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EXPERIMENTAL STUDY OF THE MEMBRANE CONTACTOR SYSTEMS FOR GAS DEHUMIDIFICATION

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ABSTRACT

The paper presents a pilot active membrane contactor system (AMCS) description and experimental results for air dehumidification. Triethyleneglycol was used as a hygroscopic liquid carrier. Polydimethylsiloxane based membranes (Lestosil) were used in a spiral wound membrane contactor. The experiments with AMCS demonstrated effective air-drying under a high ratio-feed gas flux/liquid carrier flux (10^2-10^3). The developed contactor system allows to achieve air dehumidification up to $T_{dew\ point}$= –20 ^{0}C.

Keywords: Gas/Vapour separation; Dehumidification; Polymeric membranes; Membrane absorption; Membrane contactor

INTRODUCTION

Dry gaseous mixtures are widely used in air conditioning and pneumatic systems, chemical technology and other industrial processes [1]. Traditionally, gas mixture dehumidification and separation are realized by condensing under cooling, by cryogenic adsorption, absorption and some kinds of catalytic methods (Table 1).

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Tab. 1. Comparison of air-drying methods

Method of dehumidification	Dew point up to, ºC	The estimation of installation size	The complexity of operating and service of installation	The main parts of installation
Adsorption	-50 ºC	large	medium	columns, reservoirs, heat-exchangers
Condensation under cooling	-50 ºC	large	medium	refrigerators heat- exchangers
Absorption	-20 ºC	large	complex	columns, heat-exchangers, pumps
Membrane	-40 ºC	small	simple	membrane modules, compressor, heat exchangers, vacuum- pumps
Membrane contactor	-20 ºC	small	medium	membrane modules, heat exchangers

At present, membrane methods of separation are applied in industry because of their relative simplicity, reliability, high parameters of separation, and lower energy consumption [2,3]. The relative capital cost of the membrane gas-dehumidification process is low under short time of capital recurring [4]. Air can be dehumidified up to the dew point at about –40ºC by a passive baromembrane system. Energy consumption for medium and high selective membranes can be comparable with the values for the ideal refrigerator, especially in the range of the pressure ratio between 0.001-0.005 bar. On the other hand, the passive membrane process of drying, in spite of high selectivity (water vapour/air) of the existing polymeric membranes, requires either high pressure drop or high recirculation fluxes in the case of a recirculation membrane vapor-separator. AMCS with non-porous polymeric membranes and a moving liquid carrier as the absorbent can overcome these problems [5, 6].

This paper considers the construction of new membrane contactors based on promising polymeric membranes and experimental results concerning air dehumidification.

MATERIALS/METHODS/PROCEDURES

The ideal membrane for an air-drying membrane contactor meets the following requirements:

- high water vapor permeability;
- mechanical stability;
- resistance to water vapor attack;
- no properties change in the range of working temperatures;
- high water vapor/air selectivity;
- no swelling in the liquid carrier;
- being phobic to liquid carrier.

The liquid carrier must possess high sorption capacity. A strong temperature dependence of sorptive properties is important for the effective desorption and absorption at a low temperature difference. On the other hand, the temperature dependence of other properties is expected to be weak. Low gas sorptive capacity of liquid carrier allows to prevent the feed gas wasting. The liquid carrier needs to have lower volatility and lower permeability throughout the membrane. The viscosity of the liquid absorbent must be as low as possible to keep low-pressure drop across the separation channels in the membrane module. The operation with a nontoxic liquid carrier that interacts reversibly with water is preferable in order to provide the recirculating mode of operation.

