

Study of the Pressure Drop and Flooding in a Rotating Packed Bed Equipped with Stainless Steel Wire-Mesh Packing

Usman GARBA^{a,b}, David ROUZINEAU^a, Michel MEYER^a

^aChemical Engineering Laboratory, University of Toulouse, CNRS, INPT, UPS, Toulouse, France

^bUsmanu Danfodiyo University Sokoto, Nigeria

usman.garba@toulouse-inp.fr, david.rouzineau@ensiacet.fr, michel.meyer@ensiacet.fr

Abstract. Embedded processes require compactness, low energy consumption, and insensitivity to gravity. Centrifugal processes respond to the last characteristic. Centrifugal force is used instead of the gravitational force with almost zero sensitivity to variations in the gravitational force. We studied rotating packed bed (RPB) as a gas/liquid contactor for absorption. We focused our attention on the hydrodynamic behavior of this device. Previous studies on RPB flooding and operating limits dwelled on virtual observations and/or pressure drop variations. However, physical visualizations are subjective because RPB pressure drop variations are too inconsistent to be used to determine the upper operating limit during RPB operations. A robust quantitative method of obtaining RPB upper operating limits based on the flow rate of the ejected liquid, supported by visual observation and pressure drop measurement was presented. The aim was to identify with greater accuracy, RPB hydrodynamic characteristics, and provide a more standard method of identifying the same.

Keywords: Gas/liquid contactor, hydrodynamics, rotating packed bed, pressure drop, upper operating limit

Introduction

Reliance on gravitational force makes conventional packed columns for separation processes such as distillation and absorption have unimpressive sizes and physical footprints which makes them uneconomical, especially where space and weight are essential [1], [2]. The operating ranges of non-rotating, conventional, packed bed columns (PBCs) are limited by forces such as gravitational and frictional forces acting in opposite directions on the down-flowing liquid and the gas flowing from the bottom of the column. A RPB also called HIGEE (High g) contactor, is a compact process intensification equipment in which a combination of large allowable gas and liquid flowrates is achieved by superimposing gravitational force with centrifugal force. In RPBs, the higher gravitational force factor employable raises the combined operating range of the throughputs in addition to their flexibility due to the additional degree of freedom offered by the rotation speed [3].

A fundamental aspect of the modeling, design, optimization and implementation of pilot-scale and subsequent scale-up of RPBs is the clear understanding of the principles of its hydrodynamics via accurate prediction of the pressure drops and upper operating limits [4]; [5]. Also, Zhang et al. [6] observed that the mass transfer performance and efficiency of an RPB as reflected by its gas pressure drop is closely linked to its hydrodynamic characteristics, operating costs, and energy requirements. Hydrodynamic characteristics such as the pressure drop of an RPB is a useful index in measuring its resistance and consequent consumption of energy [7]. Many studies were carried out to evaluate the influence of pressure drop in many RPB operations with empirical and semi-empirical models established [8]; [9]. RPB hydrodynamic parameters extensively reported in the literature include liquid holdup [10]; [11], gas pressure drop [12], liquid dispersion [11]; [13] and, flooding [14]; [5]. Although extensive research had been conducted and documented using RPBs, with many of its several applications explored at the industrial scale, its design approach is still case-specific and thus requires improvements [4].

In this work, a robust quantitative method of obtaining RPB upper operating limit based on the flow rate of the ejected liquid, supported by visual observation and pressure drop measurements is presented. This was achieved by connecting a tee joint pipe to the gas outlet. In addition, a comprehensive pressure drop behavior and flooding for a countercurrent water-air system and a single-block stainless steel wire mesh packing using a double jet nozzle for the liquid inlet were used to study the hydrodynamics of a pilot-scale RPB. The aim was to further improve the understanding of RPB hydrodynamics for design, scale-up, and energy conservation purposes.

