Mass transfer apparatus for a wide range of environmental processes

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Abstract. The paper presents the construction of a continuous multifunctional mass transfer apparatus which can perfectly adjust to meet technological requirements for a wide range of environmental, chemical, petrochemical, biological processes. The processes include absorption, adsorption, desorption, chemisorption, ion exchange, rectification, drying, extraction, gas scrubbing. The apparatus can carry out processes under the influence of intensifying electric fields of a given intensity, as well as performance of the nonisothermal mass transfer processes and the gas and liquid phase exothermic and endothermic catalytic reactions. The article also provides the most promising modifications of the developed mass transfer apparatus and the main details relating to the durability and adjustment to meet the requirements of a particular mass transfer process. The authors emphasize the prospects of using modifications of the developed mass transfer apparatus as a foamy bubbling dust collector for industrial gas scrubbing and for performance of electro-absorption, electro-adsorption, electro-desorption, ion exchange under the influence of a given electric field intensity in the environmental equipment for industrial applications and urban economy.

1. Introduction
Mass transfer apparatuses for various purposes are widely used in many industries of the chemical, petrochemical, oil and gas, metallurgical, construction, machine-building, metallurgical, food manufacturing, pharmacological, biochemical and other industries, as well as in ecological processes of selective purification of liquid and gas heterogeneous systems [1–44].

One of the most basic problems associated with the durability and ensuring proper performance parameters (concentration of recoverable components, the degree of liquid and gas purification, the reaction conversion level, the final moisture content of the dryable materials, etc.) is a qualitative continuous mode assurance and uniform hold-up time of mass transfer products in the plant [45–49].

Our unified work is aimed at improving within-named parameters and developing a multifunctional mass transfer apparatus which is capable to provide the developed contact and modes of interaction between mass transfer products, stable continuous mode, uniform hold-up time of external and dispersed phases, thermal management, safety of the dispersed grains of sorbents and catalysts, the imposition of...
intensifying electric fields. The fields increase the capacity of sorbents, the intensity of mass transfer processes and reduce pore diffusion resistances, etc. The apparatus should have a capability to not only be finely adjusted to the requirements of a particular process, but also be multifunctional. It means that each of the modifications can be used for a wide range of mass transfer processes (plant for changeable industrial appliances for multitopic chemical, petrochemical, oil and gas, metallurgical, construction, food manufacturing, pharmacological, biochemical industries and a wide range of environmental processes for the purification and separation of heterogeneous systems).

2. Methods and materials
The authors consider the main features relating to the construction and durability, which are common to all modifications of the engineered mass transfer apparatuses. The authors also dwell upon each of the presented modifications. The main construction feature of all modifications of the developed mass-exchange apparatus is a screw auger perforated surface, the configuration of which can be completely different and dictated by the requirements of the particular process or the system of technological related processes.

The geometry and coil angles of all modifications depend upon the rheological characteristics of mass transfer products, viscous friction angles for liquid-phase products, and angles of natural slip for grains of dispersed materials (sorbents, catalysts, dryable grains) and the qualitative motion trajectories of mass transfer products on the surface turns.

It will provide uniform hold-up time, high-quality mixing, the absence of stagnant zones, developed contact between the products of mass transfer and all this will occur in sustained continuous mode. The height of the apparatus is determined by providing of the required number of the contact auger screw turns and the required separation level (the achievement of the required concentrations of extracted components, the required conversion level, etc.) and provides an appropriate hold-up time of the mass transfer products in the apparatus.

The diameter of the plant is determined by the required flow rates of continuous phases, providing a boiling or bubbling flow mode through the dispersed phase layer, and a screw surface geometry wound around the central guide. In some cases, the guide serves as a heat exchanger, electrode or channel for setting additional contact devices.

The diameter is also calculated on the basis of the optimal geometric configuration of the helical port through which the mass transfer products are carried out and their required hold-up time in the mass transfer plant is provided.

Figure 1a shows a modification of the mass transfer apparatus with built-in heat exchangers for carrying out non-isothermal mass exchanging processes and exothermic and endothermic catalytic reactions. Modifications of the mass transfer apparatus (figure 1) consist of the vertical body 1 with a distribution chamber 2, pipes for supplying raw materials 3 and an outlet of mass transfer products 4 and pipes of input 5 and output 6 of the continuous (gas, liquid, vapor) phase.

