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Review Article

Applications of Minichannels in Gas Absorption: A Review

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Abstract

Channels with small hydraulic diameters are novel contactors that enhance mass transfer rate due to great interfacial area to volume ratio and flow hydrodynamics. One of the interesting applications of small channels is gas absorption processes including oxygen absorption, carbon dioxide capturing, methane and hydrogen sulfide absorption and volatile organic compounds (VOCs) sequestration. This research presents a brief review on the recent developments and advances in application of Minichannels in gas absorption process, flow hydrodynamics and mass transfer characteristics in Minichannels. The major studies have been conducted on the CO_2 capture and separation by aqueous solution of amines due to effect of CO_2 emission on the global warming and popularity of CO_2 separation units. Although many researches have been conducted on gas absorption in mini contactors, there is a long way to industrialize this technology.

Keywords: Small scale channels; Mass transfer; Flow regime; Gas absorption

Figure 1: The flow pattern in a two-phase flow system.

Introduction

Absorption is one of the most important processes applied in the chemical, petrochemical and refinery units to separate gaseous mixtures and purifying streams. Through the absorption process, the desired components in a gaseous stream is dissolved in a liquid phase and captured. Industrially, the packed beds and tray columns [1,2], rotating packed beds [3], falling film columns [4], agitated vessels [5], bubble columns [6], spray towers [7] and membranes [8,9] are conventional devices used in the gas absorption processes. One of the main challenges in the gas absorption technology is the low rate of mass transfer in the contactors, which influence the number of stages, contact time and solvent circulating rate [10]. Increasing mass transfer coefficient in the gas-liquid contactors enhances the rate of mass transfer between phases and results in the lower contact time in the absorbers. Many researchers investigated the effects of fluid hydrodynamics, operating condition and tower specifications on the mass transfer coefficient in the absorbers and proposed novel structures to improve the rate of mass transfer. One of the novel structures introduced in the recent decade is mini-scale channels that present a large interfacial area caused by capillary force and surface tension [11]. The small-scale channels could yield both environmental and economic benefits compared to the conventional contactors by reducing the capital cost and equipment size [12,13] Figure 1 shows the schematic diagram of a small scale channel. Typically, the channels are categorized based on the hydraulic diameter and dimension. Based on the classification of Kandlikar and Grande, the hydraulic diameter of conventional channels is upper than 3mm, while the diameter of Minichannels and microchannels are in the ranges 3000-200μm and 200-10μm, respectively [14]. Mehendale et al. described the diameter range from 1 to 100μm as microchannels, 100μm to 1mm as mesochannels, 1 to 6mm as compact tube, and upper than 6 mm as conventional contactor [15]. The small scale channels present lower mass transfer resistance and higher pressure drop compared to the conventional contactors. Therefore, optimization of process conditions and channel dimensions is a practical solution to maintain pressure drop at moderate levels [16]. Table 1 compares the mass transfer coefficient in small scale channels with common equipment. It appears that channels can improve the mass transfer coefficient up to 1000 times more than other devices. This research

presents a short review on the gas absorption topic including flow patterns and mass transfer rate in Minichannels from millimetric ranges to microscale ones, and their applications in gas separation and purification. In this regard, the absorption of gases including O_2, CO_2, CH_4, H_2S and VOCs by selective solvents is reviewed briefly.

Table 1: Comparing mass transfer coefficient of conventional and minichannels.

Type of system	$K_LA \times 10^2$ [s^{-1}]	Ref
Countercurrent packed columns	0.04-7	[17]
Co-current packed columns	0.04-102	[17]
Bubble cap plate columns	1-20	[17]
Sieve plate columns	1-40	[17]
Bubble columns	0.5-24	[17]
Packed bubble columns	0.5-12	[17]
Horizontal and coiled tube reactors	0.5-70	[17]
Vertical tube reactors	2-100	[17]
Spray columns	0.3-80	[17]
Mechanically agitated bubble reactors	0.03-0.6	[17]
Submerged and plunging jet reactors	0.03-0.6	[17]
Hydro cyclone reactors	2-15	[17]
Venturi reactors	8-25	[17]
Milli channel	10-100	[18]
Microchannel	30-2100	[19]
Special type microchannel	2597-39342	[20]

