Turbulent Flow Pump for CO_2 Capture from Combustion Emissions

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In this work, we provide detailed experiments describing the behaviour of CO_2 post-combustion capture (PCC) using Monoethanolamine (MEA) solution and integration of a Turbulent Flow Pump (TFP) into the laboratory scale system. We relate the CO_2 concentration in the inlet gas flow, total mixed gas flow rate, and solvent pump speed against the CO_2 capture efficiency. CO_2 capture efficiency computed per mass transfer and thin-film theory to estimate the overall mass transfer coefficient based on the diffusion rate between gas and liquid phases. The use of TFP showed the advantages of saving space and improve process efficiency. The interconnection between studied parameters is analysed via single variable regression models to generate design equations for developing and scale-up of carbon capture systems.

Keywords: MEA, CO_2 capture, amines solvents, absorption, desorption, mass transfer

INTRODUCTION

Sustainable energy systems are a concern for governments throughout the world. As a result, the capture and management of carbon dioxide from combustion systems is a critical element of the environmental policies of many countries [1]. Amine solutions are the most mature method for capturing carbon dioxide from mixed gas streams as part of natural gas sweetening processes [2]. This process is also applicable for the separation of CO_2 from flue gases composed mostly of N_2, CO_2 and H_2O. The use of amine solvents is effective and reliable; however, the process suffers from several drawbacks, including but not limited to high corrosivity, energy consumption, and maintenance costs [3]. In an amine-based CO_2 Post Combustion Capture (PCC) system, where CO_2 captured, compressed, and stored to prevent it from being released to the atmosphere. Aqueous alkanolamine solutions used to absorb the acid gas from the flue gas stream in countercurrent operation and the solvents need to be transported from the absorber outlet back to the inlet and undergo a regenerative heating process to release the acid gas. At present, this process requires large columns to separate CO_2 from the flue gas because the current technology of separation is limited by relatively slow mass transfer of process. Mass transfer coefficient in stirred cells and spray columns have been extensively investigated [4] [5], however the process intensification and improvement of these processes still face immense challenges to reduce

in device size. Improving spray system performance was achieved through the integration of a Turbulent Flow Pump (TFP). That integrates the solvent pump in the bottom of the column, such that TFP operation generates turbulence and superior carbon dioxide dissolution vs an in-line pump that might be installed outside of the reactor within the system piping. Integration of TFP in the process may increase the surface area interface between the gas phase and the liquid phase, stirring of the later cancel differences in concentrations which found to be beneficial in spray absorbers [6].

MASS TRANSFER

Absorption and desorption processes refer to the migration of solute from the gas phase to the liquid phase and vice versa [7]. The CO_2 is absorbed and released in certain mass transfer rates that are dependent upon both reaction rate and transport rate of the two phases. Kinetics of reaction is set by the driving force, which can be presented as the difference between the actual CO_2 concentration and the equilibrium concentration $(y^*_{CO_2})$ and is assumed to be fast using lean CO_2 amine solutions. According to film theory [8], resistance to mass transfer occurs in a thin layer of stagnant fluid while the bulk is well mixed. Mass transport through the different layers illustrated on Fig.1. The gaseous CO_2 diffuses from the gas bulk to the interface with relatively high resistance, at the interface CO_2 react with MEA and decreases significantly (dotted line), CO_2 molecules continues to diffuse through the liquid film to the well stirred bulk. An equivalent behaviour of mass transfer is shown in solid line from the interface to

liquid bulk. Fick's law, under the assumption of well stirred reactor and steady state conditions [9], [10], set the column height dependent concentration equation on the interface between two phases.

$$\frac{dY_{CO_2,G}}{dZ} = K_G a_e \cdot \left(\frac{P\left(y_{CO_2,G} - y^*_{CO_2}\right)}{G_I}\right) \tag{1}$$

where $Y_{CO_2,G}$ is the mole ratio of CO_2 in the gas phase, $P\left(y_{CO_2.G} - y^*_{CO_2}\right)$ is the expression for the mass transfer driving force, shown in diffusing plot on Fig.2, Z is the height of the absorber/stripper column, G_I is the inert gas molar flux and overall gas phase mass transfer coefficient expressed as $K_G a_e$, it includes a combination of diffusion rate on the gas phase, reaction kinetics, and thermodynamics of CO_2 absorption process and can be illustrated as labelled in Fig.1. Due to High solubility of CO_2 in aqueous alkanolamine solutions. gas phase resistance is the preponderant portion of the mass transport in this process, as indicated in Eq.2-30.

