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COMPARING THE HYDRODYNAMIC CHARACTERISTICS OF A STANDARD AND A 3D-PRINTED PACKING IN A ROTATING PACKED BED

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ABSTRACT

As rotating packed beds (RPBs) gain prominence in intensified mass transfer operations, efficient packing design is critical for optimizing performance. Traditional packing structures often face limitations in terms of pressure drop, wetting efficiency, and fluid distribution. 3D-printed packings offer new possibilities by allowing complex geometries tailored to specific fluid dynamics. This study presents a detailed comparison of the performance of standard wire mesh packings and an anisotropic 3D-printed packing, focusing on pressure drop variations under varying operational conditions. Compared to the standard packing, the hydrodynamic performance of the 3D printed packing showed a lower pressure drop of about 0.7kPa at the combination of maximum operating conditions investigated of 300Nm^3/h, 1000 rpm, and 0.72m^3/h in the gas flow, rotation speed, and liquid glow rate respectively. The wet pressure drop per unit packing length of the 3D packing compared favourably with the standard wire mesh packing. The 3D-printed RPB packings proved to be a promising way that has the potential to enhance the separation performance of RPBs.

Keywords: Rotating packed bed, Hydrodynamics, 3D-printed packing, Standard packing, Pressure drop

INTRODUCTION

Rotating packed beds (RPBs) were first introduced in the 1980s as a means of enhancing mass transfer processes by applying centrifugal forces instead of the gravitational forces utilized by traditional packed separation columns (Zawadzki et al., 2023). The rotation creates a higher relative velocity between gas and liquid phases, promoting rapid phase contact and reducing the size of the equipment compared to traditional packed columns (Pahlavan, et al. 2024; Yan et al. 2022). To tackle production costs and environmental concerns, researchers have explored the of use cost-effective and eco-friendly materials (Abubakar & Abubakar, 2020). Similarly, as conventional mass transfer equipment is being overstretched to satisfy current demands and costs in separation technologies, high gravity equipment such as RPBs is constantly being developed and improved.(Wojtasik-Malinowska et al., 2022)

The design of the RPB packings plays a crucial role in determining hydrodynamic performance, as it influences the interaction between the liquid and gas phases. RPBs are widely used in chemical engineering applications, particularly for enhancing mass transfer processes such as distillation, absorption, and reaction intensification (Zahir et al. 2023). The centrifugal force generated by the rotating bed allows for higher mass transfer rates, making RPBs a favoured technology for process intensification (Amiza et al. 2024). The packing material within the RPB is crucial for determining the overall efficiency, as it impacts both fluid dynamics and mass transfer characteristics. Traditionally, RPBs have employed standard packing materials such as wire mesh metal foams, or structured packing made from metals or plastics (Zawadzki & Blatkiewicz, 2023). While these standard packings provide reliable performance, they exhibit limitations regarding pressure drop and liquid distribution. Recent advancements in additive manufacturing (3D printing) offer the potential to create custom-designed packings with optimized geometries for specific hydrodynamic and mass transfer properties. Even though the packing structure of RPBs is complex, thus, usually simplified using computational fluid dynamics (CFD) models (Guo et al., 2024; Lucas et al. 2021; Zahir et al. 2023), additive manufacturing offers a suitable means of circumventing the challenges posed by the complexity of the structures. Pressure drops as a primary hydrodynamic characteristic serve as a key indicator of fluid distribution and energy consumption in RPBs, which is closely linked to the overall efficiency of mass transfer processes in packed separation columns. Standard packing geometries are typically designed to maximize surface area for gas-liquid contact while maintaining low-pressure drop, but these structures often struggle with non-uniform fluid distribution under varying operating conditions. Additive manufacturing (3D printing) has emerged as a novel technique to create complex packing structures with precise control over geometry. 3D-printed packing allows for the design of intricate, optimized geometries that are impossible to achieve with conventional manufacturing methods. Such designs can enhance fluid distribution, increase surface area for mass transfer, and reduce pressure drop. Recent studies have demonstrated the potential of 3D-printed packing in static-packed beds, but their application in RPBs has been less explored. (Wojtasik-Malinowska et al., 2022) had stated that an understanding of the hydrodynamics of separation equipment is important for obtaining fundamental knowledge, creating awareness, and standardizing their designs and controls. (Sun et al., 2024) reported that advanced fabrication methods such as 3D printing can be used to produce separation column packings with high surface areas that have the potential to meet the requirements of various industrial processes.