Flow Hydrodynamics

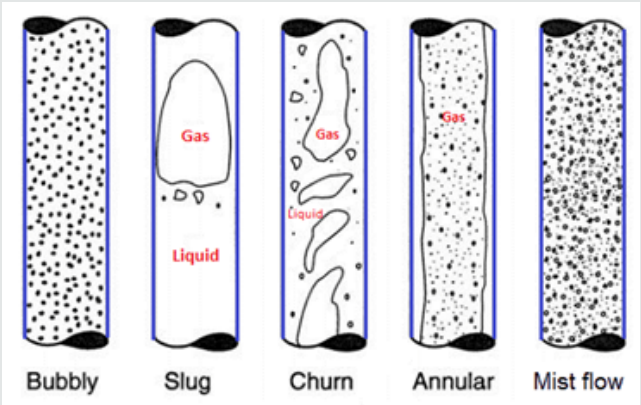

Figure 2: The schematic diagram of two phase flow regimes in minichannels.

The flow hydrodynamics has a considerable effect on the mass transfer rate in two phase flow systems. Generally, four major flow regimes including bubbly flow, Taylor flow, churn flow, and annular flow are observed when the gas and liquid flow simultaneously in Minichannels [17]. The capillary and gravitational forces, gas to liquid ratio and channel dimensions determine the flow regime type in the channels. The effect of capillary and gravitational forces can be described by Bond number as the ratio of the channel diameter to capillary constant. Although reducing channel hydraulic diameter changes transition between flow patterns to higher superficial gas and liquid velocities, channel orientation does not has any effect on flow pattern and transition lines in mini-channels [18,19]. Figure 2 shows the flow pattern in a two phase flow system [20].

In the bubbly flow regime, the gas to liquid ratio is small, and small bubbles are randomly distributed in a continuous liquid phase. Tylor flow regime as the most common flow regime in small scale channels consists of frequent gas and liquid slugs. In the Taylor regime the small bubbles coalesce and form large slugs at the same size and shape. It provides a high mass transfer coefficient, large surface area, low axial dispersion, sharp residence time distribution and low pressure drop in the channel [21]. Currently, the Taylor flow regime has attracted more attention compared to other regimes, due to its potential to intensify fast reactions which are controlled by mass transfer such as CO_2 absorption by chemical solvents. In the churn flow the bubbles form an unstable and non-uniform path in the center line of channel and pushes liquid. In the annular flow regime, the liquid develops a uniform wavy layer on the pipe walls and gas flows in the channel continuously. Chinnov et al. presented a good review on the hydrodynamics of two phase flow and flow patterns in mini and microchannels [22].

Mass Transfer Performance

The rate of heat and mass transfer in small scale channels depends on the fluid hydrodynamics and explained as volumetric mass transfer coefficient. Generally, there is two basic methods to predict flow regimes, mass transfer coefficient, gas and liquid slug lengths, gas and liquid holdups, and liquid film thickness in the small-scale channels, including experimental equations and theoretical approaches. In Taylor flow regime, which is dominant and desirable in minichannels, the overall mass transfer coefficient is usually expressed based on the operating parameters such as gas slug velocity, gas slug length, liquid slug length, dynamic gas holdup and liquid film thickness between the gas bubble and the channel wall. Besides, the mass transfer coefficient can be expressed as Sherwood, Reyonds and Schmit dimensionless numbers. Haase et al. presented a comprehensive overview on the hydrodynamics, flow regime and mass transfer in the minichannels and summarized the available correlations to predict Taylor flow characteristics, as well as mass transfer coefficients in gas-liquid systems [23].

Experimental Approach

The gas absorption from bubble phase toward the liquid results in a slug shrinking as it flows along the channel and the rate of reduction in the slug size and velocity are used to calculate the mass transfer coefficient [24]. Usually, the channels are made from famous polymeric materials such as poly–methyl-methacrylate and poly-dimethyl-siloxane through micro-mechanical cutting, wet and dry etching, lithography, embossing and imprinting, injection

molding, and different laser methods [25]. Gas and liquid streams usually flows to the channels from different entrances and join together in a Y or T junctions. The rate of bubble shrinkage and bubble position are recorded by a high-speed camera, and finally, gas and liquids are separated in a micro separator. The rate of gas absorption is determined either by titrating the accumulated liquid or analyzing the changes of the bubble volume through the channel [26]. Typically, the experimental based correlations could be utilized with an acceptable precision when the process conditions are near to the base experiment and similarity condition is satisfied. Sattari et al. reviewed the experimental studies on mass transfer in gas–liquid and liquid–liquid small-scale channels and explained the effects of operating conditions and the channel geometry on the mass transfer [27]. Typically, the mass transfer coefficient is calculated based on the balance of mass transfer rate from the gas bubble into the interface with the mass transfer rate from interface to the liquid slug as:

$$\frac{V_G}{V_G - V_{GE}} dV_G = -H_A RTK_L A dt \quad (1)$$

If the experimental measurements are based on the shrinkage of the gas bubbles, the molar rate and saturation concentration in above equation should be related to the gas slug volume with the aid of ideal gas assumption and Henry's law, respectively. This lead to the following result as:

$$K_L A = \left(\frac{1}{H_A RT} \left(V_{GO} - V_G + V_{GE} \ln \frac{V_{GO} - V_{GE}}{V_G - V_{GE}} \right) \right) t^{-1} \quad (2)$$

By knowing the initial and final volume of gas bubbles and applying the value of Henry's constant at the experimental condition, $K_L A$ is calculated [28]. On the other hand, if the titration method is selected to determine the amount of absorption, formulations should be written based on the liquid concentration as below [29]:

$$-Q_L dC_A = -K_L A \left(C^* - C_A \right) dV_{mc} \quad (3)$$

By a simple integration over the channel, the following equation is obtained.

$$K_L A = \frac{Q_L}{V_{MC}} \ln \left(\frac{C^* - C_{AO}}{C^* - C_A} \right) \quad (4)$$

The initial concentration of gas in liquid is zero and the concentration of outlet liquid is found by titration. As aforementioned, after calculating the mass transfer coefficient, it can be re-correlated based on the either the effective parameters or dimensionless numbers. Table 2 summarize some correlations to calculate the gas-liquid mass transfer coefficient in minichannels. Alternatively, the gas holdup could be computed from the gas and liquid slug lengths, liquid film thickness and bubble curvature in axial direction. These equations are explained based on Bankoff coefficient and gas input volume fraction [30]. In addition, the slug length is explained based on hydraulic diameter of channel, superficial gas and liquid velocities, gas and liquid holdups and dimensionless numbers including Reynolds, Bond and Capillary. Table 3 shows developed experimental and semi-experimental equations to calculate the slug length in the Minichannels.

Table 2: Developed correlations to calculate mass transfer coefficient in minichannels.

System	D_H [mm]	V_L [m s]	Equation	Ref
CH_4 in H_2O	1.5, 2.0, 3.1	0.01-0.4	$K_L = \frac{0.111 V_S^{1.19}}{\left[(1-\beta_G)(L_B + L_S) \right]^{0.57}}$	[33]
O_2-H_2O	1.0, 2.0, 3.0	0.09-0.65	$K_L A = 4.5 \sqrt{\frac{DV_B}{L_{UC}}} \frac{1}{d_h}$	[34]
O_2 in H_2O, EtOH	1.5, 2.2	0.0-0.56	$K_L A = \frac{2.76 D}{d_h L_{UC}} \left(1 + 0.724 \mathrm{Re}^{0.48} Sc^{0.33} \right)$	[35]
CO_2 in H_2O	0.4	0.6-1.2	$K_{GL} = \frac{D}{d_h} \left(0.1 \mathrm{Re}_L^{1.12} Sc_L^{0.05} \right)$	[36]
CO_2 in EOH, MeOH	0.3	0.05-0.35	$K_L = \frac{2\sqrt{2}}{\pi} \sqrt{\frac{DV_B}{\omega_{ch}}}$	[37]
CO_2 in H_2O, EtOH	0.4	0.07-0.55	$K_L A = \frac{D}{d_h^2} \left(1.367 \mathrm{Re}_G^{0.42} \mathrm{Re}_L^{0.72} Sc_L^{0.62} Ca^{0.5} \right)$	[38]
CO_2 in DEA	0.76	0.04-0.4	$K_L = 2\sqrt{\frac{D}{\pi t}}$	[13]

Table 3: The developed correlations to calculate gas and liquid slug length.