Context

The relatively high rotation speeds of RPBs combined with the size of the equipment make it possible to implement forces more than 100 times greater than gravity, which greatly intensifies the transfer phenomena between phases [15]. The rapid replacement of the contact surface in RPBs allows for the use of high effective surface area packings of up to 2000 to 5000 m²/m³ [15]. This allows for higher mass transfer characteristics: gas-liquid interfacial surface area, gas-side, and liquid-side volumetric mass transfer coefficients, and height of transfer unit [16]; [17]. Also, this allows for the same separation performance in RPB to have much more flexible and compact equipment with a wider operating range than a gravity column used for absorption [16]. Overall, compared to conventional gravity columns, for a comparable processing capacity and efficiency, a RPB offers rotation as an extra degree of freedom, serves as the foundation of modular plants, and is more miniaturized with higher flexibility and energy efficiency [18]. The aforementioned characteristics make RPBs emblematic equipment for process intensification. Consequently, RPBs have been employed for various purposes in diverse fields such as separation processes, synthesis, and preparation of micro and nano-particles, petroleum products processing, biodiesel production, medical sciences, and pollution control [2]; [16] and [18].

A conventional, single-stage RPB is shown in Figure 1. It is made up of a casing that surrounds a rotor mounted on a shaft and rotated by a motor. The rotor is a motor-driven, ring-shaped cylinder, which encloses an annular packing mounted on either a horizontal or a vertical shaft. In countercurrent operation mode, gas is introduced into the outer periphery of the packing from the casing. The liquid is usually introduced into the center (or “eye”) of the rotor via the liquid inlet through a stationary set of nozzles (liquid distributor) into the packing from the top of the RPB. After its transformation by centrifugal shear forces, the liquid flows in the form of rivulets, droplets, or films as determined by the speed of rotation [10], and is finally collected by the casing wall and flows downwards under the action of gravity, leaving the casing via the liquid outlet.

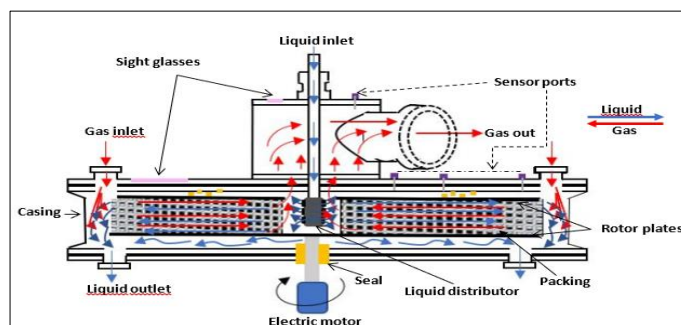


Figure 1: Schematic of a countercurrent flow RPB

As equipment for efficient multi-phase mixing and mass transfer, Yuan et al. [19] identified RPB packing as its core component. Because of its excellent mass transfer characteristics, stainless steel wire mesh is commonly used as RPB packing [20]. Conventional packed beds have constant cross-sections. Thus, during flooding, their packing pores are nearly wholly filled throughout the column causing a noticeable, steep rise in pressure drop. Due to the rotor geometry, RPB packings have variable cross-sections. The centrifugal forces are lowest at the center (eye) of the rotor. Hence, RPB flooding occurs in the eye from where the liquid is ejected. Consequently, pressure drop variations during flooding in RPBs are not consistent as the sole indicator of flooding. Neumann et al. [4], and Lockett [14] also reported that in contrast to conventional columns, for RPBs, no sharp inflection in the total pressure drop or the hold-up of the liquid with the gas velocity was observed during flooding. The procedure for the visual determination of the upper operating limit is to neutralize two of the operating variables and manipulate the third one [3]. Therefore, it is possible to carry out two procedures to reconfirm the results. The speed of the rotor and the liquid flow rate may be set to a constant value than the gas flow rate gradually increased until an excessive splash of the liquid is observed in the eye of the rotor. Allowing the gas flow rate to increase beyond the upper operating limit, will cause the liquid to accumulate in the eye of the rotor. Grob et al. [3]; Neumann et al. [4] and Xie et al. [12] recommended the use of a combination of visual and quantitative approaches to adequately study the flow behaviour in RPBs while Grob et al [3] observed that due to observed inconsistencies, the use of physical, visual observations and the measurement of pressure drop variations alone are not sufficiently adequate to predict flooding behaviour in RPBs. Burns and Ramshaw [9] used

liquid holdup while Hendry et al.[5] used the measurement of the flowrate of entrained liquid from the eye of the rotor to identify the upper operating limits in RPBs.