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{m}{k_L} \tag{2}$$

$$\frac{1}{K_G} \approx \frac{1}{k_G} \tag{3}$$

where K_G is the overall gas phase mass transfer coefficient, m/k_L represents the liquid phase resistance, and k_G is the gas mass transfer coefficient.
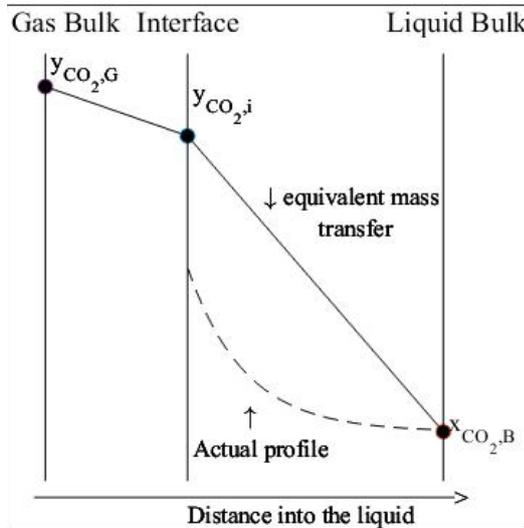

Fig.1. Illustration of CO_2 diffusion from gas phase to liquid [7]. $y_{CO_2,G}$, $y_{CO_2,i}$, , $y_{CO_2,B}$ are CO_2 concentration in gas phase, interface and liquid bulk respectively

According to Eq.1, to reduce the CO_2 concentration it is needed to increase the total area of the reactor, increasing the overall mass transfer coefficient using improve amine kinetics, increase the driving force and increase in the contact surface area between the two phases. For the investigation of the experimental absorption-desorption rate two of the paraments required are the solubility and diffusivity of the acid gas in the liquid phase, the use of overall mass transfer coefficient is due to the difficulty to measure those parameters.

EXPERIMENTAL SETUP

Schematic and a photo of the test rig are given in Fig.2. Columns consist of two Pyrex glass, each with an outer diameter of 65 mm, an inner diameter of 60 mm, and a height of 400 mm. The columns were filled with 330 ml of Reagent grade MEA 30% (w/w) with an assay of 99.0% obtained from Merck. Connecting tubes and reactors were purged with N_2 from a nitrogen tank. The system was heated and cooled in a cycle using a heating element and an ice bath respectively, for two hours to reduce any traces of other gases. Mass flow controllers (MFC) ensure a fixed gas ratio of CO_2/N_2 (Tylan 2900 series) ranges from 0-500 sccm, with an accuracy of 1% of full scale. Inlet gas is inserted in the bottom of the column and affected by the behaviour of the solution. CO_2 concentrations at the stripper and absorber outlet were measured using NDIR (Nondispersive infra-red) CO_2 sensors (SPRINTIR WF-20, SPRINTIR WF-100) ranges of the sensors is 0-20% and 0-100% of CO_2 by volume respectively both with an accuracy of 5% of reading. Two 12-watt liquid pump (TFP) with five centrifugal impellers, Fig.3, and a maximum speed of 2000 rpm connected to the bottom of the columns. Pulse Width Modulation of the control signal to pumps driver kept speed control at ±1%. Due to low concentration of amine solution, no significant raise in temperature was observed during absorption process, and the column temperature is considered constant after cooling to 40 °C. During the experiments, the temperature of the solution was measured at the top of the columns using special k type thermocouples with an accuracy of ±0.6 ˚C. Each measurement was taken after ensuring steady state behaviour of the process i.e., no fluctuations in CO_2 reading and constant temperature reading in the columns.
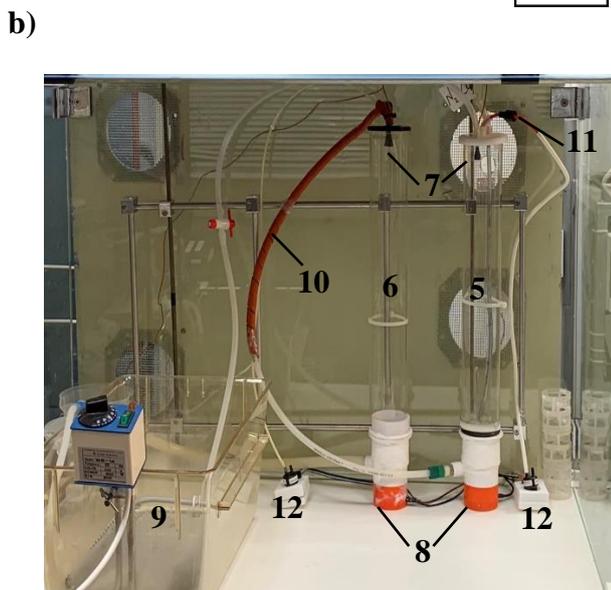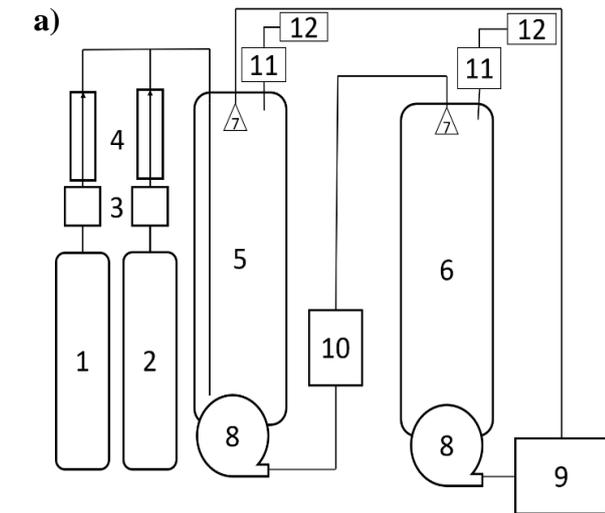
a)