The main part of an RPB unit is its internals or packing (Zawadzki et al., 2023). Available literature reveals that various designs and modifications of RPB packing have been developed to improve its hydrodynamic and mass transfer characteristics (Hacking et al. 2020; Konrad et al., 2021; Miramontes et al., 2020; Qammar et al., 2019). (Zawadzki et al., 2023) observed that structural packings can be used to overcome the limitations posed by porous packings such as elevated pressure drops, narrow operational windows, and dry zones caused by the radial direction of the centrifugal acceleration. However, only a few designs have considered changes in the cross-sectional area of the RPB along the packing length which is needed to account for the variable flow area within the RPB, aiming to equalize the flow area as it nears the centre of the rotor (Konrad et al. 2021). This paper compares the hydrodynamic performance of standard and 3D-printed packing structures in RPBs, by evaluating a key hydrodynamic parameter-the pressure. The hydrodynamic performance of a novel anisotropic RPB packing, consisting of three concentric, equiareal anisotropic layers, was compared with that of a conventional RPB wire mesh packing. The packing was designed using CAD software and fabricated from polymer through SLA 3D printing technology. By leveraging the dominant effect of gas flow rate, pressure drop measurements were used for the comparisons.

MATERIALS AND METHODS

The detailed experimental setup and description of the apparatus were presented in (Garba et al. 2023). The main apparatus consisted of a pilot-scale RPB made by Proceller, Poland. The RPB is equipped with a variable-speed motor to control the rotational speed, an inner and outer radius of 0.25 m and 0.80 m, respectively, and an axial bed height of 0.4m Two different types of packing were used in this study: standard wire-mesh packing and a 3D-printed packings with customized geometries designed using computational fluid dynamics (CFD) simulations. The standard wire mesh (SWM) packing was made of interconnected filaments and was supplied by Proceller, Poland. The packing porosity and geometrical area were 86 % and 2400m^2/m^3 respectively. The 3D-printed anisotropic packing was fabricated using a photopolymer resin (Therma DM 500) using a high-resolution 3D printer (XFAB 3500 PD). The packing was anisotropic, consisting of three interconnected rings of porosities 95, 72, and 61 % and packing areas of 200, 932, and 1265 m^2/m^3 respectively as measured from the innermost ring. An air-water counter-current flow system was used. The Experiments were conducted under a range of operating conditions, including varying liquid flow rates, L of 0.39 to 0.72 m^3/h), gas flow rates, G of 100 to 300 Nm^3/h), and rotational speeds of 500 to 2000 rpm. In each experimental run, one of the operating conditions was held constant while the other two were varied.

RESULTS AND DISCUSSION

Pressure drop data were used to compare the hydrodynamic performance of standard and 3D-printed packing. The results showed that 3D-printed packing consistently exhibited a lower pressure drop compared to standard packing across the entire range of operating conditions

3D-printed packings have the potential to revolutionize industrial applications by offering unprecedented design flexibility and customization. However, challenges like scalability, material durability, and quality control must be overcome through technological advancements and process optimization. As these hurdles are addressed, the technology is likely to see broader adoption in industries requiring high-performance packing solutions. In this study, the customized geometries of the 3D-printed packing allowed for smoother gas and liquid flow paths, reducing turbulence and energy dissipation. At higher rotational speeds, the reduction in pressure drops for 3D-printed packing became even more pronounced, highlighting its advantage in high-intensity operations.

Effect of rotation speed

To study the effect of rotation speed on the wet pressure drop of the 3D packing, the RPB was operated at a rotation speed range from 100-1000 rpm, constant gas flow rates in the range of 100 to 250 Nm^3/h and with the liquid flow rates maintained at two flow rates of 0.39 and 0.72 m^3/h). Figure 1 shows that the wet pressure drop increases steadily with an increase in the rotation speed from the lowest rotation speed of 100 rpm up to the highest rotation speed investigated of 1000 rpm. At low rotation speeds of 100 to about 500 rpm, for a given constant gas and liquid flow rates, the wet pressure drop increase is 20-33% for each 100 rpm increase in the rotation speed. However, at higher rotation speeds greater than 600 rpm, the increase in rotation speed at a constant gas and liquid flow rate generates a more rapid increase in the wet pressure drop ranging from 35-50% for each 100 rpm increase in rotation speed.