V_G [m s-1]	V_L[m s-1]	D_H [mm]	Direction	Equation	Ref
0.1–0.74	0.1–1.0	1.0–4.0	Upward	$L_B = 0.0878 d_h \frac{\mathrm{Re}_B^{0.63}}{Bo^{1.26}}$ $L_B = 3451 d_h \left(\frac{1}{\mathrm{Re}_G^{'} Bo}\right)^{1.27}$	[40]
0.0–0.4	0.03–0.4	1.5–2.3	Downward	$L_S = \frac{\left(\frac{V_{L,s}}{V_{G,s}+V_{L,s}}\right)}{1.56\left(\frac{V_{L,s}}{V_{G,s}+V_{L,s}}\right)\ln\left(\frac{V_{G,s}+V_{L,s}}{V_{L,s}}\right)-0.0014}$	[41]
0.01–0.7	0.01-0.5	0.9–3.0	Upward	$L_S = \left(\frac{V_s}{0.088\,\mathrm{Re}_g^{0.72}\,\mathrm{Re}_L^{0.19}}\right)^2$	[42]
0.01–0.25	0.01–0.25	1	Horizontal	$L_S = 1.637\varepsilon_G^{-0.893}\,\varepsilon_L^{-0.05}\,\mathrm{Re}_B^{-0.075}\,Ca_B^{-0.0687} d_h$ $L_B = 1.637\varepsilon_G^{0.107}\,\varepsilon_L^{-1.05}\,\mathrm{Re}_B^{-0.075}\,Ca_B^{-0.0687} d_h$	[43]
0.01–0.03	0.01–0.03	1	Upward	$L_B = \left(1+0.57\frac{V_{G,s}}{V_{L,s}}\right) d_h$ $L_S = \left(1+0.57\frac{V_{G,s}}{V_{L,s}}\right) d_h \frac{(1-\beta_G)}{\beta_G}$	[44]

Theoretical Approach

In the second method, the hydrodynamics of a slug flow, slug length and rate of mass transfer in the gas–liquid systems are calculated based on the modeling approach using the continuity and the momentum conservation equations coupled with mass balance and the reactions expressions [31]. In this approach, the bubble length and shrinkage through are calculated by solving two phase flow equations for species concentrations [32]. In this regard, the Navier–Stokes and continuity equations are written as:

$$\frac{\partial}{\partial t}(\rho V) + \nabla.(\rho VV) = -\nabla P + \nabla.\left[\mu\left(\nabla V + \nabla V^{'}\right)\right] \quad (5)$$

$$\frac{\partial \rho}{\partial t} = \nabla.(\rho V) \quad (6)$$

For the boundary conditions, the axial velocity (z direction) at the outer tube wall is set to the bubble velocity ($V_z = V_B$) while it is assumed to be zero at radial (r direction) coordination ($V_r = 0$). Besides, free slip boundary condition is used normal to the bubble surface. By solving Eqs. 8 and 9, the velocity distribution along the channel will be found. The convection–diffusion equation is used to determine the rate of mass transfer from gas phase to the liquid phase, as shown below [33]. In this equation, the velocity component is found from the solution of Eqs. 8 and 9.

$$\frac{\partial C_i}{\partial t} = -\nabla.\left(VC_i - D_i \nabla C_i\right) + r_i \quad (7)$$

In the above equation, all terms with i index should be written for both species, i.e. the absorbing gas component and the liquid side reactant. Besides, the equation should be considered equal to zero for taking into account the physical absorption. A more detailed description on the continuity and momentum equations could be found in the literature [34].

Applications of Minichannels

In the field of chemical engineering, channels can be used in nanoparticles synthesis [35], producing organic products [36,37] polymers synthesis [38], biodiesel production [39], phase change including boiling and condensation [40-42], and separation processes including distillation, stripping and absorption [12]. In this section, the application of Minichannels in the gas absorption process is discussed.

Oxygen Absorption

Due to non-reactivity and physical absorption, oxygen absorption in water is a common system to evaluate flow hydrodynamic, pressure drop and heat and mass transfer rates in channels [43-45]. Based on the conducted experiments on the oxygen absorption in water, the dominant flow regime in Minichannels is Taylor flow and liquid film is completely saturated when the channel length is large. Besides, the liquid slug length can be estimated from pressure drop [46].

CO_2 Capture

Carbon dioxide as the main greenhouse gas has a considerable effect on the global warming. Therefore, CO_2 separation and conversion are important topics from academic and industrial viewpoints [47,48]. Due to years, different solvents were proposed to absorb CO_2 from gas mixture in the conventional and intensified processes. Currently, carbon dioxide capture has been proposed as one of the most important application of Minichannels in the field of gas absorption due to high mass transfer rate, interfacial area to volume ratio and desirable flow hydrodynamics. Typically, the small-scale channels are economically competitive to conventional

systems and result in the lower capital cost when the plant capacity is below than 50 MMSCFD [48]. However, at higher capacities the operating costs of Minichannels is considerable compared to conventional technologies and this technology is not efficient.

