System for automated process parameters adjustment of packed absorbers intended for selective gas emissions treatment

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Abstract. The article represents the system for automated process parameters adjustment of packed mass exchange apparatuses intended for selective gas emissions treatment. It describes the flow chart and algorithm of adjustment program of the packed mass exchange apparatus. It also outlines the identification technique for required (optimal) flow dynamic operating modes of the mass exchange packed absorbers. The data obtained through automated adjustment of process parameters serve (are needed) for functioning of the self-adaptable automated mode control system of industrial absorbers for selective gas emissions treatment.

1. Introduction
Mass exchange apparatuses of various structural design and applications are widely used in chemical, petrochemical, oil and gas, construction, metal, nuclear and other industries [1-56]. The sorption processes and apparatuses play a major role in water treatment and water disposal systems [57-92]. The role of mass exchange sorption processes is of special importance for the ecological equipment intended for selective treatment of liquid and gas emissions [93-110]. It refers to such processes as absorption, adsorption, ion exchange, desorption. In ecological mass exchange equipment the major role belongs to the operating quality as it frequently deals with low or extra low concentrations of the substances to be collected. For that reason we can evidence a brisk development of mass exchange processes intensification in several directions, i.e. they are aided with physical effects, electric fields, etc. [111-114], (electrical absorption, electrical adsorption, ion exchange within electric field). But all of the said effects and mass exchange intensification methods can show their full effect if the mass exchange equipment is operated under high-rate flow dynamic modes, under ultimately high intensity of heat and mass exchange processes. For example, for absorption and ion exchange the ultimately high intensity of ion and molecule absorption from continuous gas or liquid flows is observed in case of high-rate filtration flow through the layers of absorbent and ion-exchange resins provided the absorbent surface is intensively washed with continuous flows which entails the development of inertial constituents of the filtration flow structure and formation of turbulent flows (turbulization) within the intra-pore space of the absorbent layers [115].
For absorption in packed mass exchange apparatuses, the highest mass exchange efficiency and values of collection of substances from gas flows are observed under the phase inversion (emulsification) mode. The highest intermixing degree of mass exchange products and of turbulization of gas and liquid flow within the packing layer is inherent to emulsification mode. This (phase inversion) mode of the mass exchange processes has essential advantages and disadvantages. In terms of quality the critical advantages are the intensity of mass exchange and treatment efficiency of gas emissions even if the harmful (hazardous) concentrations in continuous gas flows are low. It is connected with the creation of the most developed phase contact as well as with the intensive intermixing of mass exchange products. The essential advantages of the emulsification (inversion) mode include high retention capability of the packing block in relation to the liquid and gas phases which proves the extended duration of presence time of the mass exchange products in the packing block and has a positive resource saving effect (as to the fresh absorbent saving). The disadvantages of emulsification (inversion) mode include its instability during the industrial operation of process equipment as well as high energy consumption needed for creation (formation) of the phase contact surfaces and against the hydraulic resistance of the packing layer (at emulsification mode). The authors of the article are intensively working to eliminate the said disadvantages. As far as the first disadvantage, i.e. instability of emulsification mode is concerned, the inversion mode is as a rule observed within a rather narrow mode range and in case of increased rate of continuous gas flow or absorbent consumption, the packing block is flooded, i.e. the operating mode of mass exchanger is disrupted. It is suggested that the said disadvantage is addressed with the use of two main methods, i.e. use of dynamic packing contact devices [115-116], which show their dynamic and resonating characteristics within each individual packing element; this leads to higher intensity of intermixing of the mass exchange products within each packing element as well as all over the entire layer of the packing block. In this case the dynamic characteristics are demonstrated naturally, due to the energy of gas filtration flow through the block of packing elements in bulk; this leads to vibration excitation, to formation of the dynamic phase contact surfaces and to overall intensification of the mass exchange processes. The use of packing blocks composed of dynamic packing elements will lead to a broader range of existence of the emulsification (phase inversion) mode, which enables its identification and maintenance both in the laboratory conditions and during the industrial operation of the mass exchange process equipment.

