Control of operating modes of an electroadsorption apparatus with a fixed layer of adsorbent

N A Merentsov1, A V Persidskiy2, M V Topilin3 and A B Golovanchikov4

1Volgograd State Technical University, Volgograd 400005, Russia
2JSC Federal Scientific and Production Centre «Titan - Barricady», Volgograd 400071, Russia
3Branch of LUKOIL-Engineering VolgogradNIPImorneft, Volgograd 400078, Russia

1E-mail: steeple@mail.ru

Abstract. This paper provides a new scheme and algorithm of automated control of modes of operation of electroadsorption mass transfer apparatuses are presented on the example of a continuously operating electroadsorber with a fixed adsorbent layer. The required values of technological parameters and ranges of their regulation were obtained during the calibration of technological parameters at the stage of commissioning of the electric adsorption mass transfer equipment, also in an automated mode. A detailed description and algorithm of the stages of calibration of technological parameters of electroadsorption apparatuses with a fixed adsorbent layer are given in the second part of this work (Calibration of technological parameters of an electroadsorption apparatus with a fixed layer of adsorbent). The principle of automated control consists in self-adaptation of the mass exchange system to optimal productiveness, due to the imposition of adjustable electric fields of a given intensity on the adsorption processes and recognition of the most effective hydromechanical modes flow about of the surfaces of the adsorbent granules with a continuous gas phase flow using the turbulization index, that is, assessing the contribution of the inertial component of the structure filtration flow of a continuous gas phase flow through the adsorbent layer. A self-adaptive automated control system for electroadsorption processes will allow achieving the highest levels of gas emissions purification, with optimal energy costs for mass transfer processes, and will provide an opportunity to smooth out technological, large-scale and other factors inherent in specific mass transfer processes and apparatus designs. The most important feature of the developed self-adaptive control system is multi-functionality and a wide range of variation of operating modes from energy-saving optimal modes to emergency capture modes in cases of emergency emissions and unexpected bursts of concentrations of harmful captured substances from the continuous gas phase flow.

1. Introduction

Filtration flows are used in many industrial technological processes and products of various branches of mechanical engineering, in technologies and equipment of the chemical industry and related industries [1-41]. Filtration is used in water treatment processes and in environmental technologies [42-62]. Filtration processes are an integral part of hydrology and oil and gas production technologies. The efficiency of such heat and mass transfer processes as absorption, extraction, rectification, evaporative cooling of industrial recycled water, etc. directly depends on the quality of implementation of two-phase
filtration flows in packing contact devices [63-87]. Filtration flows are also implemented in a wide range of environmental mass transfer equipment, in such processes as adsorption, ion exchange, desorption, etc. [88-117]. The intensity of mass exchange processes in environmental mass exchange equipment and the quality of gas emissions and liquid discharges cleaning directly depends on the quality of filtration flows through the layers of sorbents and ionites, the structure of filtration flows in the micropore space, and the intensity flow about of sorbent granules by filtration flows under the conditions of the developed filtration flows through the layers of sorbents (ionites) and combined impact of physical effects [118, 119], which significantly intensify the diffusion processes, it is possible to achieve stabilized high rates of the degrees of capture of harmful substances from the flows of continuous phases and to have tools for controlling the modes of operation of mass-exchange sorption apparatuses in wide ranges.

At the stage of commissioning, programs and algorithms for calibration of technological parameters of an electroadsorption apparatuses with a fixed adsorbent layer are implemented. Calibration of process parameters allows to obtain all the necessary information about mass transfer system and the adjustment ranges of hydrodynamics, mass transfer apparatuses and electric-field parameters, lower and upper limits of variation of parameters. Thus, we obtain the necessary information for implementing a program for controlling the operating modes of an electroadsorption apparatus with a fixed adsorbent layer, a detailed description of which will be presented in this paper. The program for controlling the modes of operation of electric adsorption mass exchange apparatuses allows for the purification of gas emissions both in energy and resource-saving modes, and in the modes of total trapping of harmful substances in conditions of unforeseen surges in concentrations in streams of continuous gas phases.

