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High frequency ultrasonic-assisted CO_2 absorption in a high pressure water batch system

W.H. Tay, K.K. Lau *, A.M. Shariff

Department of Chemical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

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ABSTRACT

Physical absorption process is always nullified by the presence of cavitation under low frequency ultrasonic irradiation. In the present study, high frequency ultrasonic of 1.7 MHz was used for the physical absorption of CO_2 in a water batch system under elevated pressure. The parameters including ultrasonic power and initial feed pressure for the system have been varied from 0 to 18 W and 6 to 41 bar, respectively. The mass transfer coefficient has been determined via the dynamic pressure-step method. Besides, the actual ultrasonic power that transmitted to the liquid was measured based on calorimetric method prior to the absorption study. Subsequently, desorption study was conducted as a comparison with the absorption process. The mechanism for the ultrasonic assisted absorption has also been discussed. Based on the results, the mass transfer coefficient has increased with the increasing of ultrasonic power. It means that, the presence of streaming effect and the formation of liquid fountain is more favorable under high frequency ultrasonic irradiation for the absorption process. Therefore, high frequency ultrasonic irradiation is suggested to be one of the potential alternatives for the gas separation process with its promising absorption enhancement and compact design.

1. Introduction

Absorption is one of the typical mass transfer processes applied in gas separation. Several technologies have been developed for the gas absorption process, such as packed bed columns, mechanical agitator, membrane contactor and etc [1–4]. Nonetheless, some drawbacks are found in the current absorption technologies. For example, the conventional packed bed absorption technology is limited by the operating condition due to its excessive footprint and the presence of several maintenance issues, including scale deposition, plugging, foaming, and solvent viscosity limitation [1,3]. Besides, the mechanical agitator requires moving part system under a high pressure condition and its operability is limited to the solid impurity and solvent viscosity. Membrane contactor is another potential technology for the absorption process with larger surface areas for the mass transfer process. However, this technology also suffers in term of the constraint of operating pressure, limitation of solvent viscosity and requirement of pre-treatment process. Therefore, it is important to have an alternative absorption technology that offers robust operation, compact footprint and easier maintenance in order to suite for the specific operating conditions, such as offshore processing.

Ultrasonic irradiation is a conventional technology used in the enhancement of the multiphase reactions, mainly attributed to its physical kinetic effect [5–7]. It has been widely applied for solid cleaning, liquid chemical reactions, emulsions and others [7–10]. Besides, several studies have been performed on the ultrasonic-assisted mass transfer process [11–13]. However, application of high frequency ultrasonic in the CO_2 absorption process is scarcely reported. To date, most of the studies are performed under low frequency ultrasonic irradiation for the desorption purpose [13–16]. This is due to the fact that, the cavitation formation triggered by ultrasonic irradiation (bubble formation) is more favorable to enhance desorption process, and thus nullify the absorption processes [13]. Nonetheless, there are several researchers have conducted absorption study using low frequency ultrasonic technology. Kumar et al. (2005) has conducted their studies using two different types of method (ultrasonic horn and ultrasonic bath) for oxygen induction at ambient condition [17,18]. The results show that, ultrasonic irradiation coupled with air sparger has significantly enhanced the oxygen induction rate. However, they concluded that, it is not recommended to use stand-alone ultrasonic technology for oxygen induction due to the low power efficiency [18]. This is attributed to the induced convective current effect under low frequency ultrasonic irradiation, which is relatively lower as compared to the mechanical agitator. Sainz Herran et al. (2008) reported a study of using 20 kHz ultrasonic irradiation in

* Corresponding author.
E-mail address: laukokkeong@petronas.com.my (K.K. Lau).

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the bubble column [19]. The results show that, the mass transfer coefficient will only increase under ultrasonic power above 400 KW/m^3, which is not applicable for industry uses [19].

Fortunately, the cavitation is found to be hardly been trigged under a higher frequency ultrasonic irradiation [9,20]. This is due to that, the ultrasonic power onset for the cavitation would be increased with the increase of ultrasonic frequency. This means that, higher ultrasonic power is required for the ultrasonic cavitation formation under higher ultrasonic frequency. Besides, the ultrasonic cavitation is also believed to be reduced under higher pressure condition [9]. Laugier et al. [11] reported that, the nitrogen absorption in water can be enhanced up to 11-fold at high pressure of 11 bar using 20 kHz ultrasonic irradiation coupled with mechanically agitation. They reported insignificant enhancement in absorption at lower pressure. Therefore, based on the earlier finding, the ultrasonic assisted absorption is plausible to be enhanced under higher frequency ultrasonic irradiation and elevated pressure condition.