The characteristic curve of wet pressure drops for RPBs operated at low rotation speeds was not obtained up to gas flow rates of 250 Nm^3/h for both liquid flow rates of 0.39m^3/h and 0.72m^3/h. However, at a gas flow rate of 300Nm^3/h, the characteristic curve was observed at low rotation speeds between 100 rpm to 300 rpm for both the investigated liquid flow rates. The finding indicates that the increasing porosity toward the centre of the rotor has the potential to raise the upper operating limit of the RPB. The high porosity of about 95% for a radial length of 0.63m provided by the first ring of the packing gives ample room for the spread of the liquid from the eye of the rotor. When liquid accumulation in the centre of the rotor where the centrifugal force is lowest is minimized, the tendency for flooding is reduced. Thus, the upper operating limit within which the RPB can be operated without flooding increased.

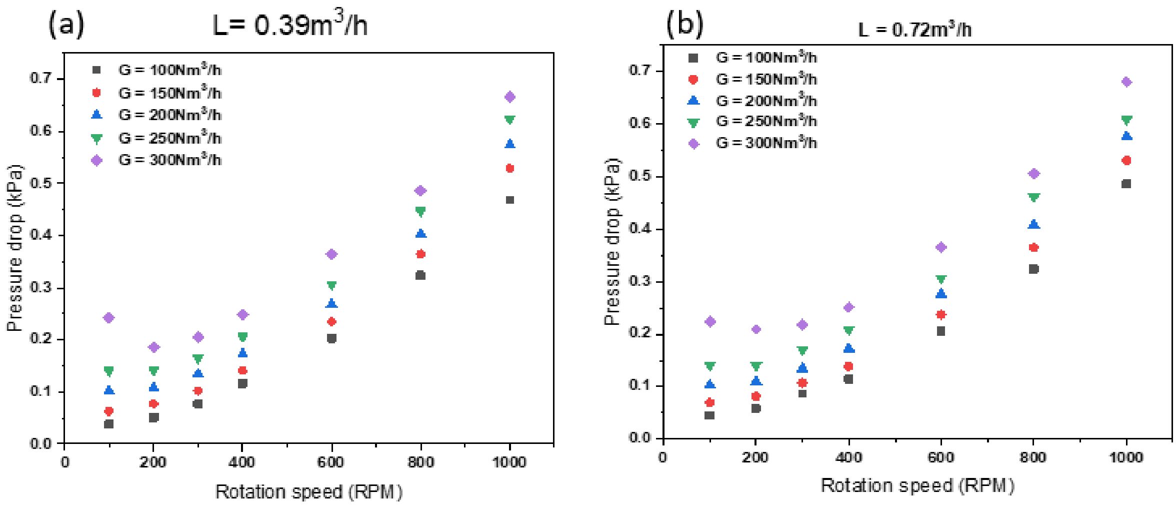

Figure 1: Effect of rotation speed on the pressure drop of the 3D printed packing for constant gas flow rate with a constant liquid supply of (a) L = 0.39 m^3/h (b) L = 0.72m^3/h

Both packing demonstrated improved pressure drop with increasing rotational speed, due to the enhanced centrifugal force promoting better phase distribution. However, the benefits of 3D-printed packing were more apparent at higher speeds, where its optimized geometry allowed for more efficient use of the available centrifugal force. At lower speeds, the difference in performance between the two types of packing was less pronounced. The hydrodynamic performance of a 3D-printed structured packing and that of a standard stainless wire mesh packing in a rotating packed bed (RPB) were investigated and compared.

The pressure planes shown in the contour plots in Figure 2 further highlight the consistency of the increase in the pressure drop as influenced by the three operating conditions investigated. The Figure shows that the contour lines are almost equally spaced and well-spaced for all the range of operating conditions, showing that the pressure drop changes gradually with changes in the gas flow rate or rotation speed. The contour plots contain mainly no curves but almost straight lines, which may indicate the possibility of relating the operating parameters using linear models.