b)

Fig.2. a) Schematic of the experimental setup. b) A photo of the test rig placed in a fume hood: 1- CO_2 tank, 2- N_2 tank, 3- mass flow controller, 4- check valve, 5- absorption column, 6- desorption column, 7- spray nozzle, 8- TFP, 9- cooling bath, 10- heating element, 11- desiccant, 12 – NDIR CO_2 sensor.

In this experiment, the use of TFPs enhanced the effect of a smooth gas-liquid interface, which who is advantageous in preserving the contact area for the reaction. The diameters of the spray nozzles and TFP set the maximum flow rate of the solution in the system for each reactor. TFPs power set the amount of liquid that accumulates at the bottom of the stripper and the turbulency flow of both gas and liquid phases. Turbulent flow allows both gas and liquid phases to remain homogeneous at the bottom of the reactors during CO_2 mass transfer and reduce film thickness.
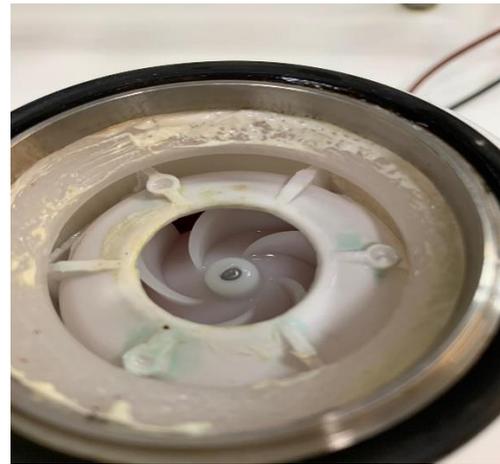

Fig.3. TFP impeller

RESULTS AND DISCUSSION

The process variables listed in Tab.1 were maintained constant, except that for each set of experiments one variable was varied to measure the effect of that variable on the CO_2 concentration vented out from the absorption column. All measurements were performed after the system is considered in steady state operation, to ensure the changes in CO_2 concentration is due to the regulated variable and not transition on other parameters.

