з водою під час ефекту індукованого тепломасообміну за температури термостата 105 °С та атмосферного тиску кипіння рідкої фази не відбувалось.

Запропоновано концептуальне рішення технічної реалізації універсального апарата з використанням ефекту індукованого тепломасообміну для виконання технологічних операцій випарювання та ректифікації без фази кипіння. За даним концептуальним рішенням створено лабораторний макет установки, в якому випарювання проводиться за атмосферного тиску за температури рідкої фази 83…85 °С. Економічний ефект розробки досягається за рахунок спрощення обладнання та скорочення енерговитрат на одиницю продукції більш ніж у 1,3 разу порівняно з вакуум-випарним апаратом

Ключові слова: ефект індукованого тепломасообміну, операція випарювання, ректифікація, кінетика температури, обтюратор термостата

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DESIGN OF THE CONCEPTUAL IMPLEMENTATION OF AN APPARATUS WITH THE INDUCED HEAT AND MASS TRANSFER FOR VAPORIZATION AND RECTIFICATION

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1. Introduction

Energy consumption worldwide increased by 25 times over the last century and is now at the level of 300 hJ per capita in industrially developed countries [1]. The energy capacity of world production doubles every 12 years; the volume of industrial production – every 15 years. Over the past decade, industrial load on the environment increased by 2.5...3 times [2]. One can predict further rapid growth of energy consumption.

Thus, the present stage of the development of industries in the world necessitates a search for solutions to problems on the efficient use of energy resources provided that the requirements to the environmental friendliness of production are met.

2. Literature review and problem statement

Of particular importance in this regard are the processes of heat-and-mass transfer, which are widely used in industry [3] to perform such technological operations as vaporization and rectification [4]. These operations are typically characterized by high energy costs related to the processes of heat-and-mass transfer and the complexity of equipment for their implementation.

Vaporization is used in chemical, food, pharmaceutical and other industries. There are more than 80 varieties of evaporator devices with steam heating [5]. However, the physical base of the process in existing evaporators is the concentration of solutions (often solids in water) by partial vaporization of the solvent through boiling, which predetermines high consumption of heat on its implementation.

Vaporization is carried out under atmospheric, reduced, or enhanced pressure, by supplying heat from the outside. The result of this operation execution is the increased concentration, density, and viscosity of the solution, as well as its boiling temperature. It should be noted that the boiling point of solutions always exceeds the boiling temperature of solvents and grows with an increase in the concentration of the dissolved substance and external pressure [6]. This establishes restrictions on using a given operation under atmospheric pressure for solutions containing thermolabile substances. The vaporization of such solutions is carried out at reduced pressure, which leads to the complicated equipment and increased energy consumption on its functioning.

Rectification is widely used in industry, for example to obtain rectified ethyl alcohol, with the separation of fusel oils and aldehyde fractions, to remove gasoline, kerosene, and other fractions from oil, etc. [7]. Rectification implies the separation of liquid mixtures into components that differ in temperatures of boiling by the constant vaporization of liquid and the condensation of vapor.

Industries are increasingly applying alternative processes and methods for separating liquid phases. They include: vaporization through a membrane [8], which is carried out in the film-type apparatuses; counter-flow crystallization with continuous mass transfer [9], and others. However, despite the increasing spread of these and other alternative processes and methods, the rectification still retains its significance in the chemical, food, and processing industries.

Rectification is carried out in the rectification columns, which enable a multiple contact between the flows of steam and liquid phases. The driving force behind rectification is the difference between components concentrations in the steam phase and the liquid phase that is in equilibrium for a given composition. Depending on the boiling temperatures of liquids to be separated, the rectification is performed under different pressures: atmospheric, reduced, enhanced [10]. However, regardless of the design of rectification devices and the conditions for providing a given technological operation, the physical base of rectification is the processes of boiling and condensation. Given this, rectification is one of the most energy-consuming technological processes.

However, at present, when carrying out the vaporization and rectification technological operations, the intensification of heat-and-mass transfer processes is conducted. Intensification is typically achieved by lowering the boiling point, by decreasing pressure in the unit, while energy efficiency – by the structural rationalization of existing equipment and the rational utilization of secondary heat.