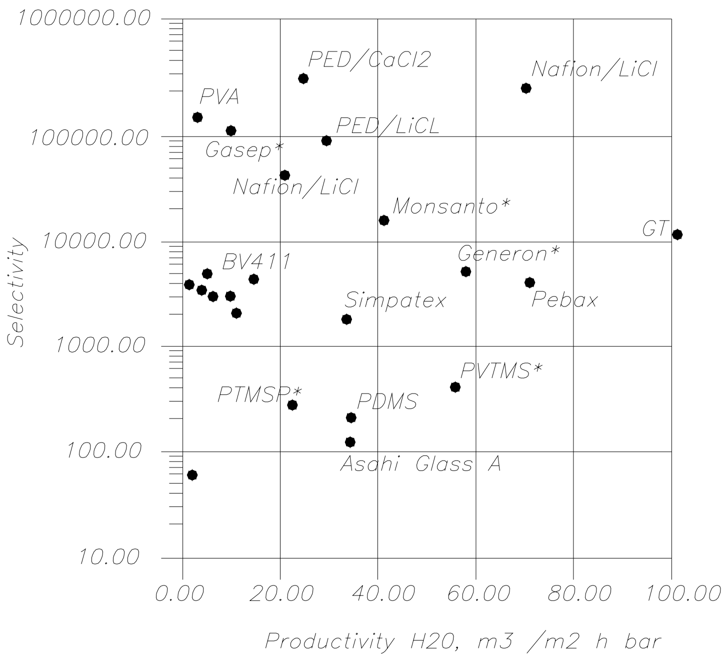

Fig. 1. The dependence of selectivity H_2O/N_2 separation on water vapor productivity of polymeric membranes.
*- permeability calculated by software "Prediction".

The real membranes which can be used in contactors can be porous and non-porous [7]. Porous membranes possess high permeability to water vapor, but they are low water vapor/air selective and leakage in this case is possible. Using non-porous membranes, in spite of their lower water vapor permeability, can be the best solution.

Triethyleneglycol (TEG) was used as a moving liquid carrier in the membrane contactor system as the standard absorbent for air and natural gas drying [9].

The critical analysis of the published permeability data for the existing, commercially available gas separation membranes was carried out. Some necessary data for water vapor permeabilities of these membranes can be predicted by using the approach developed earlier [8] (Fig. 1).

Lestosil (PDMS based membrane, produced in Russia) membranes were used in this study. Lestosil is the membrane of sufficiently high permeability under satisfactory selectivity (see Fig. 1). This membrane has several advantages: provides sterile compartments, prevents liquid leakage, and allows to operate at elevated pressures, with good mechanical properties and chemical stability to water vapors and TEG. The separation selectivity of H_2O/N_2 is 240. The productivity for H_2O is 29000 $l/m^2 \times h \times bar$.

Membrane contactor system

Two identical spiral-wound membrane contactors (membrane area 1.1 m^2) operating in a recirculating mode are the basic elements of the used membrane system. The membrane contactor is a device combining the membrane and absorption methods of gas separation to achieve gas/liquid or liquid/gas mass transfer with no contact of the phases. This is achieved by moving the liquid carrier and gas on the opposite sides of the membrane. The scheme of the suggested spiral wound contactor is shown in Fig. 2.

The scheme of the pilot AMCS which provides continuous gas dehumidification is shown in Fig. 3. The feed gas mixture under the controlled parameters of humidity, temperature, and pressure is fed from the air preparation unit to the gas cavity of the membrane absorber. Humid air is blown along the polymeric membrane and the most permeable component (water vapor) permeates through the membrane from the gas phase into the moving liquid absorbent. The moving liquid carrier is fed at the opposite side of the membranes. The dried air (low permeability) leaves the membrane contactor as a retentate. The contactor temperature corresponds to the air drying operating mode.

