Self-adapting automated mode control system of packed absorbers used for selective gas emission treatment

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Abstract. This paper describes the designed self-adapting automated mode control system of packed absorbers used for selective gas emission treatment. It contains the description of automated control chart of the packed absorber and the algorithm of control program of the mass exchange system. The paper covers the principle of self-adapting control and steady maintenance of emulsification (phase inversion) mode depending on existing concentrations to be collected from continuous gas phase flow.

1. Introduction

The heat and mass exchange contact type packing blocks of different structural design are widely used on process lines in chemical, petroleum, oil and gas, petrochemical, biochemical, pharmacological, nuclear, construction, metal food and associated industries [1-92] and in particular, in packed absorbers intended for selective gas emission treatment [93-110]. The efficiency of the contact type units of the absorbers for selective gas emission treatment strongly depends on existing gas and flow dynamic modes of the packed mass exchange blocks [1-56]. In these conditions the highest collection capability in relation to molecules to be collected is observed under emulsification (phase inversion) mode due to high degree of intermixing of the gas and liquid flows, to development and changing of the phase contact surfaces, turbulization and blowing off the infinitesimal volumes of liquid absorbent with the treated gas phase flow which reduces the diffusion resistance and dramatically intensifies the mass exchange processes. The emulsification (phase inversion) mode is also characterised with the high retention capability of the packing blocks in relation to gas and liquid phases which is in line with the requirements of gas absorption process. Steady operation of the mass exchange absorbers used for selective gas emission treatment under the above-said flow dynamic modes is especially critical for ecological processes and equipment in case the concentrations to be collected from gas flows are low or extra-low.

This paper describes the designed self-adapting automated mode control system intended to control the flow dynamic mode of mass-exchange packed apparatuses used for selective gas emission treatment. The represented algorithm and chart of the automated control system are aimed at steady maintenance of the emulsification (phase inversion) mode with the ongoing analysis of the concentrations to be collected from the gas phase flow. The automated control system is based on the
adjustment of the mass exchange system process parameters which allows identifying the availability range of the emulsification (phase inversion) mode, its top and bottom levels, for different flow rates of liquid absorbent and continuous gas phase flow. Steady emulsification (phase inversion) mode of packed mass exchange absorbers will guarantee the highest possible efficiency of gas phase flows as to collected concentrations and can entail considerable resource and power savings.

2. Methods and materials

The apparatus has the control flow chart for automated identification of the required operating parameters as well as for automated mode control which is shown in figure 1. It consists of programmable logical controller (PLC) which runs the adjustment and operation mode 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 (velocity) of the apparatus, concentration sensors of the collected substances in the continuous gas phase flow outgoing \( (S2) \) from and incoming \( (S5) \) to the mass exchange apparatus. \( S3 \) and \( S4 \) sensors are used to measure the resistance to flow (pressure difference) of the packing unit of the mass exchange apparatus. Liquid absorbent is supplied to the mass exchange apparatus by the electrically driven absorbent supply pump \( AP \), the frequency of its rotation is ensured by frequency converter \( FC1 \). Treated gas phase flow is injected into the connecting pipe in the bottom part of the mass exchange apparatus by means of blower \( B \) equipped with electrical drive \( M2 \) which rotation frequency is controlled by the frequency converter \( FC2 \). Clean absorbent is taken from the clean absorbent tank \( CAT \); it gets in contact with the treated gas phase while flowing through the packing block of the mass exchange apparatus and is disposed into the used absorbent tank where from it may 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. This is an automated process with a few established initial process and geometric parameters. During the final adjustment stage all of the automatically identified values are saved to the read-only memory of the controller and are used by the mode control program of the mass exchanger which is repeatedly executed during the continuous operation of the mass exchange process equipment.

The algorithm of the automated mode control of the mass exchange packed absorber is shown in figure 2. We will further describe the control program.

Execution of the self-adapting mode control program of the packed absorber (mass exchange system) begins with the entering by the operator of the \( C_{max} \) value which defines the maximum allowable finally collected concentration in the outgoing treated gas phase flow of the apparatus according to \( S1 \) and \( S5 \) data. Then the program identifies the \( PerC \) value which is the concentration equal to 1 % of the maximum allowable value, after that the program uploads from the read-only memory the \( dF1 \) and \( dF2 \) values of the power frequency adjustment intervals of the electrical motors as used by frequency converters \( FC1 \) and \( FC2 \), and then it calculates the minimum power frequency of the corresponding electrical engines. After those preparations the program commands the \( FC1 \) to set up the minimum power frequency for the electrical drive of the liquid absorbent feed pump \( M1 \). The packing block begins to be washed with a minimum intensity. Then, after assigning the initial value to the variable \( PerF2 \), which allows to set up a power frequency of blower \( B \) at \( FC2 \) as percentage of its adjustment range, the program undertakes its main cycle.

In the beginning of the cycle the program gives an instruction to set up the power frequency of the blower at \( FC2 \) as a percentage in accordance with the variable \( PerF2 \) value. During the first iteration with \( PerF2=0 \) the electrical motor \( M2 \) is started with the frequency defined as \( F2\text{min} \), i.e. under the lowest frequency. After that the program receives the collected concentration values of the incoming \( (Cin) \) and outgoing \( (Cout) \) continuous gas phase flow of the mass exchange apparatus from sensors \( S3 \) and \( S2 \), then it deducts the maximum allowable given concentration value from the \( Cin \) value and after that identifies the highest of the concentration values to use it for mode control of the mass exchange packed absorber as the actual one \( (C_{fact}) \). The mass exchange apparatus responds to the changes of
concentration as follows. The mass exchange apparatus resumes its maximum capacity mode if the incoming collected concentration of the apparatus $C_{in}$ becomes two times higher than the maximum allowable outgoing concentration $C_{max}$ or the outgoing collected concentration of the apparatus exceeded the maximum allowable value $C_{max}$. Otherwise the capacity of the apparatus will depend on the concentration. Then the program identifies which percentage of the maximum value belongs to this or that current concentration. If the result exceeds 100 %, the program forcedly equals it to 100 % and after that it sets up at $FC1$ the power frequency of the electrical drive of the liquid absorbent feed pump $M1$, which exceeds the minimum value by the percentage identified. After that the program receives the gas flow velocity (rate) value from sensor $S1$, and resistance to flow values of the packing block (pressure difference of the upper and bottom connecting pipes of the mass exchange apparatus) from sensors $S3$ and $S4$ which is followed by the calculation of turbulization index.