Thus, there is an obvious need to search for new approaches and principles in order to perform these technological operations. In this case, it is promising to find and apply the induced processes, which do not occur by themselves, but only under condition of overcoming a certain energy activation barrier. Such processes are characterized by high energy efficiency and environmental friendliness.

One of such induced processes is the process based on the effect of the induced heat-and-mass transfer (InHMT) [11]. The InHMT effect implies the effective diffusion of thermal energy through the phase transition of a fluid of type I. Until now, the InHMT effect is applied in practice only to dehydrate wet colloidal capillary-porous materials [12]. However, the findings from a research into the InHMT effect [13], obtained at present, prove that there is a rather broad scope of its practical application.

3. The aim and objectives of the study

The aim of this study is to improve energy efficiency of food, chemical, and pharmaceutical industries by applying the innovative InHMT effect to perform technological vaporization and rectification operations.

To accomplish the aim, the following tasks have been set:

– to investigate the kinetics of temperature, under the InHMT effect, of components of the internal thermostat volume: the gas and liquid phases, obturator;

– to examine the kinetics of temperature, under the InHMT effect, of component of the internal thermostat volume, provided that water, ethyl alcohol, as well as their mixture, are used as a liquid phase;

– to design, based on the results of research into the kinetics of a fluid temperature under the InHMT effect, a conceptual solution in order to technically implement an energy-efficient apparatus employing a given effect to perform the technological operations of vaporization and rectification excluding a boiling phase.

4. Materials and methods to study the kinetics of temperature of components in the internal thermostat volume under the InHMT effect

4. 1. The examined materials and equipment used in the experiment

For the current research, we have chosen the simplest variant to enable the InHMT: a thermostat with an obturator that holds back a liquid and a gas (Fig. 1). This research aims to model the processes of vaporization, concentration, and thickening, applying the InHMT effect.

The inside part of the thermostat used during the study was a glass transparent cylindrical tank. The upper part of the tank hosts an obturator. The function of creating the fluctuation of the gas environment in the volume of the obturator, as well as the thermostating function, were enabled by an airflow with the pre-defined temperature, which washes the outer surface of the cylindrical tank, which limits the internal thermostat environment (Fig. 1).

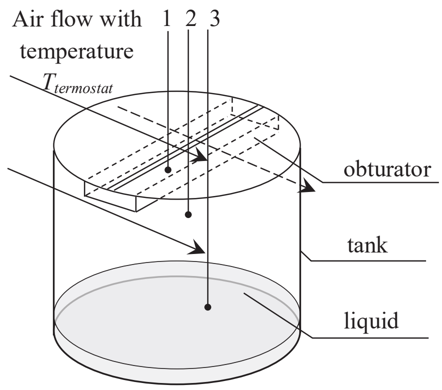

Fig. 1. Schematic of the apparatus for modeling vaporization, concentration, and thickening, applying the InHMT effect at the temperature of a thermostat greater than the boiling point of the liquid in its internal volume: 1, 2, 3 – thermocouples

4. 2. Procedure for studying the kinetics of temperature of components in the internal thermostat volume under the InHMT effect

We studied the character of the InHMT effect under the atmospheric pressure and a temperature of the thermostat greater than the boiling point of the liquid that is inside its internal selected volume. Thus, under the atmospheric pressure of 99...102 kPa, for water, such a temperature is the temperature greater than 99...100 °C; for ethyl alcohol, exceeding 77...78 °C.

The selected internal volume of the thermostat was partially or completely filled with a liquid, which in this case was water or/and ethyl alcohol. Our study was conducted under condition of using both a wet obturator and a dry obturator. The obturator was wetted with a fluid used in the current study, that is the liquid that was inside the selected internal volume of the thermostat. We observed the progress of the InHMT effect visually and based on signals from the thermocouples inside the inner volume of the thermostat. In this case, thermocouple 1 registers the temperature of the obturator, thermocouples 2 and 3, accordingly, the gas temperature and the temperature of the liquid phase in the inner volume of the thermostat.

Signals from the thermocouples were registered using the analog-digital and digital-analog converters made by DCON Utility (manufactured in the USA).