The second method to be used to ensure steady emulsification (phase inversion) mode is the use of automated systems for process parameter adjustment and for self-adapting mode control of the mass exchange absorbers similar to the developed systems [117-124]. The automated system for process parameter adjustment and mode control of the mass exchange absorbers enable the analysis of fluid and gas dynamics within broad flow rate ranges of continuous and dispersion phases, identification of the required mode ranges (existence range of phase inversion) and maintenance of the highest performance values irrespectively of the fluctuations of both continuous and dispersion phases. Besides, the developed systems for self-adapting control of the mass exchange absorbers function with the ongoing analysis of initial and final concentrations of the collected substances which enables a smooth adaptive transition of the developed systems from the total collection mode to the energy- and resource saving mode of the mass exchange apparatus.

Mathematical modelling and calculations of the packed absorbers operated under the emulsification (phase inversion) mode show that the maintenance of the steady emulsification mode leads to 40 % reduction of the packing volume if compared to the volume of a standard mass exchange apparatus and operating modes which results in smaller sizes and therefore, faster response time (less inertia) and flexible automated high quality adjustment of mass exchange systems. This can entail considerable energy- and resource saving. Thus, maintenance of steady phase inversion mode by making use of the developed systems for automated self-adapting operating mode control of the mass exchange packed absorbers is a critical task and the purpose of this study.

This study details the flow chart and the algorithm of the automated process parameter adjustment program for the packed absorbers intended for selective gas emissions treatment which may be the basis...
for the program to be used for automated self-adapting operating mode control of mass exchange absorbers.

2. Methods and materials

Figure 1 shows the control flow chart of the mass exchange apparatus designed for automated identification of the required operating parameters of the packed absorber and for automated recognition and self-adapting operating mode control. It consists of programmable logical controller (PLC) which runs the adjustment and control programs by collecting the sensor data (and sending the execution unit instructions), the gas flow rate sensor $S1$ which measures the incoming (outgoing) gas flow rate of the apparatus, concentration sensors of the collected substances in the continuous gas flow outgoing ($S2$) from and incoming ($S5$) to the mass exchange apparatus. $S3$ and $S4$ sensors are used to measure the hydraulic resistance of the packing layer. Liquid absorbent is supplied to the mass exchange apparatus by the electrically driven pump $AP$, the frequency of its rotation is ensured by frequency converter $FC1$. Treated gas is injected into the connecting pipe in the bottom part of the mass exchange apparatus by means of the blower ($B$) equipped with electrical motor $M2$ which rotation frequency is controlled by frequency converter $FC2$. Clean absorbent is taken from the clean absorbent tank $CAT$; it gets in contact with the continuous gas flow in the packing block of the mass exchange apparatus and is disposed into the used absorbent tank $UAT$ where from it can be discharged for treatment (recovery) or utilization.

The so called adjustment process is implemented for automated identification of the majority of parameters needed for functioning of the controlling program. It is an automated process with a few established initial process and geometric parameters of the mass exchange apparatuses. The rest of the parameters are identified and calculated through automated testing of the apparatus under various modes and by receiving the sensor data. The adjustment process is always launched manually. It should be launched during the start-up stage and preparation of the mass exchange apparatus for operation, it also can be launched from time to time to eliminate the faults of the steady efficient operating modes of the mass exchange system which may be caused by the changed surface of the packing elements (surface contamination of the packing elements) or by the wear of the parts of the apparatus. These can result in unacceptable gas emission treatment results. During the adjustment the apparatus cannot be a part of the technical process. The algorithm of the program for the automated process parameters adjustment of packed absorbers intended for selective gas emissions treatment is shown at figure 2.

The adjustment starts when the operator inputs the following parameters: $Emu$ - indicates the spike of turbulization index value which can be regarded as the beginning of the emulsification mode (for some of hydro-mechanical modes which are studied under the laboratory conditions). This parameter depends on the used packing type and is established in the laboratory conditions, however for new packings it can be established as 1.6–1.7. Then the height of the packing layer $H$ is to be entered. This geometric parameter depends on the structural design of the mass exchange apparatus. Then the minimum power frequency of the pump $F1\text{min}$ - this parameter can be determined either by the minimum frequency which ensures sufficient spraying of the packing with the absorbent (minimum absorbent consumption) or by the process requirements as the least allowed spraying intensity of the packing (optimal absorbent consumption). Then the operator inputs the minimum power frequency of the blower $F2\text{min}$. This parameter is established based on the minimum allowed capacity of the apparatus related to the treated continuous gas flow as specified by the process requirements.