2. Methods and materials

Figure 1 shows the control scheme of the mass transfer electroadsorption apparatus. The scheme consists of sensors for the concentration of the extracted substance in the flow of a continuous gas phase $ConS$ and $ConS_0$ installed in the outlet and inlet pipes of the mass-exchange sorption apparatus, sensors of the gas flow rate $FSS$, gas pressure sensors $PS1$ and $PS2$, installed respectively in the upper and lower pipes of the electroadsorption mass-exchange apparatus, the $VS$ voltage sensor on the electrode grids of the mass transfer apparatus and the current sensor $CurS$ in the apparatus power supply circuit. The continuous gas phase flow to be cleaned is injected into the mass transfer apparatus using the $Fan$ air blower with an electric drive $M$. The rate of the air blower is controlled by the $FC$ frequency converter. The voltage to the electrodes of the mass transfer apparatus is supplied from the power supply $G$ through a current-limiting resistor $R_{cl}$, which serves to prevent overcurrent of the power source when charging the mass transfer apparatus's own electrical capacity. The $PLC$ programmable logic controller performs a program for controlling the mass transfer electroadsorption apparatus, receiving information from sensors and generating control signals for the frequency converter $FC$ and the power supply $G$. To ensure the discharge of the mass transfer apparatus's own capacity, if necessary, reduce the voltage on its electrodes, the discharge circuit serves. It works as follows: the comparator compares the voltage $U_1$ supplied from the source $G$ with the voltage at the electrodes of the mass transfer apparatus $U_2$. As the source voltage increases the diode $VD$ opens and the voltages $U_1$ and $U_2$ become equal. When the voltage of the source $G$ decreases, the voltage at the electrodes of the mass transfer apparatus turns out to be higher, $VD$ closes, and the comparator issues a command to turn on the contactor $KM$. In this case, the own capacity of the mass-exchange electroadsorption apparatus begins to discharge through a discharge resistor $R_{dc}$ limiting the discharge current. The discharge will continue until the voltages $U_1$ and $U_2$ are equal and the comparator turns off the $KM$. 
To determine the values of parameters required for the operation of the mass transfer apparatus control system, use the calibration procedure described in detail in the previous part of this work (Calibration of technological parameters of an electroadsorption apparatus with a fixed layer of adsorbent). This procedure is performed during commissioning and can be repeated if the results of the control system of the electroadsorption apparatus become unsatisfactory.

The control program is a cycle that runs all the time while the mass transfer apparatus is in operation. The main principle of the program is to implement the mode of operation of the electroadsorption mass transfer apparatus, which provides a balance between energy saving and efficiency, with the required high rates of gas emissions cleaning.

In figures 2 and 3 shows the algorithm of the control program. After starting the mass transfer electroadsorption apparatus, the operator enters the maximum allowable concentration of the extracted substance in the output stream of the continuous gas phase. This parameter is necessary for monitoring the quality of the mass transfer apparatus operation. Then the program issues a control command to stop the Fan air blower, and then enters the waiting cycle, which checks that the gas flow through the mass transfer apparatus does not occur.
Figure 2. Algorithm of the program for controlling the operating modes of an electroadsorption mass transfer apparatus with a fixed adsorbent layer.
Figure 3. Algorithm of the program for controlling the operating modes of an electrodosorption mass transfer apparatus with a fixed adsorbent layer.
Then the program enters the cycle of determining the ion wind voltage. The program receives the current value in the mass transfer apparatus circuit from the CurS sensor, and if it is less than the value of the ion wind current determined during calibration, the program checks whether the voltage applied to the mass transfer apparatus has reached the maximum. If it is reached, the program assigns the maximum allowable voltage for a mass transfer apparatus with a sorbent to the ion wind voltage variable $U_{iw}$. If the maximum voltage has not been reached, the program issues a command to the power supply to increase the voltage by 1 step, and then the cycle repeats. If the current in the mass transfer apparatus circuit exceeds the value of the ion wind current, taking into account the sensor error, the program assigns the $U_{iw}$ variable the value of the actual voltage on the mass transfer apparatus obtained from the VS sensor.

Then the program issues a command to the frequency converter to set the air blower power frequency to 10% of the maximum, after which, using a waiting cycle, it waits until the gas flow rate through the mass transfer apparatus stops increasing. Then the program receives the pressure from the $PS1$ and $PS2$ sensors in the upper and lower pipes of the apparatus, respectively, and then calculates the porosity coefficient, which is included in the turbulence index formula.

Then the program starts to determine the turbulence index of the device. This method allows us to track the formation of the dynamics of the turbulent flow of a continuous gas phase and determine the appearance of the inertial component of the filtration flow structure. Since for environs with low porosity and relatively high hydraulic resistance at a low gas flow rate, the main flow resistance is created by the viscous component, which has a linear dependence on the flow rate, the appearance of a nonlinear increase in the pressure difference $dP/H$, minus the resistance of the adsorber gratings, can be judged on the formation of the dynamics of turbulent flow in the interstitial space of the adsorbent layer.