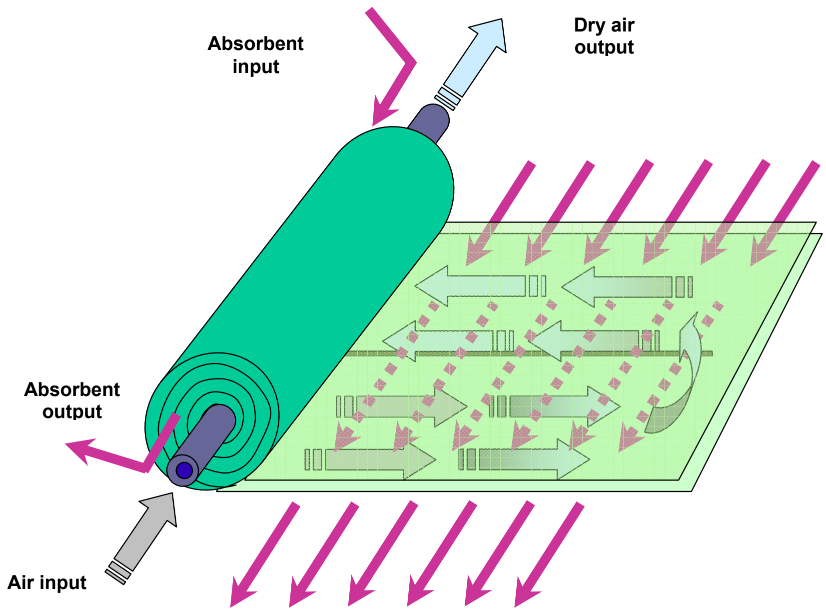

Fig. 2. Scheme of spiral wound membrane contactor.

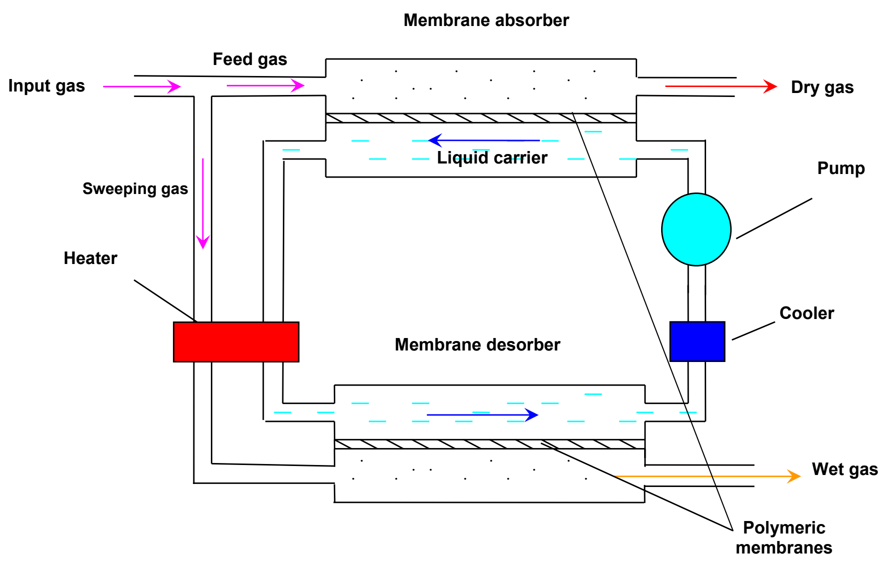

Fig. 3. The active membrane contactor system operating in recycling mode.

The driving force of the process is determined by a chemical potential gradient between the gas and liquid phases. The direction of the driving force depending on temperature and, in most cases, pressure, determines the operation mode of the contactor: absorber or desorber.

As it is known, the chemical potential of a component in the gas phase is determined by its partial pressure and temperature. In the studied case liquid phase, chemical potential is determined by the activity of water vapor over the liquid carrier (TEG). Water vapor activity for the system "water - TEG" will be estimated by the Henry coefficient (see Eq.1). The difference between the chemical potential values allows to determine the direction and value of the driving force.

The developed module construction can operate in the range of temperatures from 0^{o} C to 70^{o}C, pressure up to 5 bars, which makes the contactor suitable for absorption and desorption in a wide range of parameters variations.