After those values are entered, the program determines the adjustment interval of rotation frequency for each electrical drive as 1% of the frequency ranging from the minimum value to 50 Hz. After that the program gets to calculate the mean-square deviation of the data from the gas flow rate (velocity) sensor for the three power frequency values of the blower $M2$: 10 Hz, 30 Hz and 50 Hz.

For this purpose the program creates an array $Vfj0$ of 11 elements for recording $S1$ sensor data under the power frequency of the blower equal to 10 Hz, and after that it instructs the $FC2$ frequency converter to maintain this frequency value and undertakes a cycle when it fills out the created array with the values received from $S1$ with a 3 s interval (the time is to be established based on the inertia value of the mass exchange system which is also identified during the adjustment of the mass exchange apparatus). It also
gets the sum of the received values in the variable \( Vav \) (velocity average) to later on divide its value by the quantity of measurements and calculate the average gas flow velocity rate per 10 measurements. Then the program calculates the dispersion value and the mean square deviation, after that it deletes the array, increases the power frequency of the fan to 30, later 50 Hz and executes the above operations. After that the program identifies the highest of the mean-square deviations \( SVf \).

The program further gets to calculate (for each of the eventual power frequencies of the absorbent supply pump \( M1 \)) the coefficients accounting for the porous structure impact on the dynamics of the turbulent flow \( K \), the turbulization index at which the mass exchange apparatus packing block starts working in the emulsification mode \( nEmu \) as well as the turbulization index value preceding the flooding \( nMax \) of the packing block.

**Figure 1.** Control flow chart of the packed absorber: 1 – body of the mass exchange apparatus, 2, 3 – incoming/outgoing connecting pipes (pipe sleeves) for treated continuous gas flow, 4 – liquid absorbent distributor (sprayer), 5 – connecting pipe (pipe sleeve) for used absorbent disposal, 6 – liquid distributor (packing support), 7 – mass exchange packing block, 8 – support of mass exchange column.
Figure 2. The algorithm (block diagram) of the program for automated process parameters adjustment of packed absorbers intended for selective gas emissions treatment.

The use of the turbulization index for identification of the hydrodynamic modes of the mass exchange apparatus is based on the power-law equation

$$v_f = K_{mpi} \left( \frac{\Delta P}{H} \right)^{1/n_i}.$$

where $K_{mpi}$ is the coefficient accounting for the porous structure impact on the dynamics of the turbulent flow; $I/n_i$ is the exponent reflecting the force of inertia of the filtration flow. Since the $K_{mpi}$ and $<I/n_i>$ values are the functions of filtration velocity, this equation can be used for description of dependence $\Delta P/H=f(v_f)$ only within the narrow range of the filtration velocity changes. Approximation by linear dependence of these experimental data represented in the coordinates $\ln(\Delta P/H)=\ln(v_f)$ enables calculation of $K_{mpi}$ and $<I/n_i>$ values. The $<I/n_i>$ values identified for the range of the increasing filtration velocity intervals can indicate the increase in the intensity of the constituent of the overall pressure differential due to inertia force which is determined by the increasing turbulization within the porous space. The program uses the strong dependence

$$n_i = \frac{\ln(\Delta P/H)}{\ln(v_f/K_{mpi})}.$$

The details of the turbulization index and its applications are described in the study [115]. It is important to note that the modified equation [111, 112, 115] can be also used to identify the intervals of existence of the flow dynamic modes and for the self-adapting mode control of the mass exchange packed absorbers, the equation allows assessing the formation of the turbulent flow dynamics and the development of the inertial constituents of the filtration flow reduced by viscous components [111, 112, 115].

The adjustment program undertakes a cycle where each iteration corresponds to one power frequency of the absorbent feed pump which increases before each iteration from the established minimum value to 50 Hz through 100 intervals. After the power frequency of the pump at $FC1$ is established, the program begins to increase the power frequency of the blower at $FC2$ with a 10 % or less increment (to be set up by the operator) unless the gas flow velocity, according to the $S1$ sensor, is other than zero and steady. The steady mode is identified due to the cyclical obtaining by the program of the two flow velocity values with a 1 second interval from the $S1$ sensor. If the first value lies within the interval of the mean-square deviation of the second value, then they are almost equal and the mode can be regarded as steady. After that the program increases the power frequency of the blower at $FC2$ by another 10 %
by means of the cycle similar to the above-described one which can be called a “waiting cycle”, the program waits till the gas flow mode is stable and then it gets to measure and calculate the coefficient accounting for the impact of the porous medium structure (of the packing block) $K$.