5. Results from studying the kinetics of temperature of components in the internal thermostat volume under the InHMT effect

The kinetics of temperature under the InHMT effect in the thermostat with a wetted obturator are shown in Fig. 2. The temperature of the thermostat in the current study was changed in steps and was equal, at the first stage, to 95...96 °C; at the second stage, to 115...116 °C. A change in temperature was performed in two stages, stepwise, the purpose being to "kickstart" the InHMT effect: the dynamic system "environment – thermostat" has certain inertia – "kickstarting" the InHMT effect necessitates ensuring appropriate required conditions.

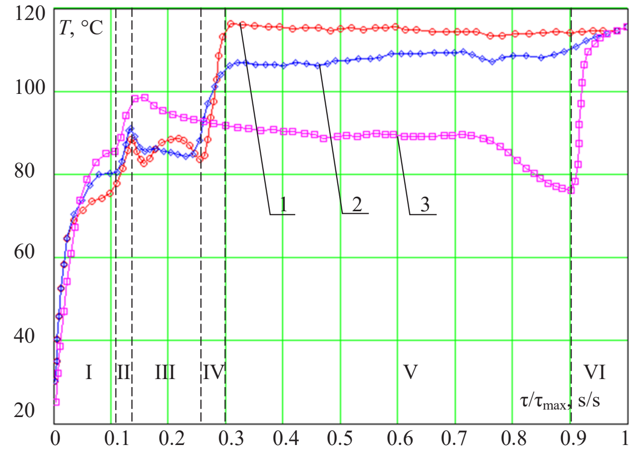

Fig. 2. The kinetics of temperature of components in the internal thermostat volume (1, 2, 3 – thermocouples from Fig. 1) under the InHMT effect at a thermostat temperature of, °C: I – 95...96; II–VI – 115...116

One of such required conditions is to ensure the uniformity of the internal gas environment inside the thermostat. This condition is met as the partial pressure of the steam of water inside the internal gas environment reaches the value of pressure of the saturated steam under a given atmospheric pressure and at a given temperature.

Another necessary condition, which has certain inertia, is the presence of fluctuation in the gas environment inside the volume of the obturator. Since the obturator is a hole in the thermostat with a capillary-porous body, and given the fact that in the current study we wetted the obturator, it is necessary then, to ensure the existence of the environment for gas fluctuation, that part of the moisture should evaporate. It is obvious that a certain predefined time is required to meet both the first specified condition and the second one.

It is possible to select, in the kinetics of temperature of components in the internal environment of the thermostat, several sections separated by dotted lines (Fig. 2). The first section (I) corresponds to the event when the dynamic system reaches a bifurcation point and the InHMT effect is "kickstarted"; in this case, the temperature of the thermostat is equal to 95...96 °C. After "kickstarting" the InHMT effect, which is matched by the event when the kinetics of temperature of components in the internal environment of the thermostat enter the horizontal section, the temperature of the thermostat was increased to 115...116 °C. An increase in the thermostat temperature is matched by a jump-like temperature change along section II. Along the third section (III) the water is removed from the obturator with a simultaneous transition of the volumetric water inside the internal thermostat environment into a gaseous state. The end of the liquid water in the obturator is shown by its jump-like heating to the temperature close to the thermostat temperature (IV). The fifth section corresponds to the transition of the volumetric water into a gaseous state when the obturator is "dry" (the absence of liquid water in the obturator). The end of the volumetric water in the inner selected volume of the thermostat and the completion of the InHMT effect is matched by a jump-like increase in the temperature of the gaseous environment inside the internal part of the thermostat to the value of the thermostat temperature (VI).

Along sections II–V, the dynamic system "liquid – gas – obturator" is in the metastable state at p, V=const. In this case, at the beginning of the third section (III) enthalpy of the internal environment of the thermostat is:

$$I_1 = c_{termostat1} m_{termostat1} T_1 + r \cdot m_{liquid} \quad (1)$$

and at the end of section V:

$$I_2 = c_{termostat2} m_{termostat2} T_2, \quad (2)$$

where $c_{termostat1}$, $m_{termostat1}$, T_1 are the heat capacity, mass, and temperature of the internal thermostat environment, which consists of a liquid, a gas, and the obturator capillary-porous body at the beginning of InHMT; $c_{ctermostat2}$, $m_{termostat2}$, T_2 are the heat capacity, mass, and temperature of the internal thermostat environment, which consists of a gas and an obturator at the end of the InHMT effect; m_{liquid} is the mass of a fluid inside the selected internal volume of the thermostat; r is the specific heat of vapor formation by a liquid.