CO_2 Capture by Sodium Hydroxide

Since sodium hydroxide is a strong base, the CO_2 is chemically absorbed in the aqueous solution of NaOH and related salt is produced in the liquid phase. This reaction is very fast and mass transfer controls the rate of CO_2 absorption. Thus, enhancing mass transfer coefficient in CO_2 absorption process is a practical solution to decrease plant size and improving process performance. Generally, the channels with small hydraulic diameter yield a considerable reduction in the residence time, and reactor size [46]. This reduction is enhanced by applying higher solvent concentration and operating temperature. Yue et al. studied the absorption of CO_2 in aqueous solution of NaOH in a minichannel with hydraulic diameter of 667 μm [19]. They measured pressure drop in the channel and reported that the liquid mass transfer coefficient in the volumetric basis is upper than $21s^{-1}$. Shao et al. simulated CO_2 capture in NaOH solution by Computational Fluid Dynamics in channels with diameter less than 1mm and showed that physical absorption increases with the channel diameter, while the reverse is true in the case of chemisorption [47]. Aoki et al. investigated the effect of flow rate, channel dimension, and gas holdup on CO_2 absorption by sodium hydroxide solution [49]. They concluded that the slug length depends on the channel diameter in the tee junction. Besides, the contacting angel less than 90˚c decreases the slug length at low flow rates. Tan et al. concluded that by curving the channel, the mass transfer rate will be enhanced in CO_2 absorption by aqueous solution of sodium hydroxide [50].

CO_2 Capture by Amines

Typically, the aqueous solution of amines such as monoethanolamine, diethanolamine, methyl diethanolamine, piperazine and their mixtures are primary absorbers for CO_2 capture [51,52]. In industrial processes, carbon dioxide is absorbed by the aqueous solvent, and the CO_2-rich amine stream feeds to the stripper. In that unit the amine mixture is regenerated with heat and steam, and lean amine is recycled to the main bed [53]. Spray towers, packed beds, tray columns mixers and falling film column are conventional apparatus used in gas sweetening and flue gas purification processes to separate CO_2 from a gaseous mixture. Although the kinetics of CO_2 absorption by primary and secondary amines is fast, desired purification level can only be achieved by very large columns due to the limited interfacial area between gas and liquid phases and mass transfer coefficient. Currently, small scale channels are proposed as the high-performance contactors to use in the CO_2 capturing process due to high interfacial area and hence enhanced mass transfer characteristics [54-56]. Chunbo et al. investigated CO_2 absorption into aqueous solution of monoethanolamine in a T-type minichannel [57]. They investigated the effect of mass transfer driving force, operating temperature, contact time, and enhancement factor on the absorption rate and capacity. It was concluded that the rate of chemical reaction plays an important role on the absorption rate. Since the monoethanolamine and CO_2 react fast and absorption is controlled by diffusion, the Minichannels are good candidate for CO_2 capturing. Kundu et al. studied CO_2 chemisorption in aqueous solution of diethanolamine in circular millimetric channels [58]. They studied the effect of feed composition and channel diameter on the CO_2 absorption rate. It was found that flow regime has a significant effect on the absorption performance, and the optimal feed rate and channel dimensions could be founded by formulation and optimization problem. Yang et al. showed that rate of CO_2 absorption in diethanolamine enhances when the gas and liquid phase superficial velocities increase in Minichannels and the maximum mass transfer coefficient is achieved in the slug and churn flow regimes [59]. Since absorption rate of MDEA solution is low, it is used with an activator in CO_2 capturing process. Pan et al. investigated the CO_2 absorption in aqueous solution of MDEA and PZ in a microchannel [60]. They reported that the volume mass transfer coefficient reaches to $1.70\ s^{-1}$ when Minichannels is used as gas-liquid contactor. Liu et al. investigated the desorption rate of CO_2 from MDEA in a minichannel contactor [61]. The mass transfer coefficient of desorption was in the range of 0.36-2.68 s^{-1}, which is in the same order with that of absorption and much greater than conventional equipment.