The body 1 is equipped with a hollow central guide 7, on which a single-threaded auger screw 8, with a perforated screw surface and radial plates 9 located on the lower auger screw surface 8 with a clearance 10 about the upper surface of the next auger screw turn 8, is fixed. The upper surface of the auger screw 8 was made finned with a certain configuration of channels.

A perforated support grid 11 separates the distribution chamber 2 from the auger screw 8. In modification 1a, the body 1 is equipped with a heat exchange jacket 12 and the guide 7 is equipped with pipes for supplying 13 and draining 14 heat carriers and acts as an internal heat exchanger (core).

The heat exchange jacket 12 was made with pipes for supplying 15 and outlet 16 of heat carriers and envelops the body outer surface of the mass transfer apparatus. In modification 1b, collecting and scattering perforated contact conic trays 17 and 18 are set in the central hollow part of the apparatus.

The trays accomplish the retaining function and develop contact between the contacting mass transfer products. The quantity and angles of slope of the collecting 17 and scattering 18 contact trays tie in with the angle of slope of the perforated auger screw surface 8 for providing a uniform hold-up time for the mass transfer products in the apparatus.
Figure 1. Mass transfer apparatus for a wide range of environmental processes and related fields of industrial purposes, 1a – modification with integral heat exchangers, 2b – modification with efficient use of the internal hollow volume of the apparatus: 1 – body; 2 – gas distribution chamber; 3, 4 – pipes for supplying of raw materials and outlet of mass transfer products; 5, 6 – pipes for input and outlet of the continuous phase; 7 – central guide; 8 – perforated auger screw; 9 – radial plates; 10 is the clearance for the passing of the dispersed phase; 11 is a perforated grid; 12 is a heat-exchange jacket; 13, 14, 15, 16 – pipes for supplying and outlet of the heat carriers; 17, 18 – collecting and scattering conical funnels.

Through the pipe 3, the supplied dispersed phase (for example, liquid, suspensions, grain of dispersed drying material, sorbent, catalyst) enters the upper part of body 1, then slowly moves the top downward by gravity along the upper finned surface of the auger screw turns 8 through the clearances 10 and out of the body 1 through the pipe 4. Through the pipe 5 in the distribution chamber 2 is served upward flow of the continuous phase (mixture of gases, reaction products, steam), which is uniformly distributed over the section of the mass transfer apparatus passing through the perforated grid 11. The continuous phase flow, passing through the holes in the perforated screw turns screw 8, forms a bubbling (“boiling”) layer with the dispersed phase in which a mass transfer occurs between the supplied dispersed phase and the ascending continuous phase. The continuous phase flow leaves the body 1 through the pipe 6. As between the turns of the perforated auger screw 8 are installed radial plates 9, bounding a layer of liquid or solid dispersed phase, the continuous phase movement is difficult through the screw channel in the body in the clearance 10 between the supplied phase and the bottom surface of the perforated auger screw turns 8 and makes it to move vertically through the holes (perforations) of the auger screw 8.

The heat transfer media (or refrigerants) flow into the jacket 12 and heat-exchange hollow shaft 7 through pipes 13, 14, 15, 16 to perform non-isothermal mass transfer processes or exothermic and endothermic gas phase (catalytic) reactions in mass transfer apparatus of the modification 1a (figure 1). The heat transfer medium (or refrigerants) flow according to various flow schemes relative to the mass transfer products and reaction, for example, parallel flow, countercurrent, mixed current, following their technological requirements and thermal characteristics of heat transfer media. The heat transfer media carry out the outlet or supply of heat to the products of mass transfer processes and gas-phase catalytic reactions, controlling and managing thermal conditions of operation. The contact finned perforated
screw auger surface is fixedly connected to the hollow shaft 7. The surface is fixed in an interference fit with the apparatus body 1, which provides the best thermal conductance conditions. It means that the entire helical surface will function as heat exchange fins, in addition to the main heat transfer surfaces 7 and 12.

Figure 1b shows a modification of the mass transfer apparatus of the wide range of purpose, for the performance of developed contact between gas-phase, liquid-phase and dispersed products of mass transfer in the continuous operation mode. A distinctive feature of this modification is the efficient use of the work volume of the apparatus, due to the use of the internal hollow space of the apparatus, arising from the necessity to give the screw auger surface the configuration of the spiral channel, providing a uniform hold-up time of the dispersed phase. Of special note is the purpose of this modification of the mass transfer apparatus as a foam bubbling dust collector. For this purpose, the configuration of the auger screw is designed to provide a stable film flow of the liquid. The gas, coming through the turns, creates a foam layer that fills all sections between the turns. A layer of foam with a highly developed surface catches dispersed particles and provides the highest separation efficiency of dust-laden gases, and the internal geometric configuration of the apparatus actively contributes to washout of the dirty foam out of the apparatus in a continuous uniform mode and eliminates stagnant zones.