Turbulization index is an experimentally determined index that reflects the contribution of the inertial component of the filtration flow structure minus the viscous component, which must be objectively taken into account in conditions of filtration flows through layers of relatively low-permeable porous environs for such processes as ion exchange, adsorption, filtration drying, etc. In this case, the modified equation proposed by the authors is used, which provides a smooth transition from a linear viscous section of the filtration curve to a transient nonlinear one without breaking the velocity and pressure fields:

$$\frac{\Delta P}{H} = \alpha \mu \nu_f + \left( \frac{\nu_f - \nu_{kr}}{B} \right)^m,$$

where $m$ is the exponent called the index of turbulence (for the layers of sorbents and ionites), $B$ is the coefficient determined by the structure of the porous environ, $\alpha$ is coefficients reflecting the effect of the structure of the porous layer on the resistance to filtration flow, by the forces of viscous friction, $\mu$ is the dynamic viscosity of the continuous phase, $\nu_f$ is the filtration rate of the continuous phase through the sorbent layer, $\nu_{kr}$ is critical filtration rate limiting the linear section of the filtration curve, $\Delta P/H$ is specific flow friction of the sorbent layer.

As the filtration rate increases through the adsorbent layer, the component of hydraulic resistance, due to the action of inertia forces and increasing due to the development of turbulence in the interstitial space at a more intensive rate than the viscous friction forces, reaches a value sufficient to detect its presence in the total hydraulic resistance using the pressure measurement tools used. From this point on, the experimentally obtained dependence $\Delta P/H=f(\nu_f)$ becomes nonlinear, gradually deviating in the direction of increasing the total hydraulic resistance. The filtration rate at which the appearance of nonlinear filtration is detected is the critical value of the $\nu_{kr}$, which determines the upper limit of the possible application of Darcy's law within the limits of the pressure measurement error allowed by the experimental technique and the accuracy of the graphical approximation of the experimental data. The algorithm presented in this paper makes it possible to automatically recognize the value of the critical rate of the $\nu_{kr}$ and to perform fine control of the filtration modes of flow through the layers of adsorbents in the inertial turbulent sector, up to the beginning of the fluidization mode and further.
Further, the control program of the electroadsorption mass transfer apparatus implements control of hydrodynamics through the adsorbent layer in the optimal range of turbulence indexes corresponding to the desired hydrodynamic modes from energy-saving modes to modes corresponding to the most intensive flow about of the surfaces of adsorbent granules and the maximum available dynamics of the turbulent flow of a continuous gas phase in the interstitial space when the filtration flow through the adsorbent layer is realized.

Then the program sets the initial value of the variable $\text{PerF}$ (percent of frequency), which determines the frequency of the $\text{Fan}$ air blower supply voltage as a percentage of the maximum, equal to 20. After that, the main work cycle begins. The program issues a command to the frequency converter to set the fan power frequency to 20% of the maximum and enters the waiting cycle, which provides waiting for the end of the increase in the gas flow rate through the mass transfer apparatus. After that, the program calculates the lower and upper limit values of the actual turbulence coefficient, taking into account the sensor errors, and then compares them with the optimal $\text{mopt}$ value (the passport value for the sorbent, entered during calibration). If the optimal value is less than the upper limit of the range of actual values, the program adds 10 to the variable $\text{PerF}$, then at the beginning of the next iteration of the cycle, the frequency of the voltage that feeds the air blower will increase by 10%. If the optimal value is not less than the lower limit of the interval, the program will reduce the speed of the air blower by 10%. If the optimal value is in the interval, the program proceeds to the next steps without doing anything.

At the next stage of the cycle, the program controls the voltage that is applied to the electrodes of the mass transfer apparatus. To do this, the program receives $\text{Con}$ and $\text{Con0}$ values from the concentration sensors of the extracted substance at the output and input of the apparatus, and then compares them with the maximum permissible concentration set by the operator. If the initial concentration of extracted substances at the entrance to the mass transfer apparatus $\text{Con0}$ does not exceed the permissible $\text{CONmax}$, or the concentration at the exit from the apparatus $\text{Con}$ is zero, the voltage is not applied to the electrodes (the lower limit of energy saving is implemented). If $\text{Con0}$ exceeds the permissible concentration by no more than 25%, or $\text{Con}$ is no more than 0,25 of the maximum concentration, the voltage $U_{iw}$ is applied, at which the "ion wind" current was detected. If the concentration at the input to the mass transfer apparatus $\text{Con0}$ exceeds the permissible concentration by 50% or the $\text{Con}$ concentration at the output is greater than 0,5 $\text{CONmax}$, the applied voltage is determined by the formula:

$$U_{ps} = U_{iw} + 0,5(U_{max} - U_{iw}),$$

where $U_{max}$ – maximum voltage that can be applied to a mass transfer apparatus with a sorbent. If the $\text{Con0}$ concentration exceeds the permissible concentration by 75% or $\text{Con}$ becomes more than 0,75 $\text{CONmax}$, respectively, the voltage applied to the mass transfer device will be equal to

$$U_{ps} = U_{iw} + 0,75(U_{max} - U_{iw}).$$

If the concentration of extracted substances at the $\text{Con0}$ inlet exceeds the permissible concentration by more than 75% or $\text{Con}$ exceeds 0,75 $\text{CONmax}$, the maximum voltage is applied to the mass transfer apparatus.