CO_2 Absorption by Ammonia

Ammonia is an potential solvent for CO_2 capture due to low energy consumption for solvent regeneration, low degradation rate, high CO_2 removal efficiency and loading capacity [62]. Kittiampon et al. presented a comprehensive comparison between performance of microchannels, packed bed column, spray tower, bubble column and multistage spraying tower to absorb CO_2 by aqueous solution of ammonia, in terms of operating conditions, absorption rate, and mass transfer coefficient [63]. The hourly volumetric flow rate of gas and liquid mass transfer coefficient in the small channel system were exceptionally high, indicating the potential of aqueous solutions of ammonia for CO_2 absorption. Therefore, the absorber volume can be greatly reduced by changing the type of contacting device to Minichannels.

CO_2 Absorption into Alcohols

Although alcohols are not primary absorbers for carbon dioxide, they can be used as working fluids to study CO_2 absorption performance in Minichannels. Ji et al. presented a novel method to measure mass transfer coefficient in liquid phase through the Pressure-Volume-Temperature correlation of the gas phase [64]. They used CO_2-H_2O, CO_2-ethanol and CO_2-n-propanol systems to evaluate performance of proposed method in square channels with dimensions of 40×240μm, 100×800μm, and 100×2000μm. The results showed that the channel diameter and the capillary number are effective parameters on the mass transfer rate, and the maximum value of the mass transfer coefficient is achieved in annular flow regime. For short timescales, below 0.001s, gas bubble diffuses very fast and the initial dissolution rate is found proportional to the Henry's constant and diffusion coefficient [65].

CO_2 Absorption by Potassium Carbonate Solutions

Recently, carbonate solutions are the alternative of MEA solutions for carbon dioxide capture from power plants and natural

gas due to the availability, low volatility, degradation resistance and environmental friendliness [65]. The main drawbacks are the slow CO_2 absorption rate and difficulty to handle solid participation. The solubility and kinetics of carbonate solutions to absorb CO_2 is the subjects of various studies [66,68]. In this family, aqueous solution of K_2CO_3 is one of the oldest solvents for CO_2 capture from natural gas utilized in Benfield process [69]. The performance of carbonate solutions in small channels were rarely studied. Sobieszuk et al. investigated the mass transfer rate of CO_2 from its mixture with N_2 into aqueous mixture of K_2CO_3 and $KHCO_3$ [70]. The volumetric mass transfer coefficient in the liquid phase was determined in terms of superficial velocities of gas and liquid. Besides, the rate of absorption was measured and the Dankwerts plot were generated. Finally, a correlation to predict mass transfer coefficient were presented [71].

CO_2 Absorption by Novel and Green Solvents

Recently, finding green and efficient solvents for CO_2 capturing is an attractive area from academic viewpoint. Between considered solvents, deep eutectics[72], ionic liquids [73-75] and amino acid ionic liquids [76] are the most important ones. Currently, the efficiency of mixture of MEA and [Bmim][BF_4][77], aqueous solution of [Bmim] [BF_4][75], and [Emim][BF_4] [78] have been proved for physical absorption of carbon dioxide in small channels. The main benefits of such solvents are that the regeneration can be easily performed at moderate conditions.

CH_4 Absorption

While the majority of the articles used CO_2 as the absorbing gas, a few studies were reported to absorb methane in the Minichannels. Special type of ionic liquids can absorb high amount of methane and utilized in a multichannel system for separating it from a mixture with nitrogen [79]. As mentioned before, since the ionic liquid mixture can be regenerated only by heat, the suggested structure contains the regeneration unit as well.

H_2S Absorption

Hydrogen sulfide removal is an important economic and environmental challenge faced by the oil and gas industries. Shah et al. reviewed H_2S separation using reactive and non-reactive absorption and adsorption, membranes, and cryogenic distillation [80]. Generally, a few studies have been conducted H_2S absorption in microchannels. Su et al. studied the mass transfer rate of H_2S into MEA solution in a T-junction microchannel [81]. It is concluded that T-junctions lead to higher mass transfer rate in the gas side and H_2S can be removed up to 99.5 % in such channels. Pan et al. focused on the absorption of H_2S and CO_2 mixture into MDEA in a microchannel reactor [82]. The results showed that the efficiency of the system could be up to 99.85% and the H_2S removal efficiency increases with increasing the MDEA concentration, liquid flow rate and decreasing gas flow rate.