Materials and methods

The experimental setup is shown in Figure 2. The RPB used was a pilot-scale RPB 500 from Proceller® located at the [Laboratoire de Génie Chimique](#) (LGC), in Toulouse (France). The RPB was a single-stage, vertical rotor type with a casing diameter of 0.676m, an inner rotor diameter of 0.160m, and an outer rotor diameter of 0.500m. The packing was a conventional, multi-layered, single-block, stainless steel wire mesh with an axial height of 0.040m, a specific surface of 2400m²/m³, and a porosity of 86%. Visual observation was possible using two sight glasses placed directly above the eye of the rotor and another on the casing (Figure 3a). To aid the systematic collection and subsequent measurement of ejected water from the eye of the rotor during flooding, a tee joint pipe was connected to the gas outlet as shown in Figure 3(e). A countercurrent air-water system was used for all the experiments. The rotation speed of the rotor was selected and auto-controlled via a variable frequency drive. The liquid was pumped to the RPB using a peristaltic pump and controlled with a valve. The liquid flow rate was measured with a panel-type rotameter and sprayed from the center of the RPB using a dual nozzle, flat fan liquid distributor. The liquid was recirculated to the feed tank using a by-pass line. Air supply from the laboratory general compressor was used. The gas was introduced into the outside of the RPB into the casing through twin gas inlets and leaves after passing through the packing via the gas outlet. While the liquid sprays outwards from the center of the packing to its periphery. To measure the pressure drop between the packing periphery and gas outlet, a pressure sensor connected to a pressure transmitter was placed across the two points. Pressure drop was measured in real-time by interfacing the sensor to a computer using a data acquisition system.

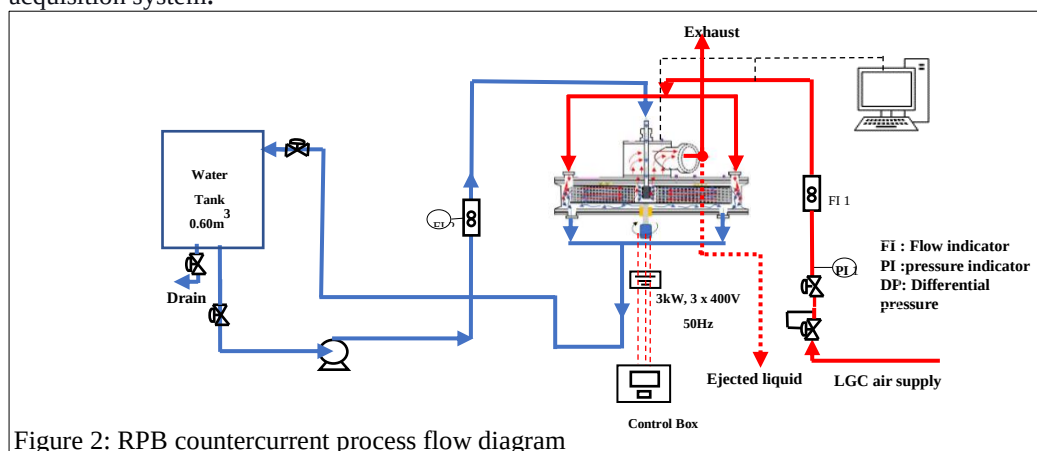


Figure 2: RPB countercurrent process flow diagram

The range of operating parameters studied was: gas flowrate (V_G), 0–400 Nm³/h; liquid flow rate (V_L), 0–0.75 m³/h and rotation speed 0–1500 revolutions per minute (RPM). Each experimental run was for 2 minutes. In the dry pressure drop measurements, the frictional pressure drop was first measured by passing air at 100 Nm³/h through the stationary rotor and then measuring the pressure drop. The experiment was repeated by increasing the airflow rate in steps of 50 Nm³/h. The same procedure was repeated with the rotor at various rotation speeds. Next, the effect of the rotation speed was investigated, initially via the centrifugal pressure drop. In the absence of liquid flow and gas flow, the rotor was set to an initial speed of 100 rpm. The rotation speed was subsequently changed step-wise. The effect of rotation speed was further investigated by varying the rotation speed at constant gas flow rates. For the wet pressure drop, rotation speeds, and liquid flow rates were kept while the gas flow rate was increased stepwise. This was followed by another set of experiments during which the gas flow rate and rotation speed were kept constant while the liquid flow rate was increased. To determine the upper operating limit, the liquid flow rate and rotation speed were kept constant, while the gas flow rate was increased step-wise until the first drops of water are observed from the gas outlet according to the arrangement shown in Figure 3e. This point was taken as the upper operating limit of the RPB at the prevailing combination of operating factors. The reduction in rotation speed was continued gradually with the amount of ejected water measured at each step after attaining a steady state of operation. Flooding points of the RPB operations were determined on the attainment of visual observation of excessive splashing of water at the RPB eye, with or without a sharp increase in pressure drop. The volume of water ejected at each step change of the gas flowrate was collected and