The next most important step in the development of the chosen direction of the mass transfer apparatus engineering of stable continuous action is the imposition of intensifying electric fields of a given intensity and the ability to carry out processes of electroabsorption, electro-adsorption, electrical desorption, ion exchange in an electric field. It leads to a significant intensification of mass transfer processes, increase the capacity of sorbents, reduce the pore diffusion resistance of the sorbents and increase the capacity of electrosorption mass transfer apparatus.

The authors consider the applied example which is the effect of the application of electric fields to the adsorption of acetone molecules from active air by activated carbon [50]. The application of an electric field \( E \) intensifies the mass transfer process, increases the capacity of the sorbent, decreasing its intra-diffusion resistance, thereby increasing the time of the protective action and the use degree of the capacity of the adsorbent (figures 2 and 3).

![Figure 2](image_url)

**Figure 2.** The dependence of the acetone molecules concentration in the adsorbent on the layer height (continuous lines with an electric field \( E = 0 \) kV/m - normal adsorption; intermittent lines with an electric field \( E = 50 \) kV/m) for time periods from the start of adsorption: 1 - 1 hour, 2 - 2 hours; 3 - 3.5 hours; 4 - 6 hours; 5 - 7.293 h (at the end of the protective action time for \( E = 0 \) kV/m); 6 - 12.15 hours (at the end of the protective action time for \( E = 50 \) kV/m).

The modifications of the developed mass exchanger for electrosorption processes are presented in Figure 4a and 4b.

The mass transfer apparatus for electrosorption processes (figure 4a) consists of a vertical body 1 made of electrically conductive material with pipes for supplying 2 and outlet 3 sorbents, inlet pipes 4
and outlet 5 for the cleanable continuous phase (gas, liquid), single-threathed auger screw 6 made of a dielectric material, uniformly perforated over the entire screw surface, with radial plates 7 also made of a dielectric material fixed to the hollow shaft 8. The distribution chamber 9, located in the lower part of the body 1, is separated from the auger screw 6 with a perforated grid 10 made of dielectric material. Each radial plate 7 has a clearance 11 relative to the upper surface of the next turn of the auger screw 6.

![Figure 3](image3.png)

**Figure 3.** Dependence of the protective action time $\tau$ (1) and the use degree of the capacity adsorbent $\eta$ (2) in the intermittent adsorber to adsorb acetone vapor from air by activated carbon, depending on the working pressure and electric field strength $E$ (continuous lines at a pressure of 1.033 atm intermittent lines at a pressure of 5 atm).

![Figure 4](image4.png)

**Figure 4.** Mass transfer apparatus for electrosorption processes: (a) – for a wide range of electrosorption processes; (b) – electro-adsorber.

The body 1 and the hollow shaft 8 of the mass transfer apparatus for electrosorption processes (figure 4a) are connected to oppositely charged poles of constant voltage source. The connection polarity of the body 1 and the hollow shaft 8 depends on the purpose of the mass transfer apparatus and can be changed.
depending on requirements for the current operation mode. Through the pipe 2 the supplied dispersed phase (absorbent, adsorbent, sorbent grains, ion exchange resins, catalyst) enters the upper part of the electrically conductive body 1, for example, connected to a negatively charged constant voltage source. Then the dispersed phase slowly moves from top to bottom by gravity along the upper finned surface of the turns of the dielectric auger screw 6 through the clearance 11 and leaves the body 1 through the pipe 3. At the same time, through the pipe 4, an upward flow of the continuous phase (gas, liquid) is supplied into the distribution chamber 9, which is uniformly distributed over the cross section of the mass transfer apparatus, passing through the perforated grid 10. The continuous phase flow (gas, liquid) passes through the holes in the turns of the perforated auger screw 6, forms a bubbling layer with the supplied phase, in which the mass transfer occurs between the supplied dispersed phase (sorbent) and the upward continuous phase. The continuous phase flow leaves the body 1 through the pipe 5. As between the turns of the perforated auger screw 6 are installed radial plates 7, bounding a dispersed phase layer, the continuous phase movement is difficult through the screw channel in the body in the clearance between the supplied phase and the bottom surface of the perforated auger screw turns 6 and makes it to move vertically through the holes (perforations) of the auger screw. An electric field of adjustable intensity appears between the oppositely charged electrically conductive body 1 and the hollow shaft 8 (connected to a positively charged constant voltage source). The increase in the capacity of sorbents (ion exchange resins) and the decrease of their diffusion resistance occur under the influence of the electric field. As the result, there is an intensification of sorption mass transfer processes and a capacity increase of the mass transfer apparatus. The creation of the auger screw, the radial partitions and the perforated grid separating the distribution chamber from the auger screw from the dielectric material provides electrical insulation between the body 1 and the hollow shaft 8. The circuit-breaker QF serves to protect the circuit from short-circuit currents.