After the absorber, the liquid carrier is heated and put to the membrane desorber where water vapor is recovered from the liquid carrier by permeation through membrane. Vapor is evacuated by pre-heated sweeping gas, taken from the initial feed flow. Recirculation of the liquid carrier is carried out by a peristaltic pump.

RESULTS AND DISCUSSIONS

To determine the Henry constant for the TEG/water system, the measurements of water vapor partial pressure without the membrane under the definite water content TEG with a variation of temperature were carried out.

As a result, it was found that the Henry law in the range of 20-50^{o}C could be written as:

$$P_{H2O}=K\times X_{H2O} \qquad (1)$$

where $K= 11{,}25\times 2^{(t-20)/10{,}0}$ is Henry's constant, mbar; P_{H2O} is partial pressure of water vapor in the gas phase, mbar; X_{H2O} is mole fraction of water in TEG; t is process temperature, ^{0}C.

The temperature dependence of Henry's constant is rather strong: a 10^{o}C rise causes twice P_{H2O} increase. The Henry constant for the "water-TEG" system has a low value at the operating temperatures providing high sorption capacity.

To estimate the operating conditions of AMCS, the absorber and desorber were tested at temperatures 20^{o}C and 45^{o}C, respectively. The dependences of the outlet gas RH% on the feed gas flow at a variation of average gas pressures in the absorber (curves 1-3) under the initial water content of about 6.5 mass% in the liquid carrier are shown in Fig. 4. In each case, the feed air humidity was 40% RH. The liquid absorbent flow was always 2 ml/s. The outlet air humidity outside the contactor was measured under atmospheric conditions (20^{o}C, 1 bar).

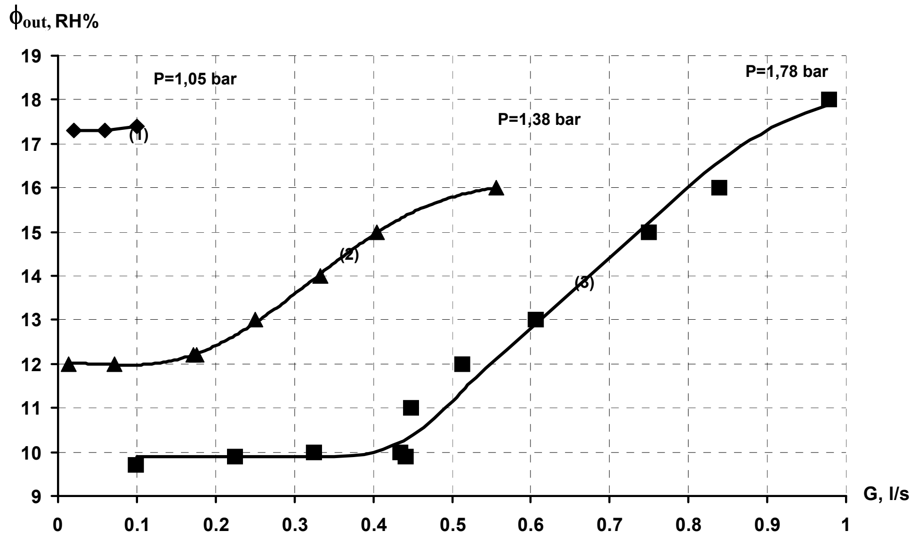

Fig. 4. The dependence of the outlet gas humidity on the feed gas flow for absorber. Feed flow humidity: 40 %RH, liquid carrier flow: 2×10^{-3} l/s, water content in TEG: 6.5 mass%.

As it is seen from Fig. 4, the effectiveness of the contactor operation rises with an increase in average gas pressure (compare curves 1, 2, and 3). Evidently, this fact can be explained by the driving force increase because of an increase of partial pressure of water vapor in the gas phase. A limitation of the airflow operation range at different average pressures is caused by hydraulics of the contactor gas cavity. The level of air dehumidification is determined by the initial water content in TEG (about 6,6 mass%) while water consumption practically does not change the water concentration in the liquid carrier. As it is seen from Fig. 4, relative humidity of the output gas flow increases with the gas feed flow rise.