measured using a measuring cylinder and the flooding point was taken following the recommendation of Hendry et al. [4] when,

$$\text{flowrate of ejected liquid} \geq 8\% \text{ liquid flowrate} \quad (1)$$

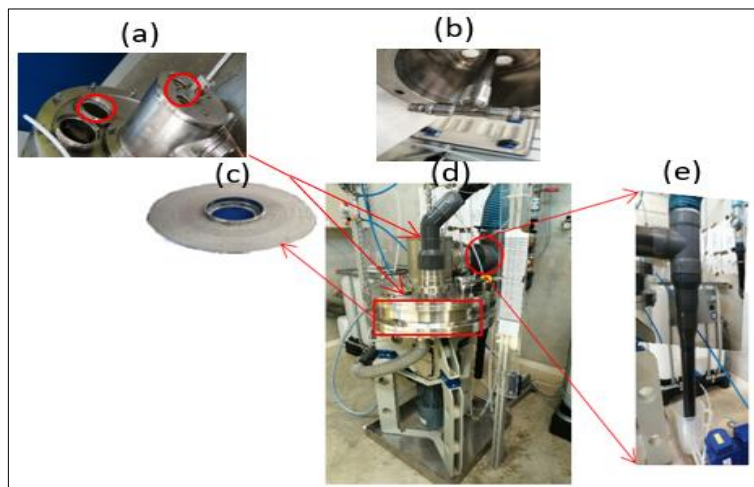


Figure 3. RPB set up for flooding point measurements. (a) sight glasses for visualizations (b) double jet nozzle (c) stainless steel wire mesh packing (d) Photo of RPB setting (e) ejected water collection system.

Results and discussion

Figure 4(a) shows that dry pressure drop increases with increased rotor speed. A slow increase in pressure drop was obtained at low rotational speeds from 100 to 550 RPM. Above 600 RPM, a rapid and almost linear increase in pressure drop was obtained. This phenomenon may be due to the greater need to overcome the pressure drop caused by rotation, (centrifugal head) at higher rotational speeds which consequently, causes the air in the rotor and between it as well as in the casing to rotate. The dry bed average increase in pressure drop per unit increase in rotation speed in the range investigated was 0.75Pa/rpm. Figure 4(b) also shows a substantially linear increase in pressure drop with increasing gas flow rate. This is largely caused by the effects of gas inertia and friction. On average, Figure 4(b) shows that the average increase in pressure drop per unit increase in gas flow rate was 4.11Pa/Nm³h⁻¹ within the operating range investigated.

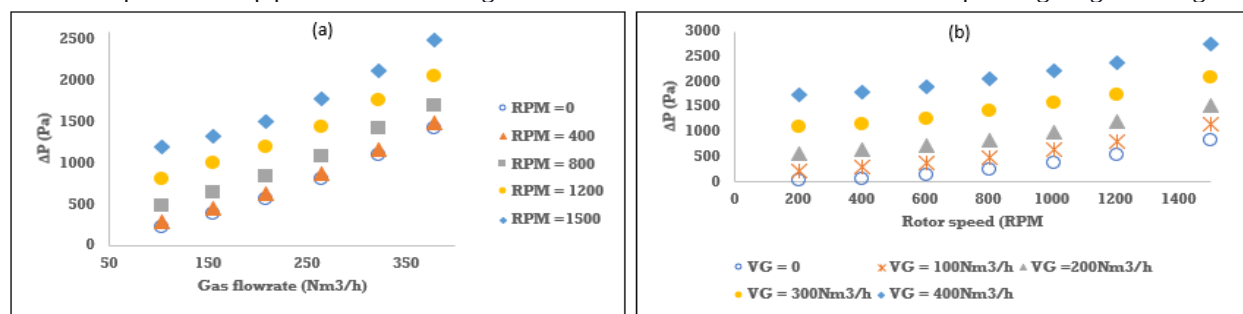


Figure 4: Dry bed pressure drop (a) effect of rotation speed (b) effect of gas flowrate