A change in enthalpy under the InHMT effect is equal to:

$$\Delta I = I_2 - I_1. \quad (3)$$

In this case, it should be noted that the change in enthalpy occurs due to a change in the heat content of the thermostat, which considerably exceeds the change in enthalpy, and due to the kinetic energy of the airflow moving relative to the obturator.

The boiling of water did not occur inside the internal environment of the thermostat in the course of our experiment at the thermostat temperature of 115...116 °C, that is at the temperature greater than the boiling temperature of volumetric water. This is proven, first, by visual observation, and, second, by the kinetics of temperature from thermocouple 3, which registers temperature of the volumetric water (the temperature did not exceed 97 °C).

The boiling of a fluid is observed in the thermostat under condition that there is no "kickstarting" of the InHMT effect due to a failure in meeting any necessary conditions. Thus, if the temperature of the thermostat with a wet obturator is maintained at 115...116 °C, then, because of the lack of fluctuation of the gas environment in the obturator, as described above, the InHMT effect is "blocked". The temperature of the internal environment begins to approach the thermostat temperature – the volumetric water then boils. However, as we achieve the conditions required to "kickstart" the InHMT effect, followed, accordingly, by "kickstarting" it, the boiling stops. Next, InHMT occurs according to section III–IV along the kinetics of temperatures in Fig. 2.

The same result was obtained for ethyl alcohol, as well as for a mixture of alcohol and water. Fig. 3 shows the kinetics of temperature of components in the internal allocated volume of the thermostat (Fig. 1) during InHMT where we alternately used ethyl alcohol and water as a liquid phase.

During the experiment, the results from which are shown in Fig. 3, the obturator was not wetted, the thermostat temperature was maintained at 105...106 °C. Similar to the previous study, the water boiling did not occur neither for alcohol, nor for water.

The kinetics of temperature of components in the internal thermostat volume under the InHMT effect, where we used a mixture of ethyl alcohol and water as a liquid phase in a volume ratio of 1:1, have the same character (Fig. 4).

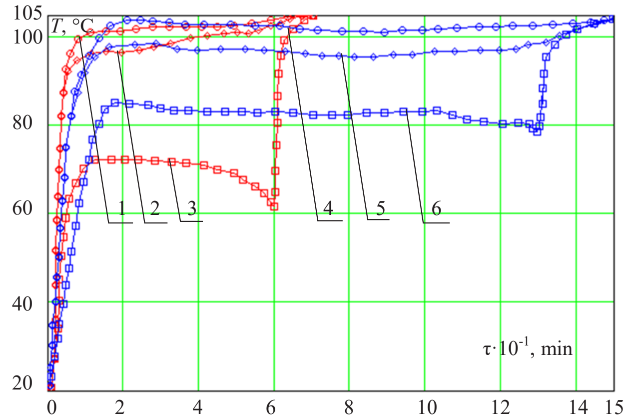

Fig. 3. The kinetics of temperature of components in the internal thermostat volume during InHMT under condition of using, as a liquid phase: 1, 2, 3 — ethyl alcohol (a signal from thermocouples 1, 2, 3 in Fig. 1, respectively); 4, 5, 6 — water (a signal from thermocouples 1, 2, 3 in Fig. 1, respectively)