An analysis of the experimental data shows that the operating conditions of the dehumidification process are those, that the value of partial water vapor pressure in gas phase just before module output is constant (17%RH) under any total of experiment pressure values. Thus, the operating conditions are close to the equilibrium between water vapor in the gas phase and TEG at near the output point. Measured RH increasing under keeping of average total gas pressure (Fig. 4, curves 2, 3) can be explained by a decrease in total pressure at the output of the membrane module (increasing air flow is due to pressure drop increasing). In the other words, the mole concentration of water vapor increases what leads to relative humidity increasing.

In the case of the desorber operation the whole range, the outlet gas humidity was equal to 26°C dew point.

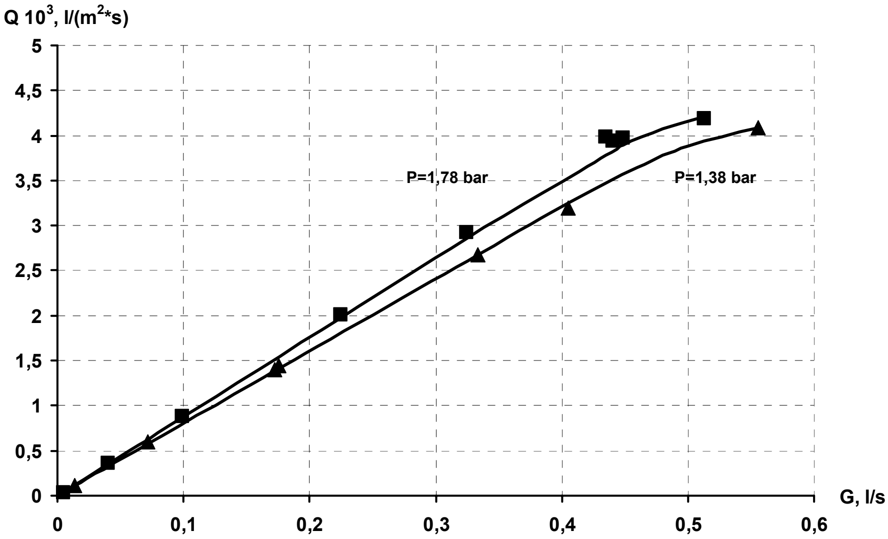

Fig. 5. The dependence of membrane productivity on feed gas flow.
Feed flow humidity: 40% RH; liquid carrier flow: 2×10^{-3} l/s; water content in TEG: 6.5 mass%.

The facts mentioned above, illustrated by dependencies of the membrane productivity on feed flow at the same average pressures shown at Fig 5. The linear part of the curves can be explained by the linear dependence of water vapor amount on the feed flow under low feed flow conditions when the pressure drop in the membrane module is negligible. The dependencies of humidity difference between the inlet and outlet airflows on water content in TEG are demonstrated at Fig. 6. The dependence character is mainly defined by the Henry law (1). When water content in TEG increases, air drying becomes worse and at the inversion point (16 mass% water in TEG) absorber starts to operate as a desorber. The temperature dependence of the module productivity explains the transaction point shift with a rise in temperature and the change of the operating mode from absorption to desorption.

$\Delta\varphi=\varphi_{in}-\varphi_{out}$ dependence on temperature is shown at Fig. 7. The respective curve resembles exponential function. This curve shows the critical temperature point, when the absorber starts to operate as the desorber. At the same water content in TEG, the temperature controlled processes in the absorber and desorber the full recirculation scheme can be realized. Dependence character in Fig.7 is practically by the dependence of Henry's constant on temperature.