Comparing Figures 4(a) and (b), it can be seen that based on the sensitivity analysis mentioned above, the gas flow influences the dry pressure drop of the RPB more than the rotational speed. For the irrigated bed, Figures 5(a) and (b) as well as Figure 6(a), showed that the trend of the pressure drop variation was almost the same as that of the dry bed, with the pressure increasing with an increase in rotational speed and with the gas flow. Liu et al. [6] identified the wetting of the surface of the packing which affects the frictional pressure drop and the blockage of the pores of the packing by the liquid to the passage of gas as the two principal contributors to the rise in pressure drop in wet RPBs. Figure 6(b) is indicative of the lower effect of liquid flowrate on the overall pressure drop in RPBs. For example, for a gas flow of 350Nm³/h, the 50% increase in liquid flow rate from 0.3 to 0.6m³/h produces small changes in the pressure

drop with the increase in the speed of rotation, showing that the effect of the gas flow in the RPB is more than that of the liquid flows. This phenomenon is more visible when we represent this at constant rotational speeds with a variation of the gas flow (Figure 5b) or a variation of the liquid flow (Figure 5(b)). These results confirm the trends described by the work of Grob et al. [3] and Neumann et al. [4].

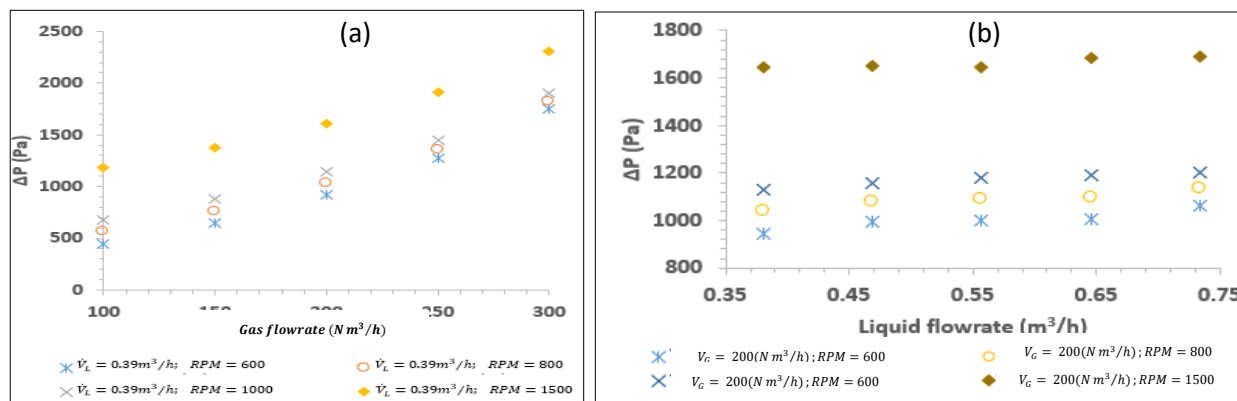


Figure 5: Wet bed pressure drop (a) effect of gas flowrate (b) effect of liquid flowrate

Figure 6(a) shows that the flooding data follows a typical RPB equipped with a vertical axis pressure drop variation curve with rotation speed at constant gas flowrate and liquid flowrate as highlighted by Neumann et al. [4]. At a decrease from the maximum rotation speeds, a lowering of centrifugal pressure drop is obtained while liquid holdup causes only a slight increase in frictional pressure drop. Further decrease in the rotation speed will cause an accumulation of liquid in the eye of the rotor which leads to an increase in the frictional pressure drop and a sharp increase in the total pressure drop.