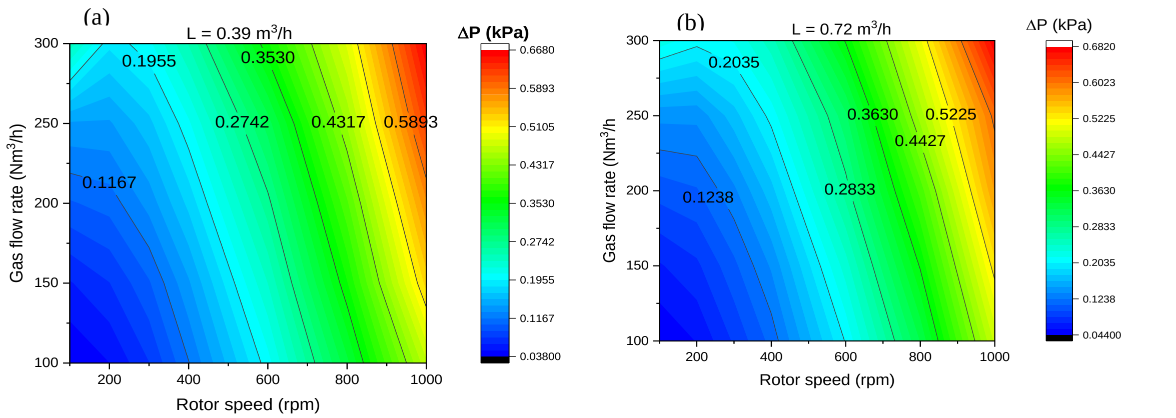

Figure 2: Pressure planes at varying rotor speeds and gas flow rates for the 3D packing at (a) L= 0.39m^3/h, (b) L= 0.72m^3/h

To investigate the influence of liquid and gas flow rates with change in rotation speed on the wet pressure drop, the data from Figure 2 was further plotted for the lowest and highest gas flow rates investigated (100Nm^3/h and 300Nm^3/h) at the two liquid flow rates investigated. The information is presented in Figure 3.

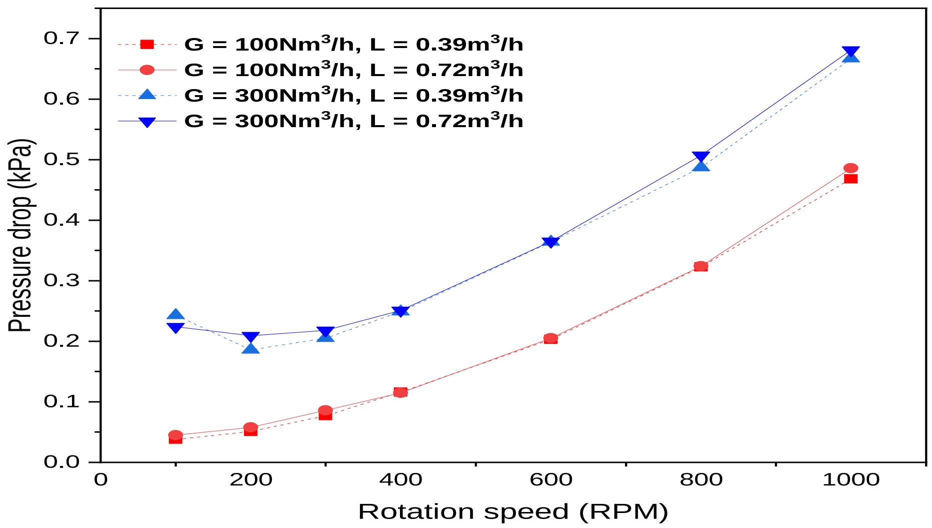

Figure 3: Comparing the impact of gas and liquid flow rates with increasing rotation

As shown in Figure 3, for any given rotation speed within the range investigated, an increase
in the gas flow rate from 100 to 300 Nm^3/h at the same liquid flow rate produced a significant increase of about 115% in the wet pressure drop with increasing rotation speed.
On the contrary, for the same gas flow rate, an increase in the liquid flow rate from 0.39 to 0.72 m^3/h at low rotation speeds ($\leq 600\ rpm$) within the range investigated produced an average increase in the wet pressure drop of just about 12%. At moderate rotation speeds (400 to 800 rpm for L= 0.39m^3/h and 400 to 600 rpm for L= 0.72m^3/h), increasing the liquid flow rate when the other operating parameters are kept constant seems to show no noticeable change in the wet pressure drop. The findings further point to the possibility of a promising normal operating range for the anisotropic packing. A noticeable difference in the wet pressure drop was observed at rotation speeds more than 800 rpm, indicating that at very high rotation speeds, the effect of the liquid flow rate may become significant.