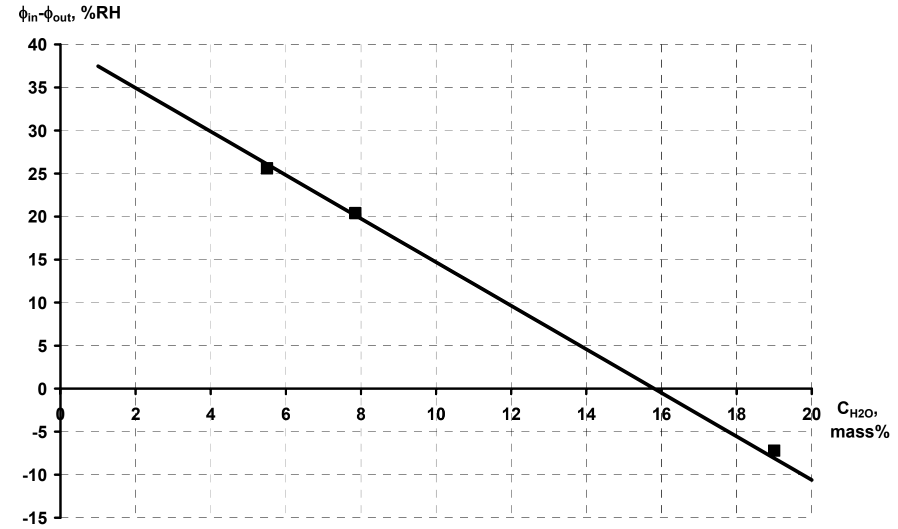

Fig. 6. The dependence of difference between input and output air flows humidity on the water content in TEG. Feed flow humidity: 40% RH, feed gas flow: 0.4 l/s, liquid carrier flow: 2×10^{-3} l/s, process temperature: 20°C.

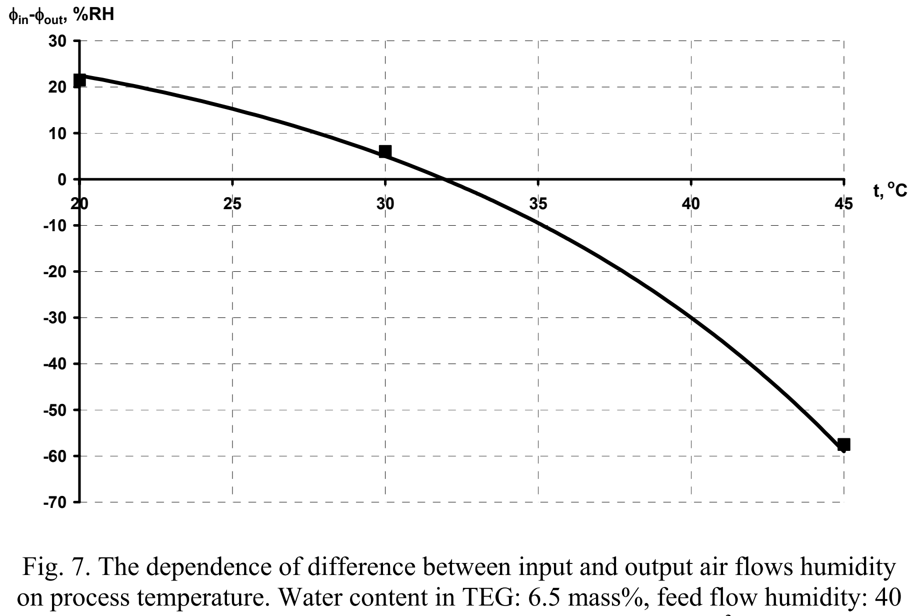

Fig. 7. The dependence of difference between input and output air flows humidity on process temperature. Water content in TEG: 6.5 mass%, feed flow humidity: 40 %RH, feed gas flow: 0.4 l/s, liquid carrier flow: 2×10^{-3} l/s.