In this paper, the control program includes arbitrary values of excess concentrations of captured substances in the continuous gas phase flow and an algorithm for adaptive flexible control of mass transfer system parameters. The operator control program can include any required technological parameters and limits of concentrations of captured substances, based on the properties (requirements) of a specific technological process and mass transfer sorption apparatus, properties of captured substances and their maximum permissible concentrations, etc.

Then the program checks if there is a threat of exceeding the concentration of the extracted substances in the outgoing stream of the continuous gas phase over the maximum allowable. If the $\text{Con}$ concentration becomes equal or exceeds the value of 0,95 $\text{CONmax}$, the program issues a warning "The apparatus does not provide a stable capture mode or the sorbent needs to be replaced". The main cycle repeats during the entire operation time of the electroadsorption mass transfer apparatus.
3. Conclusions
In the third part of this work (Control of operating modes of an electroadsorption apparatus with a fixed layer of adsorbent), a program and algorithm for controlling the modes of operation of electroadsorption mass transfer apparatuses with a fixed adsorbent layer are presented, which allow mass transfer sorption systems to be self-adaptive and flexible by optimizing the hydrodynamics of the filtration flow of a continuous gas phase through the sorbent layer and a wide range of control parameters of the electric field that intensifies mass transfer processes and increases the capacity of sorbents, extending the time of protective action and reducing the diffusion resistance of sorbents. At the same time, all the necessary parameters of the mass transfer system, ranges of parameter variation, optimal control ranges necessary for the implementation of the control program are recognized automatically at the stage of commissioning of mass transfer sorption equipment using the program and algorithm for calibration of technological parameters, a detailed description of which is given in the previous part of this work (Calibration of technological parameters of an electroadsorption apparatus with a fixed layer of adsorbent).

All operations of the program for controlling the operating modes of an electroadsorption apparatus with a fixed adsorbent layer proceed with a constant current analysis of the concentrations of extracted components at the inlet and outlet of the mass-exchange electroadsorption apparatus. In cases of emergency emissions, the apparatus can automatically switch from energy-saving to emergency modes for capturing components extracted from gas flows, due to the increase in inertial components of the filtration flow structure and electric field strength parameters to the upper limit of regulation, which intensify mass transfer processes, increase the capacity of sorbents and ionize the flow of a continuous gas phase.

The developed system for controlling the modes of operation of electroadsorption mass transfer apparatuses, in combination with the developed new designs of mass transfer electro sorption apparatuses (Designs of electroadsorption mass transfer apparatuses), allows us to create self-adaptive systems for purifying gases emissions with the ability to operate effectively in significantly wider ranges of gas flow rates and concentrations of extracted harmful components, which makes the developed systems not only highly efficient, but also universal.

Systems for automatic calibration of technological parameters and self-adaptive flexible regulation of operating modes of electroadsorption mass transfer apparatuses with fixed layers of adsorbents have been developed. These systems are based on recognition of optimal hydrodynamic conditions for mass transfer processes that accompany active flow about of adsorbent surfaces by a continuous gas phase filtration flow, as well as optimization of electric field strength parameters taking into account the "ion wind", which leads to a significant intensification of mass transfer processes, increases the degree of capture of components extracted from gas (especially in conditions of ultra-low concentrations), reduces the intra-diffusion resistance of adsorbents, increases the capacity of sorbents, extends the time of the protective action of adsorbents in energy-saving conditions during the operation of electroadsorption apparatuses.

Systems and algorithms of automatic calibration and control of operation modes electro sorption mass transfer apparatuses with fixed layer of adsorbents in conjunction with the registration tools structures flows by continuous and dispersed phases [120] will ensure the highest performance and degrees of purification of gas emissions for different designs of mass transfer sorption apparatuses with the features of a specific mass transfer process. The developed systems and the intensifying effects on which they are based are especially relevant in conditions of capturing ultra-low concentrations of harmful substances extracted from gases, which is often found in environmental processes and is a very acute problem.

A self-adaptive flexible control system for operating modes of electroadsorption apparatuses with fixed layers of adsorbents allows achieving the highest available indicators of gas emission purification levels, with optimal energy costs for mass transfer processes and the ability to smooth out technological, large-scale and other factors inherent in specific mass transfer processes and apparatuses designs. It should be noted the ability of the developed control system for the modes of electroadsorption mass...
transfer apparatuses to quickly and self-adaptively respond to emergency emissions and sudden unexpected spikes in the concentrations of extracted harmful substances in the streams of continuous gas phases to be cleaned.

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