It should also be noted the expediency of using this mass transfer apparatus (figure 4a) for the desorption processes (electro-desorption). The imposition of the intensive electric fields will make possible to influence on the quality of the regeneration of sorbents significantly.

Figure 4b shows a modification of the mass transfer apparatus of stable continuous action for the providing of the electro-adsorption process, in which the screw auger surface was made in the form of a “flat” condenser. The auger screw was made in the form of a “flat” condenser. It consists of two parallel helical electro-conductive surfaces separated by a dielectric layer. This provides even higher quality and uniform influence of the controlled electric field on the sorbents moving along the upper surface of the auger screw, increasing their capacity and reducing the intradiffusion resistance, thereby increasing the performance of the adsorber, the efficiency of gas cleaning, the degree of use of the adsorbent capacity and the prolonged time of the protective effect of the adsorbent.

Figure 5 shows the turn of the electric adsorber shown in figure 4b with electrically conductive screw electrodes 1 and 2 separated by a layer of dielectrics 3 mounted on a dielectric central guide 4. The face dielectric strip 5 isolates the turns from the body of the mass transfer apparatus. This modification of the electrical absorber (figure 4b, 5) is the most perfect and equal in application of electric polarization processes, regardless of the complexity of the geometry of the turns and the overall dimensions of the continuous mass transfer apparatus.
Figure 5. The turn of an electric adsorber with a dielectric interlayer between charged screw electrodes and the face dielectric spacer.

3. Conclusions
The paper presents a new direction of designing and producing unified high-performance mass transfer apparatuses of stable continuous action. The apparatus is of a wide range of environmental, chemical and petrochemical mass transfer processes. This mass transfer apparatus implies a stable unimpeded continuous action and the possibility of assigning the most complex internal geometrical configurations, providing the developed interfacial contact, high intensity of mass transfer processes and a uniform hold-up time of mass transfer products in the apparatus.

The developed constructions of unified mass transfer apparatus allow changing their industrial orientation during equipment operation. If necessary, the same plant can be used as an absorber, adsorber, desorber, ion exchange apparatus, extractor, primary distillation apparatus, foamy bubbling dust collector, the apparatus for drying of the dispersed materials and food thermolabile products. In addition, after calculating the optimal unifying geometrical parameters of the body, the plant can have quick-changing auger screw working surfaces. It will allow using the developed mass transfer apparatus for a wide range of mass transfer ecological (chemical, petrochemical, food, construction, biochemical, metallurgical, etc.) processes with even more accentuated efficiency.

The developed construction of the mass transfer apparatus gives unique possibilities of using its modifications for the implementation of non-thermal mass transfer processes and gas and liquid-phase catalytic reactions with moving and fixed layers of catalysts flowing with heat release or absorption, with the possibility of implementing various current schemes of heat transfer media relative to the flow of contacting mass transfer products and reaction products (figure 1a).

The authors being researchers, developers and engineers of ecological and petrochemical equipment, are interested in modifications of this mass transfer apparatus that allows carrying out mass transfer processes in a stable continuous mode, with the highest intensity and controllability of processes and under the influence of electrical fields of a given directivity and intensity. The provision of mass transfer sorption ecological processes (electro-absorption, electro-adsorption, electro-desorption, ion exchange in an electric field) in electric fields will significantly intensify mass transfer processes, increase the capacity of sorbents, reducing their diffusion resistance. It increases the purification rate of liquid and gas heterogeneous systems, and the performance of modifications of the developed mass transfer apparatus with all declared positive technological characteristics. Modifications of mass transfer apparatuses for electrosorption processes (figure 3, 4) allow the combined use of pressure and electric field, which is especially advisable for the ultra-low permissible concentrations of recoverable components in continuous media at the output of the mass transfer apparatus of environmental equipment.

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