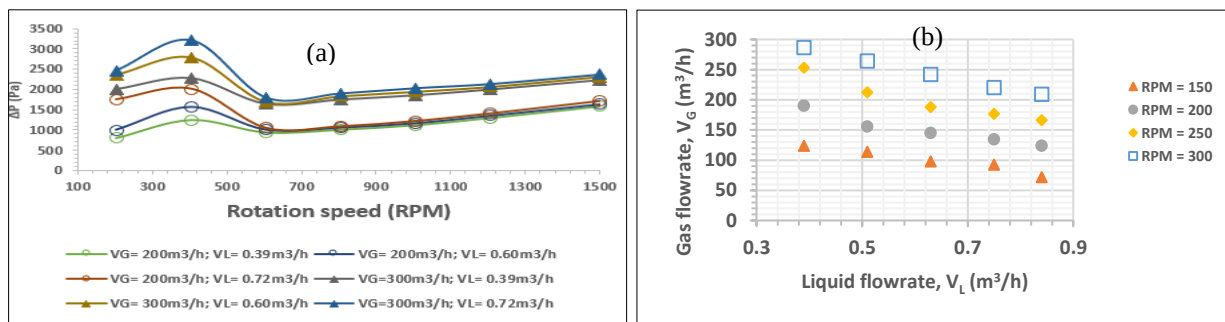


Figure 6: (a) Effect of rotation speed at constant gas and liquid flowrates (b) upper operating points.

As the rotation speed is further decreased, rapid ejection of liquid from the eye of the rotor to the gas outlet is obtained due to the acceleration of the liquid droplets., the pressure drop increases significantly and the presence of water is visually observable in the rotor eye. Figure 6(b) shows the upper operating limits of the system investigated. At a constant rotation speed, the gas flow rate at which the ejection of liquid droplets was observed and decreased with increased liquid flowrate. Normal operation of the RPB without liquid ejection and possible high-pressure drops which increase power consumption is obtained by operating the RPB below the indicated points. The operating limit at a given condition can be improved by simply increasing the rotation speed from the given point.

Conclusions and perspective

This paper focused on furthering the understanding of the upper operating limits of RPBs as an essential aspect of its design, modeling, scale-up, and use for the intensification of mass transfer processes. The gas pressure drop of a pilot-scale RPB equipped with stainless steel wire mesh packing for an air-water system using a twin-nozzle liquid distributor was explored. A robust approach to determine RPB operating limits based on quantifying the volume of liquid ejected from the eye of the rotor was explored. The operating limits for RPBs are influenced mostly by the three operational parameters: gas flow rate, liquid flow rate, and rotational speed in that order. These studies will be explored

further by developing a new, 3D-printed RPB packing based on the hydrodynamic characterization from this work. The interfacial area of the new packing using a CO₂–NaOH absorption system will also be measured.

Acknowledgment

This work was conducted under support funding from the Overseas Scholarship Scheme (OSS) of Petroleum Technology Development Fund (PTDF), Nigeria (Grant Number: PTDF/ED/OSS/PHD/UG/1543/19).