Effect of gas flow rate

The effect of the gas flow rate on the wet pressure drop of the 3D packing was studied by operating the RPB at a gas flow rate range from 100-300 Nm^3/h, a constant liquid flow rate of 0.39 m^3/h, and two levels of rotation speeds: 600 rpm and 1000 rpm.

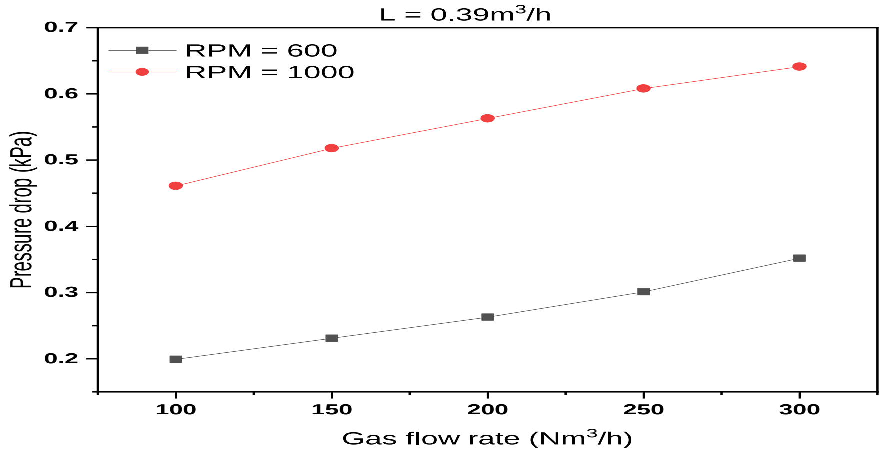

Figure 4: Effect of gas flow rate on the wet pressure drop of the 3D printed packing

The results are shown in Figure 4. The Figure shows that the wet pressure drops increase almost linearly with an increased gas flow rate. The trend in the increase was similar for both rotation speeds investigated. For the range of gas flow rate investigated, a 67% increase in the rotation speed from 600 to 1000 rpm produced an average increase of 82% of the wet pressure drop. The almost linear relationship between the gas flow rate and the wet pressure drop indicates the possibility of a consistent flow of the gas from one ring to the other (intra-lattice link) in the anisotropic arrangement of the three concentric rings in the 3D packing. Perhaps if the wires in the successive rings were not properly aligned, the gas flow might have caused more erratic liquid dispersion in the packing resulting in less consistency of the data points.

Comparing the wet pressure of the 3D packing and that of stainless steel wire mesh packing

The hydrodynamic performance of the 3D printed packing in terms of the wet pressure, as determined by the effect of the three major operating parameters of the RPB, was compared with that of stainless steel wire mesh packing.
For the comparison, the radial lengths of the packings were taken into consideration. The inner diameter for both packings is 160 mm, however, for the stainless-steel wire mesh

packing, the external diameter is 460 mm while for the 3D printed packing, the external diameter is 440.2 m as shown in Figure 5. Therefore, the radial lengths of packing crossed by the fluids for the stainless steel is 150 mm, and for the 3D printed packing, it is 139.91 mm when the small gaps between consecutive rings are considered. The radial lengths, as shown for each packing, as shown in Figure 5, were used to calculate the wet pressure drop per unit radial length for the respective packings, and the results were compared.

(a) (b)

Figure 5: Photo showing the radial length of (a) the stainless-steel packing (b) 3D printed packing

Effect of rotation speed

To compare the effect of rotation speed on the wet pressure of the 3D packing and that of stainless steel wire mesh packing (SWM), the rotation was varied from 100-1000 rpm, two constant gas flow rates of 100 and 300 Nm^3/h and two liquid flow rates of 0.39 and 0.72 m^3/h were considered. The results are shown in Figure 6.