VOCs Sequestration

The emission of volatile organic compounds in atmosphere causes serious issues in the environment and diseases in humans such as cancer and various allergies [83]. Therefore, VOC capturing and conversion including adsorption on activated carbon, zeolite and MOF [84-86], thermal or catalytic incineration [87], membrane separation [88], biological conversion [89], and absorption by selective solvents [90] are the topic of many researches. One of the important categories of VOCs is chlorinated VOCs such as tetrachloroethylene (TCE), dichloromethane (DCM), and chlorobenzene (CB) emitted mainly from cleaning industries. The absorption by di-wasethylhexyl-adipate (DEHA), di-ethylhexyl-phthalate (DEHP), and Tetra-Ethylene-Glycol-Dimethyl-Ether (TEGDME) is common method to separate chlorinated VOCs from gas mixtures [91,92]. Monnier et al. studied the absorption of TCE by DEHA in plates containing microchannels and compared the results with unstructured plates [93]. The results showed a considerable increase in mass transfer rate by utilizing mini structure plates, especially when liquid flow rate is low. Mhiri studied TCE absorption from air by DEHA at atmospheric pressure in a micro-absorber [94]. The effects of gas flow rate and cavity thickness on absorption performance were investigated and it was found that reducing cavity thickness, especially at low gas velocity, improves the gas side mass transfer coefficient around 7 times.

Scale Up

Typically, small scale channels suffer from low capacity, and thousands to tens-of-thousands of small channels are necessary to achieve required resistance times and throughput for industries [95-99] Therefor their application in industrial scale is a serious challenge. Several structures, such as parallel and series channels and channels dimension enlargement have been suggested to overcome these issues [100]. Among them, parallel numbering-up is the most common method for scaling up Minichannels. The performance of these structures are highly related to the phases distribution at the entrance of channel [101]. Usually internal and external methods are suggested for scaling-up small channels. In the first method, two phases are mixed together and distributed in all small channels, afterwards. The main challenge of this method is that the flow pattern and pressure drop will vary from one channel to another. Although, the bigger manifolds can be used to uniform the pressure across all channels, it results in deviation from Taylor flow pattern. The second solution is to enter both phases separately into each channel. Although the flow distribution will be more similar to a single channel, the equipment size and cost increased a lot. Therefore, an intermediate approach is proposed considering internal method for one phase and external method for two phase contacting. In other words, one phase is distributed in all channels while the other one will be injected to them separately [102]. This method will reduce both size and cost of the equipment and uniforms the flow pattern as high as possible [103-110].

Conclusion and Future Outlooks

In this work, a brief review on recent advances in application of Minichannels in the gas separation processes including O_2, CO_2, CH_4, H_2S and VOCS absorption were presented [111-114]. In all cases, a considerable enhancement in mass transfer rates were observed

due to high surface area to volume ratio and desirable flow hydrodynamic regime. Between considered absorption processes, carbon dioxide absorption by conventional amines in Minichannels has attracted more attentions because of CO_2 on global warming and environmental issues. Although CO_2 absorption by green solvents such as deep eutectic solvents and ionic liquids is an active research area, a few researches have been conducted on the application of green solvents in Minichannels. Some structures suggested to scale up Minichannels, by putting many of them together and designing a parallel multichannel system. In spite of conducted efforts on industrialization of small-scale channels, more theoretical and experimental studies are still essential in the field.

Nomenclature

Dimensionless group		Symbols	
Bo	Bond number	A	Channel area [m^2]
Ca	Capillary number	C	Concentration [mol/m^3]
Re	Reynolds number	d	Diameter [m]
Subscripts and super subscripts		D	Diffusion coefficient [m^2/s]
		H	Henry's constant [$Pa.m^3/mol$]
0	Initial	K	Mass transfer Coefficient [m/s]
A	Gas component	L	Length [m]
B	Gas bubble	n	Moles [mol]
C	Channel	N	Molar flux [$mol/m^2.s$]
E	Equilibrium	P	Pressure [Pa]
G	Gas	r	Reaction rate [$mol/m^3.s$]
H	Hydraulic	R	Gas constant [J/mol.K]
L	Liquid	t	Time [s]
S	Liquid slug	T	Temperature [K]
TP	Two phase	V	Volume [m^3]
UC	Unit cell	V	Velocity vector [m/s]
MC	Micro Channel		
Greek Letters			
ω		Channel width [m]	
ε		Void fraction	
μ		Viscosity [Pa.s]	
ρ		Density [kg/m^3]	

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