**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. Algorithm of the mode control program of a packed absorber (Part 1).
Figure 2. Algorithm of the mode control program of a packed absorber (Part 2).
The use of the turbulization index for identification of the apparatus modes is based on the power-law equation

\[ \nu_f = K_{mpi} \left( \frac{\Delta P}{H} \right)^{1/n_i}, \]  

where \( K_{mpi} \) is the coefficient accounting for the porous structure impact on the dynamics of the turbulent flow; \( 1/n_i \) is the exponent reflecting the force of inertia of the filtration flow. Since the \( K_{mpi} \) and \( 1/n_i \) 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 \( \lg(\Delta P/H)÷\lg v_f \) enables calculation of \( K_{mpi} \) and \( 1/n_i \) values. The \( 1/n_i \) 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 

\[ n_i = \frac{\ln(\Delta P/H)}{\ln(\nu_f/K_{mpi})}. \]  

The details of the turbulization index and its applications are described in the study [111]. It is important to note that the modified equation [111-113] 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 [111-113].

Then the program checks whether the identified actual turbulization index \( n_f \) lies within the interval from \( n_{Emu}[PerC] \), i. e. turbulization index which indicates the starting point for emulsification (phase inversion) mode, to \( n_{Max}[PerC] \), i. e. turbulization index preceding the flooding of the packing block and reflecting the upper limit of the emulsification (phase inversion) mode. Those values are uploaded from the corresponding arrays which are stored in the read-only memory of the programmable logic controller (PLC), and the selection of the array elements depends on the adjustment interval (expressed as a percentage) of the power frequency of the liquid absorbent feed pump \( M1 \), which the program equals to the percentage of the above-the-limit collected concentration \( PerC \) of continuous gas phase flow. The data stored in the arrays were received as a result of adjustment of the packed absorber. If the turbulization index \( n_f \) is less than \( n_{Emu}[PerC] \) value, 1 is added to the variable \( PerF2 \), i. e. the power frequency of electrical motor of blower \( M2 \) will be increased by 1 %, if \( n_f \) is higher than \( n_{Max}[PerC] \) value, then the \( PerF2 \) value is reduced by 1. To keep the \( PerF2 \) value within the limits of the adjustment interval the program forcibly assigns zero-value to this variable if its actual value drops below zero or 100 or if it is beyond 100. After that the above operations are repeated.

The repeated execution of the program for self-adapting mode control of the mass exchange packed absorber leads to continuous monitoring of collected concentrations of continuous gas phase flow and to the corresponding response of the mass exchange system (control program) to the concentration spikes. This results in decreased energy costs needed for mass exchange processes, in a cost-efficient absorbent consumption due to the operation of the apparatus under the most efficient mode of emulsification (phase inversion), it enables a 40 % reduction of the packing block volume with no loss of treatment quality of continuous gas flow if compared to the packed mass exchangers which are not capable of maintaining steady emulsification (phase inversion) mode.
3. Conclusions
It is important to note that the described automated control program of the packed absorber intended for selective gas emissions treatment uses the arbitrary threshold exceeding values for the collected concentrations of continuous gas phase flow and the algorithm of the corresponding self-adapting flexible adjustment of the process parameters of the mass exchange system. The operator can enter any required process parameters and collected concentration limits in the program based on the features (requirements) of each specific process or mass exchange absorber, on properties of the substances to be collected and their maximum allowable concentrations in the gas phase flows, etc. The adjustment and mode control programs of the packed absorbers can be transformed, improved or adapted to different mass exchange systems and structural designs of the apparatuses.

The use of the developed self-adapting automated mode control program of the packed mass exchanger (packed absorber), maintaining steady emulsification (phase inversion) mode with the ongoing analysis of the collected concentrations in continuous gas phase flows in combination with maintaining of the highest possible gas treatment efficiency can entail considerable power and resource savings.

The systems for automated adjustment of the process parameters and for the self-adapting mode control of the packed absorbing mass exchangers become critical during the start-up stage of process equipment as they can compensate for the scale factor or others and also at the time of transition from laboratory testing of the contact units and structural designs of mass exchangers to their industrial operation.

The designed systems for automated process parameters adjustment and for mode control of the packed absorbers intended for selective gas emission treatment in combination with the self-adapting mode control feature of mass exchangers can perform the discriminant function when they compare the efficiency of operation of the mass exchange packing contact units as those systems can identify the availability ranges of the intensive fluid and gas flows. This scientific tool opens a new direction in the development and designing of packing contact units [111] and structural designs of mass exchangers [114-124] which can ensure the required intensifying effects within a broader range of modes than the existing (well-known) packing contact blocks and designs of the mass exchangers currently used in industries. Designing of new contact units and structures of mass exchangers which would demonstrate the required intensifying features within a broader range of modes and can be operated under different ratios of continuous and dispersion flows is an up-to-date task and will lead to increased accuracy and quality of functioning of the designed systems for automated adjustment and mode control of the mass exchangers intended for selective gas emissions treatment.

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