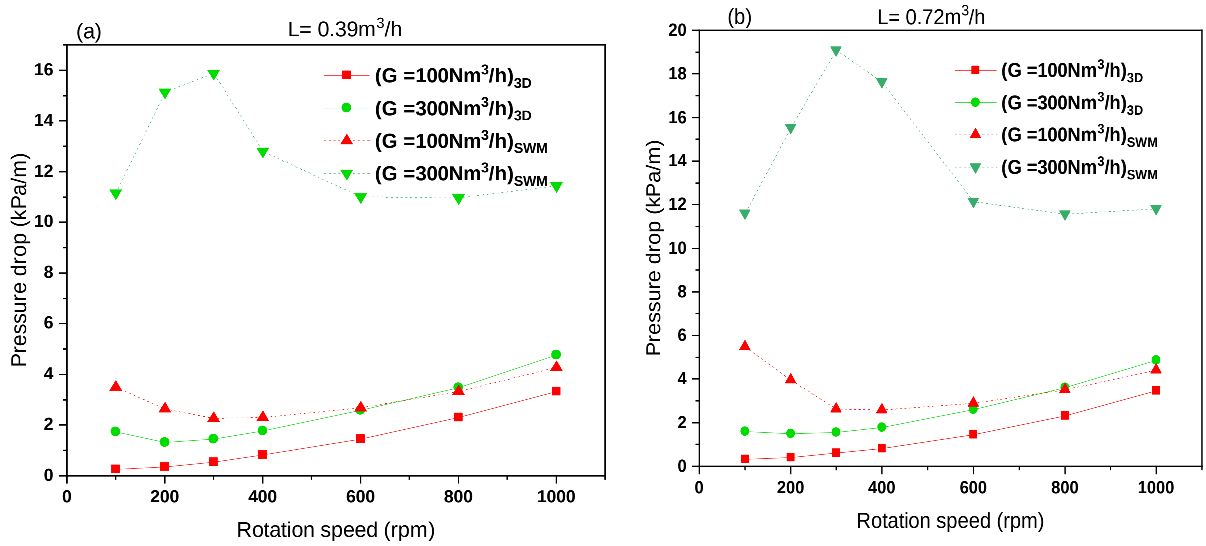

Figure 6: Comparing the effect of rotation speed on the wet pressure of the 3D packing and that of steel stainless steel wire mesh packing at (a) L = 0.39 m3/h (b) L = 0.72 m3/h

Figures 6a and 6b show that at a constant gas flow rate of 100Nm^3/h, for all the range of rotation speeds investigated, the 3D printed packing produced an average 92% lower wet pressure drop than the stainless wire mesh packing, irrespective of the liquid flow rate used. The percentage deviations between the two pressure drops reduce with increased rotation speed. A similar trend was obtained at the maximum gas flow rate investigated, 300Nm^3/h. The characteristic curve of wet pressure drops of RPBs that signifies the approach to flooding conditions was not produced by the 3D printed packing within the experimental conditions investigated, unlike the wire mesh packing which exhibited the behaviour at a gas flow rate of 300Nm^3/h for both liquid flow rates investigated. Additionally, the astronomical increase in pressure drops of over 345% produced by the stainless-steel wire mesh packing when the gas flow rate was increased from 100 to 300Nm^3/h at a constant liquid flow rate was not produced by the 3D printed packing. The phenomenon indicates the possibility of the variable specific surface area of the anisotropic 3D printed packing to regularise the flow of the gas, which is the dominant factor influencing the gas pressure drop of the RPB.