On the other hand, ultrasonic absorption can be enhanced under high frequency and pressure with the streaming turbulence effect and ultrasonic fountain caused by the ultrasonic power [21]. Streaming turbulence refers to the acceleration effect of liquid phase created by strong and high frequency ultrasonic irradiation [21–23]. This effect induces a convective dynamic current in liquid phase, which can be functioned as an agitator by transporting the liquid from the bottom to the top liquid surface. Based on several researchers [22,23], the ultrasonic streaming force can be increased by the ultrasonic frequency. Besides, ultrasonic fountain with atomization effect is created under a sufficient supply of ultrasonic power. Ultrasonic fountain and atomization are the phenomena where liquid droplet is pinched out by the strong vibration on the gas–liquid interfacial. The generated fine liquid droplet provides a large surface area for the mass transfer process, which the size of the droplet can be varied through ultrasonic frequency [24,25]. It is noted that, higher frequency generates smaller droplet and thus increasing the surface area for the mass transfer process [25].

Based on the literatures study, high frequency ultrasonic assisted absorption is a potential alternative that exhibits high mass transfer enhancement and several advantages, including compact design, no moving part and high resistance to solid and scale deposition. Therefore, the present studies investigate effect of high frequency ultrasonic irradiation of 1.7 MHz toward physical absorption and desorption of CO_2 in a batch system under elevated pressure.

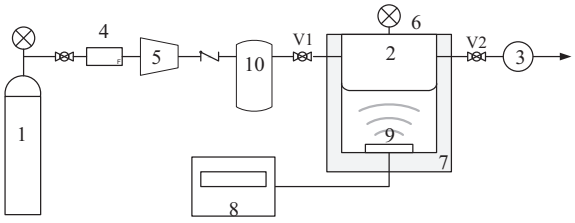
2. Methodology

Generally, the mass transfer experiment which was conducted in a batch vessel is presented in Section 2.1. The mass transfer coefficient which was measured using dynamic pressure-step method is described in Section 2.2. The measurement of the ultrasonic power is described in Section 2.3.

2.1. Gas–liquid mass transfer experiment setup

The experiment was set up based on dynamic pressure-step method to determine the mass transfer coefficient. The schematic diagram of the experiment setup is shown in Fig. 1.

The ultrasonic vessel was located in a water bath under temperature 30 °C with a 1.7 MHz ultrasonic piezoelectric transducer. The ultrasonic vessel was filled with 100 ml distilled water, which acted as the physical absorption solvent, and tightly closed under 1 bar. The pure CO_2 gas was then fed into the gas storage vessel with the flow rate of 10 SLPM using a compressor. The pressure



1. CO_2 gas tank
2. Ultrasonic vessel
3. Back pressure regulator
4. Mass flow controller
5. Compressor
6. Pressure sensor
7. Water bath
8. Ultrasonic power system
9. Ultrasonic piezoelectric transducer
10. Gas storage vessel

V1 Valve 1
V2 Valve 2

Fig. 1. Experiment setup for the ultrasonic mass transfer study.

in the gas storage vessel was increased to a higher pressure than the designed initial absorption pressure. The ultrasonic vessel was then pressurized by opening the valve 1. The pressure in the ultrasonic vessel pressure was controlled using a back pressure regulator. The valve 1 and valve 2 were closed immediately after achieving the designed initial absorption pressure. The absorption process of CO_2 was observed from the pressure drop profiles. The time dependent pressure was manually recorded. The absorption experiment was then repeated for the experiment with different ultrasonic power (range from 0 to 18 W) and initial absorption pressure (range from 6 to 41 bar).

For the desorption study, the CO_2 saturated water was prepared at 11 bar of initial absorption pressure prior to the desorption process. Valve 2 was then opened to reduce the pressure to 1 bar. The desorption process can be observed from the increment of pressure in the vessel. The time dependent pressure was manually recorded. The desorption experiment was then repeated for the experiment with different ultrasonic power (range from 0 to 18 W).

2.2. Mass transfer coefficient measurement

The resistance of the mass transfer from pure CO_2 into water is mainly located in the liquid layer. Therefore, the ultrasonic-assisted mass transfer coefficient $(k_La)^{us}$ can be obtained from the pressure drop profiles using physical absorption method [26], which is determined based on Eq. (1):

$$\ln\left(\frac{p_0 - p_{eq}}{p(t) - p_{eq}}\right) = \left(\frac{p_0 - p'_{eq}}{p_{eq} - p'_{eq}}\right)(k_La)^{us}(t - t_0) \quad (1)$$

where $(k_La)^{us}$ is the mass transfer coefficient, p_{eq} is final equilibrium pressure, p_0 is the initial absorption pressure and p'_e is the equilibrium pressure before compression. By plotting Eq. (1), the gradient of the plot, which is equal to $(k_La)^{us}$, can be obtained.

Besides, the overall mass transfer coefficient enhancement factor, E_c can be determined by using Eq. (2):

$$E_c = \frac{(k_La)^{us}}{(k_La)^0} \quad (2)$$

where k_La^{us} is the mass transfer coefficient with ultrasonic waves and $(k_La)^0$ is the mass transfer coefficient without ultrasonic irradiation.

2.3. Ultrasonic power system and measurement

A high frequency ultrasonic system was fabricated using a piezoelectric transducer. For the power system, a voltage-