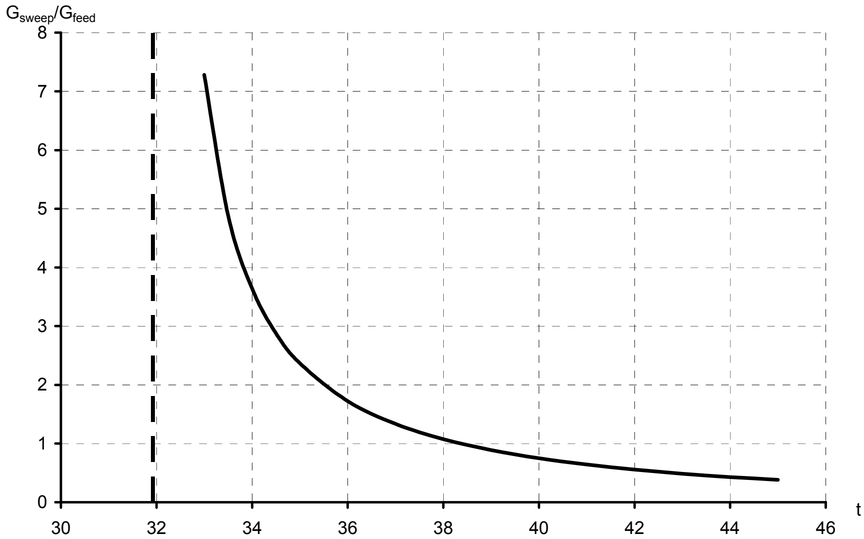

Fig. 8. Theoretical dependence of sweep and feed gas flow ratio on desorber temperature. Feed flow humidity: 40 %RH, water content in TEG: 6.5 mass%, absorber temperature: 20^{o}C.

Dependence of sweeping desorber and feed absorber gas flows ratio on desorber temperature is shown in Fig. 8. The sweeping gas flow is determined by condition, that water amount, absorbed and desorbed in modules are equal. The curve was calculated at constant values of absorber temperature and input gas humidity by using Henry's law (1). As it is seen from Fig.8 (dotted line) under desorber temperature 32^{0}C the equilibrium between liquid carrier and desorber sweeping gas flows is obtained under input 40 % RH. On this reason the infinitely high gas flow for the scheme operating is needed. Fig. 8 shows, that needed sweeping gas flow is decreasing with the contactor operating temperature rising and, in general, it can be the optimization parameter of the system. Liquid carrier and sweeping gas heating at desorber input mainly determine energy consumption of system. As far as we deal with high gas and liquid flows ratio, energy consumptions on gas and liquid flows heating under desorber input are comparable.

Another parameter of the process is the liquid flow. The estimations show that the liquid flow value 2 ml/s is sufficient to make the water content gradient in the liquid phase membrane channel negligible. This corresponds to the gas and liquid flows ratio about $10^2 \div 10^3$.

The preliminary comparison of AMCS and the passive recycle membrane vapor separation system [10] on energy consuming was carried out. Main energy consuming of passive system is the gas compression and in case of AMCS is the liquid carrier and sweeping gas heating. Estimation showed that AMCS energy consumption could be substantial lower in comparison with passive recycle system.

CONCLUSIONS

Membrane contactor system for gas dehumidification based on non-porous polymeric membranes was developed. The experiments with AMCS demonstrated effective air-drying. The developed contactor system allows to achieve air dehumidification at more than -20^oC dew point.

AMCS need no high gas flow pressures to carry out dehumidification. That enables the construction to be low energy consuming and compact.

The study of TEG/water system properties showed that TEG possess good characteristics as the liquid carrier. The Henry law dependence for the system was obtained. The operation mode, when the output air humidity does not depend on the airflow was obtained experimentally. It was demonstrated that air-drying is more efficient when gas pressure increases. Due to not large temperature variation, the absorption and desorption were realized.

High sorption capacity of TEG allows to achieve high dehumidification effectiveness under the feed gas flow liquid carrier flow ratio ($10^2 \div 10^3$).

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