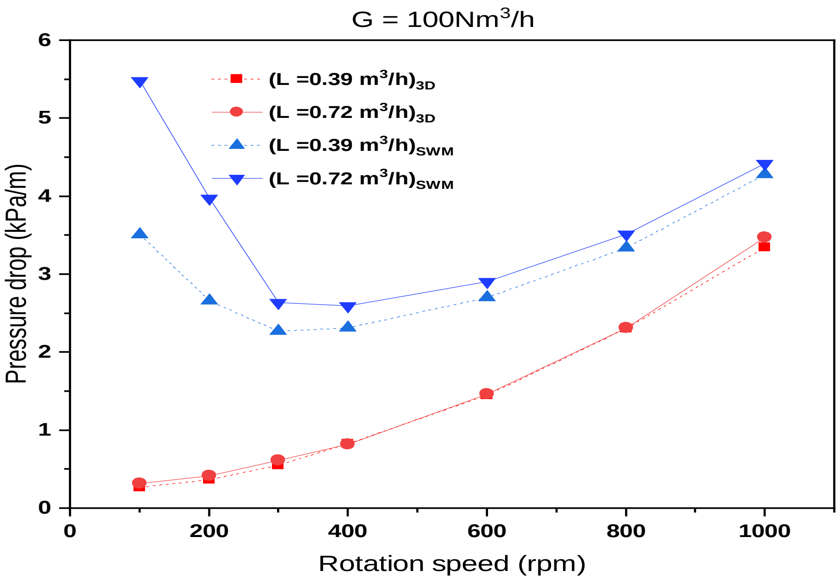

Figure 7: Comparing the effect of rotation speed on the wet pressure of the 3D packing and that of s stainless-steel wire mesh packing at (a) L = 0.39 m^3/h (b) L = 0.72 m^3/h

The influence of the two liquid flow rates **(**0.39 and 0.72 m^3/h **)** when the packing was subjected to the same flow rate as the rotation speed was increased were also compared. The result is shown in Figure 7. The Figure shows further that the 3D-printed packing produced lower pressure drops than the standard packing. Figure 7 also further highlighted the low influence of liquid flow rate on the wet pressure drop of RPBs.

Comparing the effect of gas flow rate

Figure 8 compares the rotation speed's effect on the wet pressure per unit packing length of the 3D packing and that of stainless steel wire mesh (SWM) packing. The Figure shows that especially for high gas flowrates (G $\geq 150Nm^3/h$) the wet pressure drops of the 3D printed anisotropic packings are substantially lower than that for the isotropic stainless-steel wire mesh packing. The complex geometry of the 3D-printed packing provided more sites for liquid film formation, promoting enhanced interaction between the phases. This improvement was evident in the higher mass transfer rates observed during absorption experiments.

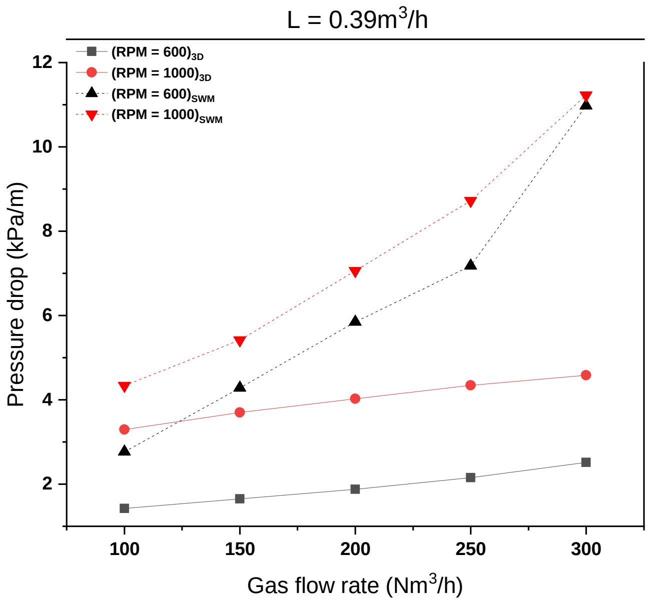

Figure 8: Comparing the effect of rotation speed on wet pressure of 3D packing and that of stainless steel wire mesh packing (SWM)

The gas flow rate and the rotation speed strongly influenced the difference. At a rotation speed of 600 rpm, for the lowest and maximum gas flow rates investigated, pressure drop varies by 94 and 336%, respectively. Similarly, at a rotation speed of 1000 rpm, for the lowest and maximum gas flow rates investigated, pressure drop varies by 32 and 146%, respectively. The result further highlighted the effect of low rotation speeds on wet pressure drops. Thus, based on the effect of gas flow rate at constant liquid flow rates and rotation speeds, the 3D printed packing produced significantly lower wet pressure drop per unit packing length than the stainless-steel mesh packing. Moreover, Figure 8 shows a clear difference in the appearance of the pressure drop curves between the 3D-printed packing and the SWM. The curves are linear for the 3D printed packing with a slope of 6.4 x 10^{-4} kph/Nm^3/hr whereas SWM has a steeper slope of 2.9 x 10^{-2} kph/Nm^3/hr on its linear part and is not linear throughout the range.