Table 1. List of experiment variables

Variable	value	Units
Absorption temperature	35	$°C$
Desorption temperature	90	$°C$
Total flow rate	200	ml/min
Inlet CO2 concentration	11	% VOL
TFP Power	12	W
Pressure	114	kPa

Changes of CO₂ concentration

While changing the CO_2 concentration using the mass flow controllers, reading from the NDIR sensor gives the CO_2 concentration in the outlet of the absorption tower was recorded. The results in Fig.4 show the overall mass transfer coefficient decreases as CO_2 concentration increases. The expression of driving force increases with the increase in CO_2 concentration, resulting in a

decrease of the overall mass transfer coefficient. The relationship between CO_2 inlet concentration and the mass transfer coefficient, per the results in Fig.4, was observed to be exponential, which show a significant drop off in the mass transfer coefficient as the carbon dioxide concentration increases from 10% to 20% and high decline at higher concentrations. This behaviour is expected, due to CO_2 solubility decrease with reduced active MEA molecules. The liquid phase rates become significant in the process, and thus, a linear relation is not agreed.
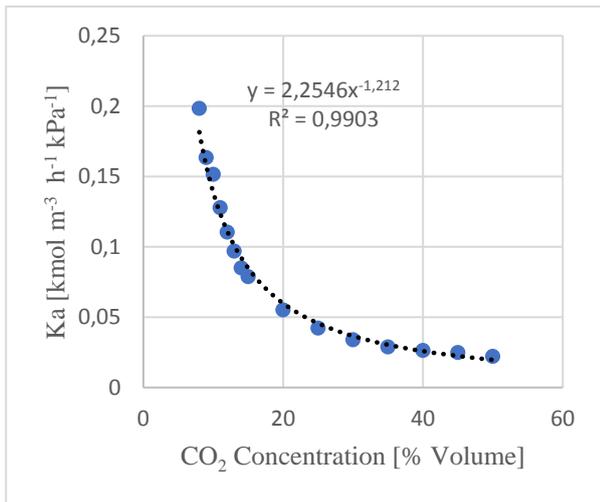

Fig.4. Impact of inlet gas CO_2 Concentration on mass transfer coefficient

For low CO_2 concentrated inlet gas, the results shown in Fig.5, suggests that as for low concentrations of CO_2, the linear behaviour is according to the reduction in driving force on Eq.1.
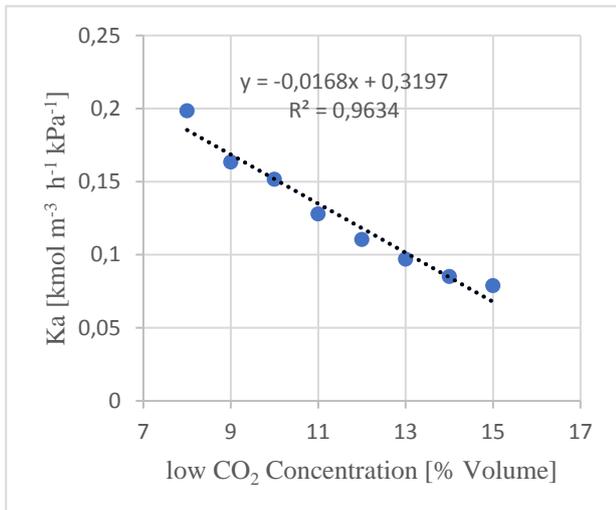

Fig.5. Impact of low concentrated CO_2 on mass transfer coefficient

Changes of inlet gas flow rate

The results shown in Fig.6 are consistent with thin film mass transfer theory the overall mass transfer coefficient is proportional to the gas flow rate. Since no packing used in the columns, no flooding consideration was needed when varying the gas flow rate. The trending observed was expected given high flow rate causes increased points of contact between the solvent and the mixed gas.
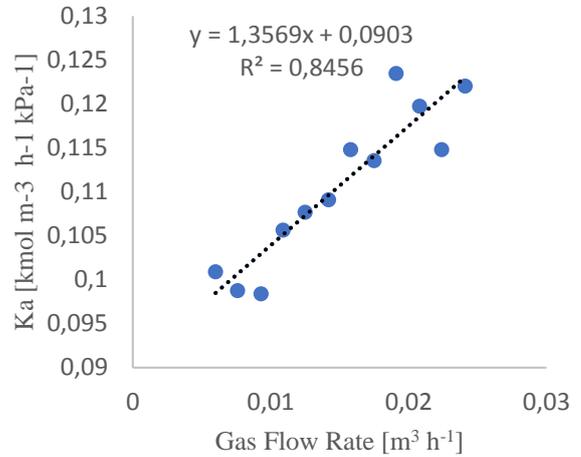