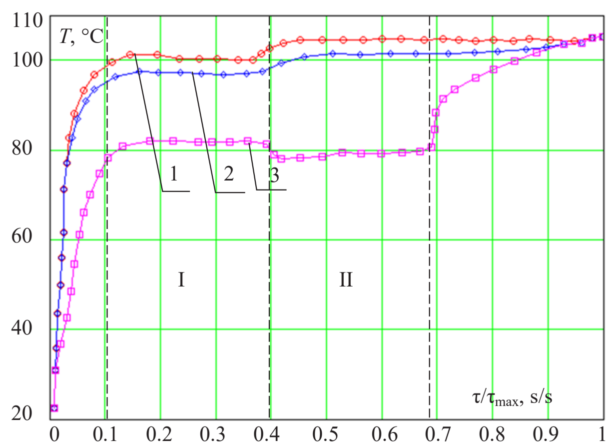

Fig. 4. The kinetics of temperature of components in the internal thermostat volume under the InHMT effect on condition of using, as a liquid phase, of the mixture of ethyl alcohol and water in a volume ratio 1:1 (1, 2, 3 — signals from the thermocouples in Fig. 1)

However, the section of the kinetics of temperature of the fluid inside the internal allocated volume of the thermostat, which corresponds to the liquid phase transition into a gaseous state, has two parts, I and II. These parts are different from each other in the value of temperature, and the transition between them occurs in a jump-like fashion. A given jump-like transition corresponds to the end of ethyl alcohol vaporization inside the internal thermostat environment and to the start of the liquid water transition into a gaseous state.

It should be noted that for a given mixture during InHMT and at the thermostat temperature (105 °C) greater than the boiling point of a given liquid (83 °C), the boiling did not occur.

6. Discussion of results from studying the kinetics of temperature of components in the internal thermostat volume under the InHMT effect

Our study of the kinetics of temperature of components in the internal volume of a thermostat has established that it is impossible for the volumetric water inside the internal volume of the thermostat to reach the temperature of boiling under condition of the InHMT effect. This fact has been proven by the visual observation, as well as by the temperature value for the volumetric liquid in a thermostat.

If a mixture of ethyl alcohol and water is used as a liquid phase, it was established that ethyl alcohol and water are transferred to the gaseous state under the InHMT effect separately; in this case, it is possible to register the removal of the liquid phase of the mixture components based on the kinetics of a fluid temperature.

It should be noted that in terms of practical application of the InHMT effect in industry, a given feature could be used for such technological operations as rectification, vaporization, or distillation, excluding a boiling phase. In this case, it should be noted that the intersection between the kinetics of temperature of the internal environment components in a thermostat is the reflection of their thermophysical properties, which could be used to experimentally examine these properties, and the thermostat with the InHMT effect – as laboratory (scientific-experimental) equipment.

The established fact that the liquid phase boiling is impossible under the condition of InHMT effect has allowed us to design a conceptual solution for the technical implementation of an apparatus using a given effect in order to perform the technological operations of vaporization and rectification operations (Fig. 5) excluding a boiling phase.

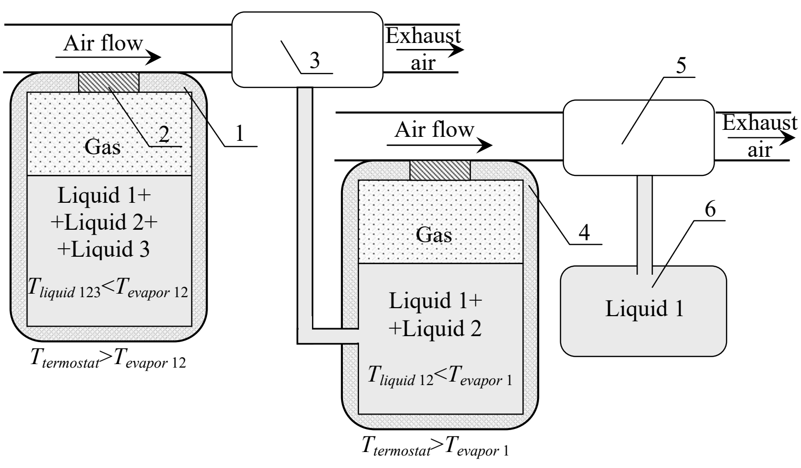

Fig. 5. Conceptual solutions for the practical implementation of heat-energy devices using the InHMT process for rectification or distillation: 1, 4 – thermostats; 2 – obturator; 3, 5 – capacitors; 6 – container for a liquid