The low-pressure drop produced by the 3D packing in this study is crucial for enhancing mass transfer efficiency in RPB-utilised chemical processes like distillation, absorption, and chromatography. By leveraging the geometry and arrangement of the packing, these innovations can significantly improve the performance of separation processes across industries. Practical implications of 3D packings include improved separation efficiency, ease of implementation reduced energy consumption, cost saving, increased capacity, and enhanced process scalability. However, the material used needs to be selected carefully durability of the packing for each process.

Statistical Analysis of the Methods and Results

To further ascertain the validity of the results, descriptive statistical tools were used. In Table 1, the result for a constant liquid flow rate of 0.39 m^3/h at a low, and a high gas flow rate of 100 and 300 Nm^3/h are presented.

Table 1: Statistical analysis of results at L =0.39 m^3/h

	G = 100 Nm^3/h		**L = 0.39 m^3/h G = 300 Nm^3/h**	
	SWM_0.39	**3D_0.39**	**SWM-0.72**	**3D_0.72**
Mean pressure drop	2.871	1.248	12.231	2.407
Standard deviation	0.733	1.101	2.003	1.302
Lower CI (95%)	2.193	0.229	10.379	1.202
Upper CI (95%)	3.549	2.265	14.084	3.611
P(T<=t) one-tail	0.00404	0.00394	0.00449	0.003974
P(T<=t) two-tail	0.00807	0.00788	0.00898	0.00795

At constant gas flow rates of 100 and 300 Nm^3/h, the mean pressure drop for the 3D-printed packing was lower by 78.81 and 134.23% respectively. With all the p-values obtained showing much less than 0.05, at a 95% significance level, it shows a statistically significant difference in the pressure drops generated by the two packings, with the 3D-printed packing producing significantly lower pressure than the SWM packings. Also, while the SWM showed wide variability in the pressure drops as obtained at low gas compared to high gas flow rates, the 3D-printed packing shows a more consistent deviation in the means at both gas flow rates. Hence, the 3D-printed packing produced more consistent fluid flow. Consistent fluid flows are important in process design, simulation, and control. Additionally, The non-overlapping confidence intervals (CI) obtained at both gas flow rates suggest a significant difference between the two packings, hence the need to explore further, the use of 3D-printed packings for various applications in RPBs.

CONCLUSION

This study presented a comparative experimental study of the hydrodynamic performance of a pilot-scale RPB equipped with two different packings. A standard stainless-steel wire mesh packing and a 3D-printed resin packing anisotropic packing, tailored for RPBs were used. Using an air-water counter current system, the influence of the three major operating parameters of the RPB was investigated. The results revealed that the dominant operating factor influencing the hydrodynamic behaviours studied was the gas flow rate, followed by the rotation speed and, to a minor extent, the liquid flow rate. For a combination of maximum operating conditions investigated consisting of 300Nm^3/h, 1000 rpm, and 0.72m^3/h in the gas flow, rotation speed, and liquid glow rate respectively, the hydrodynamic performance of the anisotropic3D printed packing showed lower pressure drops of 0.7kPa. Hence, the 3D-printed RPB packings have the potential to enhance the separation performance of RPBs. The gas flow rate and the rotation speed strongly influenced the difference. Hence, the 3D packing approach is a promising concept for enhancing the hydrodynamic performance of RPBs at operating conditions for which other packings may be limited. The lower pressure drop was particularly noticeable at higher rotational speeds, making 3D-printed packing a promising option for high-intensity mass transfer applications in RPBs. Future work should explore the long-term durability of 3D-printed packing in industrial applications, as well as the potential for further optimization of packing geometries. Additionally, the scalability of 3D-printed packing production will be critical for widespread adoption in commercial systems. Hence, the anisotropic 3D packing approach is a promising concept for enhancing the hydrodynamic performance of the RPB at operating conditions for which other packings may be limited. However, it is recommended that the long-term durability and scalability of 3D-printed packings for RPB use be explored further using higher flow rates and various working fluids.

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