Fig.6. Impact of inlet gas flow rate on Mass Transfer Coefficient

Changes of TFP Power

TFP Power was set within the range of 4-13 watt. Results shown in Fig.7 show a clear tendency of the behaviour of the overall mass transfer coefficient when increasing the TFP power. Constrained in flow rate by the spray nozzle, the excess power of the TFP is related to the liquid stirring and creation of vortexes in accumulated solution at the bottom of the column. Below 6 watt no change in the liquid surface due to turbulence flow was observed, and under 4 watt there was not enough power to run the system. The range of operation 4-6 watt considered as laminar flow in the liquid phase. It is deduced that the turbulence flow of the solution and gas in the reactor decreases the boundary layer between the liquid and gas phase and therefore increases both gas phase and liquid phase mass transport. The laminar flow region starts with no difference in mass transfer measurement, and an increasing tendency is observed as the transition to turbulent flow occurs. The relationship between the pump power and mass transfer was linear and can be explained as the small increase in liquid phase mass transfer can

raise the equivalent overall gas phase mass transfer linearly Eq.4. This behaviour expected to increase both gas phase transfer and reaction rates enables the eddies to move into the boundary layer due to a decrease in laminar film thickness.
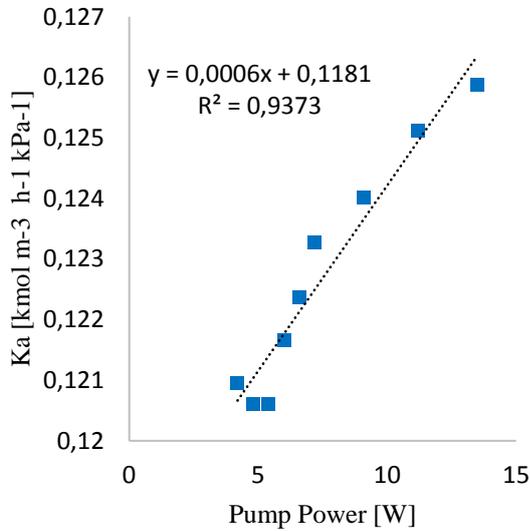
$$K_G \cong k_G \cdot \Delta k_L \tag{4}$$

Fig.7. TFP power on overall mass transfer coefficient

REGREATION MODEL

Regression models have been applied according to Tab.2. The regression models explain the expected behaviour of the system.

Table 2. Regression models for experimental results

Parameter	Effect	Model
CO_2 partial pressure	Change in driving force	Power,
Gas Flow rate	Increase in gas phase molecule transfer	Linear,
TFP power	Increase in packing volume	Linear,

CONCLUSIONS

A study on the gas-liquid mass transfer enhanced using a TFP was proposed to improve the process efficiency. The use of a TFP both simplifies mass transfer calculation due to solution turbulence stirring and increases mass transfer coefficient in compare to laminar flow. Using TFP integrated absorption desorption cycles, the mass transfer coefficient was measured to determine the effect of different variables on the process efficiency. The increase in CO_2 concentration

reduces the overall mass transfer coefficient. A nonlinear trend was observed for high concentrated inlet gas streams as the mass transfer linear model is no longer valid. An increase observed when increasing the inlet gas flow rate and TFP Power. Integration of the TFP in laboratory scale model found to be beneficial for use in CO_2 removal process to reduce columns size. However, the results presented only indicate the behaviour of the system, and for scale-up purposes, a larger scale laboratory experiment is needed.

ACKNOWLEDGEMENTS

NOMENCLATURE

$Y_{CO_2,G}$ - CO_2 mole ratio in gas phase, mol%;

$y^*_{CO_2,G}$ - CO_2 equilibrium mole ratio in gas, mol%;

$y_{CO_2,B}$ - CO_2 mole ratio in liquid bulk, mol%;

$y_{CO_2,i}$ - CO_2 mole ratio in liquid-gas interface, mol%;

P - pressure, kPa;

G_I - inert gas molar flux, $\frac{kmol}{m^2 \cdot h}$;

k_G – gas phase mass transfer coefficient, $\frac{m}{h}$;

k_L – liquid phase mass transfer coefficient, $\frac{m}{h}$;

K_G - overall gas phase mass transfer coefficient, $\frac{m}{h}$;

η – CO_2 removal efficiency;

a_e – interface effective contacting area, $\frac{m^2}{m^3}$;

Z – column height, m;

T - temperature, K;

TFP – turbulent flow pump;

MEA - monoethanolamine;

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