References

- [1] A. Lawal, M. Wang, P. Stephenson, and O. Obi, “Demonstrating full-scale post-combustion CO₂ capture for coal-fired power plants through dynamic modelling and simulation,” *Fuel*, vol. 101, no. July 2020, pp. 115–128, 2012, doi: 10.1016/j.fuel.2010.10.056.
- [2] M. Hilpert and J. U. Repke, “Experimental Investigation and Correlation of Liquid-Side Mass Transfer in Pilot-Scale Rotating Packed Beds,” *Ind. Eng. Chem. Res.*, vol. 60, no. 14, pp. 5251–5263, 2021, doi: 10.1021/acs.iecr.1c00440.
- [3] K. Groß, K. Neumann, M. Skiborowski, and A. Górak, “Analysing the operating limits in high gravity equipment,” *Chem. Eng. Trans.*, vol. 69, pp. 661–666, 2018, doi: 10.3303/CET1869111.
- [4] K. Neumann, S. Hunold, K. Groß, and A. Górak, “Experimental investigations on the upper operating limit in rotating packed beds,” *Chem. Eng. Process. Process Intensif.*, vol. 121, no. August, pp. 240–247, 2017, doi: 10.1016/j.cep.2017.09.003.
- [5] J. R. Hendry, J. G. M. Lee, and P. S. Attidekou, “Pressure drop and flooding in rotating packed beds,” *Chem. Eng. Process. - Process Intensif.*, vol. 151, May 2020, doi: 10.1016/j.cep.2020.107908.
- [6] W. Zhang, P. Xie, Y. Li, L. Teng, and J. Zhu, “Hydrodynamic characteristics and mass transfer performance of rotating packed bed for CO₂ removal by chemical absorption: A review,” *J. Nat. Gas Sci. Eng.*, vol. 79, no. May, p. 103373, 2020, doi: 10.1016/j.jngse.2020.103373.
- [7] X. Liu, M. Jing, S. Chen, and L. Du, “Experimental study of gas pressure drop in rotating packed bed with rotational-stationary packing,” *Can. J. Chem. Eng.*, vol. 96, no. 2, pp. 590–596, 2018, doi: 10.1002/cjce.22936.
- [8] S. P. Singh et al., “Removal of Volatile Organic Compounds from Groundwater Using a Rotary Air Stripper,” *Ind. Eng. Chem. Res.*, vol. 31, no. 2, pp. 574–580, 1992, doi: 10.1021/ie00002a019.
- [9] W. Z. Jiao, Y. Z. Liu, and G. S. Qi, “Gas pressure drop and mass transfer characteristics in a cross-flow rotating packed bed with porous plate packing,” *Ind. Eng. Chem. Res.*, vol. 49, no. 8, pp. 3732–3740, Apr. 2010, doi: 10.1021/ie9009777.
- [10] J. R. Burns, J. N. Jamil, and C. Ramshaw, “Process intensification: Operating characteristics of rotating packed beds - determination of liquid hold-up for a high-voidage structured packing,” *Chem. Eng. Sci.*, vol. 55, no. 13, pp. 2401–2415, 2000, doi: 10.1016/S0009-2509(99)00520-5.
- [11] J. R. Burns and C. Ramshaw, “Process intensification: Visual study of liquid maldistribution in rotating packed beds,” *Chem. Eng. Sci.*, vol. 51, no. 8, pp. 1347–1352, 1996, doi: 10.1016/0009-2509(95)00367-3.
- [12] P. Xie, “Hydrodynamics and Mass Transfer of Rotating Packed Beds for CO₂ Capture,” 2019.
- [13] P. Xie et al., “A mesoscale 3D CFD analysis of the liquid flow in a rotating packed bed,” *Chem. Eng. Sci.*, vol. 199, pp. 528–545, 2019, doi: 10.1016/j.ces.2019.01.038.
- [14] M. J. Lockett, “ITS . APPLICATION TO CONVENTIONAL PACKED,” pp. 379–384.
- [15] S. Y. Pan, P. Wang, Q. Chen, W. Jiang, Y. H. Chu, and P. C. Chiang, “Development of high-gravity technology for removing particulate and gaseous pollutant emissions: Principles and applications,” *J. Clean. Prod.*, vol. 149, pp. 540–556, 2017, doi: 10.1016/j.jclepro.2017.02.108.
- [16] L. L. Zhang, J. X. Wang, Y. Xiang, X. F. Zeng, and J. F. Chen, “Absorption of carbon dioxide with ionic liquid in a rotating packed bed contactor: Mass transfer study,” *Ind. Eng. Chem. Res.*, vol. 50, no. 11, pp. 6957–6964, 2011, doi: 10.1021/ie1025979.
- [17] H. H. Cheng and C. S. Tan, “Removal of CO₂ from indoor air by alkanolamine in a rotating packed bed,” *Sep. Purif. Technol.*, vol. 82, no. 1, pp. 156–166, 2011, doi: 10.1016/j.seppur.2011.09.004.
- [18] K. Neumann et al., “A guide on the industrial application of rotating packed beds,” *Chem. Eng. Res. Des.*, vol. 134, pp. 443–462, 2018, doi: 10.1016/j.cherd.2018.04.024.
- [19] Z.-G. Yuan, Y.-X. Wang, Y.-Z. Liu, D. Wang, W.-Z. Jiao, and P.-F. Liang, “Research and development of advanced structured packing in a rotating packed bed,” *Chinese J. Chem. Eng.*, 2022, doi: 10.1016/j.cjche.2021.12.023.
- [20] Y. S. Chen, F. Y. Lin, C. C. Lin, C. Y. Der Tai, and H. S. Liu, “Packing characteristics for mass transfer in a rotating packed bed,” *Ind. Eng. Chem. Res.*, vol. 45, no. 20, pp. 6846–6853, 2006, doi: 10.1021/ie060399l