It is possible to organize the implementation of these technological operations employing the InHMT effect in the thermostats whose internal environment is a closed container with a gap that hosts an artificially created obturator (Fig. 5). This figure shows an example of separating a mixture of three liquids with varying boiling points when using the InHMT effect in a thermostat. We assume that the temperatures of liquids grow in a stepwise fashion – $T_{evapor1} < T_{evapor2} < T_{evapor3}$. The first thermostat (1) enables the separation of fluid 1 and fluid 2 from fluid 3. The air flow that brings the vapor of liquids 1 and 2 from thermostat 1 enters capacitor 3 where the vapor of fluids 1 and 2 condenses and enters the second thermostat (4). The second thermostat enables the separation of fluid 1 from fluid 2. The vapor of fluid 1 condenses in capacitor 5 and enters container 6. The number of liquids, which are subject to separation, determines the required number of stages "thermostat – capacitor".

It should be noted that the proposed conceptual solution is universal. Its versatility implies the possibility of using a single apparatus to perform both the operations of vaporization and rectification at minimal structural changes in the apparatus.

Based on a given conceptual solution, a laboratory prototype of the installation was built, in which the vaporization is carried out under atmospheric pressure at a temperature of the liquid phase of 83...85 °C. To compare energy consumption in the process of vaporization, we concentrated the blueberry juice in the designed laboratory installation and in the vacuum evaporator apparatus, which is widely used to execute a given operation.

It should be noted that in the food concentrate production, when obtaining concentrates of juices by vaporization, the vaporization process is carried out at pressure below the atmospheric pressure. Thus, for the boiling to occur at a temperature of 83...85 °C, the pressure should be equal to 0.5...0.6 atm. Ensuring such conditions requires more complicated vaporization equipment and additional energy consumption. The obvious advantage of vaporization in a thermostat employing the InHMT effect is that the vaporization at the same temperatures (83...85 °C) occurs under atmospheric pressure. In this case, the duration of the process, based both on the method and second methods, differs by not more than 10 % of the total. Energy consumption in the vacuum evaporator apparatus was 1.57 MJ per product unit, and 1.19 MJ in the designed laboratory installation. Calculations prove that the designed installation enables a reduction in energy consumption per product unit by more than 1.3 times compared to the vacuum evaporator apparatus, which confirms economic feasibility of the design.

Further studies are planned to scale the designed laboratory installation for vaporization and rectification employing the InHMT effect excluding a boiling phase in order to build an industrial installation. In addition, it is planned to design basic functional nodes of such equipment and to choose the rational modes of its operation.

7. Conclusions

1. We have established that it is impossible for a volumetric fluid inside the internal allocated volume of a thermostat to achieve the temperature of boiling under condition of the InHMT effect, which has been proven by visual observations and the temperature value for its temperature. In our experiment, under atmospheric pressure, the thermostat temperature was equal to 115...116 °C, while the volumetric

water temperature did not exceed 97 °C. It was established that for a thermostat temperature of 105...106 °C, and under atmospheric pressure, the ethyl alcohol temperature did not exceed 72...73 °C; for water – 83...85 °C, under condition of the effect from the induced heat-and-mass transfer.

2. It has been established that for a mixture of ethyl alcohol and water inside a thermostat the kinetics of temperature demonstrate a jump-like transition that corresponds to the end of vaporization of alcohol in the thermostat and the onset of the liquid water transition into a gaseous state. An important result is the established fact that ethyl alcohol and water are transferred to a gaseous state during InHMT separately; in this case, it is possible to register the removal of the liquid phase of the mixture components based on the kinetics of temperature. It has been established that the liquid phase did not boil for a mixture of ethyl alcohol with water under the effect of the induced heat-and-mass transfer at a thermostat temperature of 105 °C and under atmospheric pressure.

3. We have designed a conceptual solution for the technical implementation of a universal apparatus employing the InHMT effect in order to perform technological operations of vaporization and rectification excluding a boiling phase. Based on a given conceptual solution, a laboratory prototype of the installation has been built, in which the vaporization is carried out under atmospheric pressure at the liquid phase temperature of 83...85 °C. Economic attractiveness of the design implies a reduction in energy consumption per product unit by more than 1.3 times compared to a vacuum evaporator apparatus.

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