Since the impact of the dynamic constituent of the resistance is rather low at the low velocity range of gas flow through the packing layer, the turbulization index under such range is almost equal to 1. Thus, $K$ can be calculated with the use of equation (1) as follows:

$$K = \frac{H \cdot \nu_f}{\Delta P}.$$  

(3)

Then the program checks whether there is a gas flow through the packing layer at the set minimum allowed power frequency of the blower at $FC2$. If the check occurs during the 100th iteration of the cycle, i.e. the spraying of the packing with the absorbent is at its maximum and the established minimum allowed power frequency of the blower is less than the current one, the program changes the minimum allowed frequency value to the current one and saves it.

The purpose of the next adjustment stage is to identify the turbulization index at which the packing block of the mass exchange apparatus is exposed to emulsification (phase inversion) and also the turbulization index which precedes the flooding. The criterion of emulsification (phase inversion) mode is the occurrence of spike periods of the turbulization index, i.e. hydrodynamic «spikes». The example of identification of each period is shown in figure 3.

![Figure 3. Hydrodynamic modes with corresponding turbulization indices (operations with turbulization indices).](image)

The program undertakes the cycle where at each iteration the power frequency of the blower at $FC2$ increases with a 10 % increment (the interval is to be set by the operator), the program is waiting for the steady gas flow mode and after that it gets the hydraulic resistance value of the packing block (pressure difference) and then calculates the turbulization index by using equation (3).

After that the program checks whether the condition which testifies to the turbulization index spikes presence is fulfilled - the identified turbulization index must not be less than the product of the index
identified at the previous step and the Emu coefficient introduced at the beginning of adjustment process. If the condition is not fulfilled, the identified index is saved into the variable which stores the previous turbulization index value, the power frequency of the blower at FC2 is increased increases by another 10 % (the increment is to be set by the operator) and the operations are repeated. If the condition is fulfilled, then the current turbulization index is saved as the relevant element of the nEmu array as the beginning value for the emulsification mode at the established power frequency of the absorbent feed pump FC1 (absorbent consumption).

After that the program continues increasing the power frequency of the blower at FC2 by 10 % (with a set increment), it identifies the turbulization index at each stage and saves it into the nMax array as the maximum allowed turbulization index which is followed by the flooding of the packing block. If according to the SI sensor the gas flow velocity (rate) becomes equal to zero or if at 100 % power frequency of the blower at FC2 there is no flooding of the packing block, the program quits the cycle and the value of the nMax array element as identified during the previous iteration is to be saved as the required one. After that the program goes to the next iteration of the main cycle. The power frequency of the absorbent feed pump at FC1 increases by 1 % and all the above operations are repeated.

Upon completion of the 100th iteration of the main cycle the program saves to the permanent controller memory the arrays K, nEmu and nMax as well as the values of the frequency adjustment intervals for converters FC1 and FC2. After that the program stops the both electric motors. This is the end of the adjustment process. The data obtained by the program during the adjustment of the process parameters are used by the program for automated self-adapting operating mode adjustment of the apparatus which is continuously functioning during the operation of the mass exchange equipment.

3. Conclusions
Thus, the developed flow chart and algorithm of the program for automated adjustment of the process parameters of the packed absorbers intended for selective gas emissions treatment allow identifying and storing in the controller’s memory of the ranges of emulsification modes based on the turbulization index and also obtaining the required data for functioning of the program for automated self-adapting control with account of initial and final concentrations to be collected.

It is important to note that adjustment of the process parameters of the packed absorbers can be based on other scientific tools, such as, for example, structures of the gas and liquid phases of the flow. Both in the laboratory and industrial conditions the adjustment of the process parameters can go on under the integrated system of parameter recording and identification of the required operating modes. The results of the integrated system for identification of the operating modes (with account of the continuous and dispersion flows) can be linked to the corresponding turbulization indices. The automated system for process parameters adjustment as described in this study will enable obtaining even more precise data on the mass exchange system, mode control ranges, mass exchange optimization which gives an opportunity for efficient adaptive automated mode control of the packed absorbers.

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