Gas Mixtures Separation Using the Membrane Cascade Type of «Continuous Membrane Column»

Artem A. Atlaskin

Keywords: membrane cascade, gas separation, high purification, CO_2 capture, process intensification, unsteady-state, process simulation, techno-economic analysis.

Issue urgency. At present, novel technologies are being intensively developed and existing technologies are being optimized in the field of gas processing. One of the reasons is the deterioration of the ecological situation due to the high technogenic impact on the environment. Therefore, these solutions should not be aimed only at increasing performance to ensure greater economic benefits, but also new technological solutions must meet the growing requirements of environmental standards. In the existing ecological and economic context, the possibilities of membrane gas separation are becoming attractive. The membrane gas separation is a pressure-driven process, which may be implemented in the absence of phase transitions and characterized by easy scalability compared to conventional gas separation techniques.

One of the potential fields, where the membrane gas separation may be successfully applied instead of conventional energy-intensive techniques, is the gases high purification. High-purification may be performed using multi-stage membrane cascades increasing the number of stages. However, the design complexity, a large number of mixing points, capital costs, and high energy consumption of the process associated with the compression on each stage makes it economically inefficient.

Another field, where the membrane-based techniques may be applied is the CO_2 capture from the flue gases of power plants according to the CCS (carbon capture and storage) strategy, which implies the capture of CO_2 directly in the power plant technological path. The amine absorption is the state-of-the-art technique for CO_2 capture, which has proven its efficiency. Nevertheless, it is characterized by a number of critical drawbacks and it was noted, that the absorption process required up to 30 % of produced energy to capture 90 % of CO_2 from flue gases. According to the modeling of CO_2 capture, the membrane-based technique may propose an increase in energy efficiency and a decrease in CO_2 capture cost.

An alternative approach is the concept of membrane cascade type of «Continuous membrane column», which is based on the continuous membrane column, originally proposed by S.-T. Hwang. It replicates the conventional distillation columns in their separation principles, where the gas mixture may separate continuously by creating two counter-current contours, one of which is constantly enriched by a highly permeable component through the high-performance membrane, and the separation is implemented in the absence of phase transitions and at ambient conditions and does not require heat supply or removal.

The present study deals with the evaluation and determination of specific functioning features of the membrane cascade type of «Continuous membrane column» in the gas high purification and CO_2 capture applications in order to obtain the key dependencies in terms of separation performance/productivity, which provides the understanding of the cascade ultimate separation ability at the specific parameters set. According to that, the study establishes the regularities of various cascade configurations functioning in the total reflux and near-total reflux operational modes and evaluates the possibility to intensify the gas mixtures separation applying the unsteady-state conditions. Based on the experimental data obtained for gas high-purification and CO_2 capture processes, the developed mathematical model was validated and proven its adequacy. Using the developed model, the technological scheme membrane cascade was simulated during the CO_2 capture power plant flue gases. In order to determine the parameters ranges available for optimization, the sensitivity analysis was performed.

Goals and objectives. To study the functioning of a membrane cascade type of «Continuous membrane column» for gas high purification application and CO_2 capture from power plant flue gases in order to identify dependencies in terms of separation performance/productivity; to determine the ultimate separation ability and parameters ranges available for optimization.

In accordance with the goal, it was necessary to solve the following tasks:

1. To develop a mathematical model of mass transfer in a membrane cascade and validate it experimentally.
2. Experimentally determine the regularities of various cascade configurations in the total reflux and near-total reflux operational modes.
3. Experimentally obtain the separation performance/productivity dependencies for both, the gas high purification and CO_2 capture from power plant flue gases applications.
4. Analyze the impact of both, the stripping and the enrichment section on the overall cascade separation performance.
5. To evaluate the possibility to intensify the gas mixtures separation applying the unsteady-state conditions.
6. To design and simulate the technological scheme of the membrane cascade for the CO_2 capture from power plant flue gases.

Scientific novelty. For the first time, the mathematical model of mass transfer in a membrane cascade, type of «Continuous membrane cascade» which is adequate for both, the diluted and bulk gas mixtures separation was developed.

The regularities in the functioning of various cascade configuration in the total reflux and near-total reflux operational mode are experimentally determined.

The membrane selectivity influence of the gas high purification performance studied experimentally.

For the first time, the continuous membrane column gas high purification performance was directly, experimentally compared to the membrane cascade type of «continuous membrane column».

The impact of both, the stripping and the enrichment section on overall cascade separation performance was studied experimentally for the diluted and bulk gas mixture separation processes.

The technological scheme of membrane cascade for the CO_2 capture from power plant flue gases was designed, simulated, and techno-economically evaluated.

The main findings.

1. Two- and three-module configurations of a membrane cascade type of «Continuous membrane column» may be used to perform the low-permeable component high purification separating diluted gas mixtures.
2. Three-module configuration of the membrane cascade type of «Continuous membrane column» may be used to capture the high-permeable component, separating bulk gas mixtures.
3. The developed mathematical model of mass transfer in a membrane cascade type of «Continuous membrane column» provides an adequate simulation for both, the diluted and bulk gas mixtures separation.
4. Implementation of the process under unsteady-state conditions, namely, in the pulsed retentate mode in the stripping section, provides an increase in separation performance compared to steady-state conditions.
5. Technological scheme of the three-module membrane cascade type of «Continuous membrane column» may be used to perform the efficient CO_2 capture from power plant flue gases.

The practical significance of the work. The results of the work are of practical importance for the development of new and optimization of existing membrane gas separation devices used both in the field of low-permeable component high purification and high-permeable component capture. The experimentally obtained dependences demonstrate the features of the gas separation process. The developed and experimentally validated mathematical model of mass transfer allows to perform the separation process simulation in the cascade over the wide range of parameters and to evaluate the performance of industry-scale technological schemes. The proposed scheme of the membrane cascade type of «Continuous membrane column» may be considered as an attractive solution for gas high purification and CO_2 capture tasks.