ISSN: 2754-6675

Journal of Chemistry & its Applications

SCIENTIFIC
Research and Community

Research Article

Open Access

Process Intensification in Distillation using HiGee Rotating Packed Bed

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ABSTRACT

For decades, improving the gas-side mass transfer coefficient in rotating packed beds has been a formidable challenge. Distillation, often limited by gas-phase resistance, requires substantial innovation to enhance these coefficients. Rotating packed beds offer a distinct advantage over conventional columns, primarily due to the intense micro-mixing within fluid channels. This micro-mixing significantly boosts mass transfer between phases and facilitates rapid attainment of steady-state conditions, making them a superior choice for processes where gas-side resistance is the bottleneck. The current study emphasis on the mass transfer performance of rotating packed for acetone water system with two different packing materials viz., wire mesh and ceramic beads. Working principle of HiGee, typical flow pattern, modeling equations have been discussed in this paper. The effects of rotational speed, gas flow rates and radial thickness of the packing on mass transfer performance were also investigated. The mass transfer coefficients of the rotating packed bed HiGee were increased with increasing the rotational speed. The Height Equivalent to Theoretical Plates (HETP) of the rotating packed bed used in this study was 5-6 times less than the conventional packed columns. This study contributes to significantly advancing the industrial applications of rotating packed beds.

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Received: August 26, 2024; **Accepted:** August 31, 2024; **Published:** September 11, 2024

Keywords: Process Intensification, HiGee, Distillation, Gas Liquid Mass Transfer, Rotating Packed Beds

Nomenclature

a=Specific surface area, m2/m3
G=Molar flow rate of vapour per unit area, mol/m^2s
G_m=Molar flow rate of the gas, *mol/s*
H_c=Henry's law constant
HTU=Height of Transfer Unit, m
HETP=Height Equivalent to Theoretical Plate, m
Kya=Overall gas side mass transfer coefficient, $kmol/m^2s$
Lm=Molar flow rate of liquid per unit area, *mol/s*
m=Slope of the equilibrium curve
n=Number of moles
NTU=Number of Transfer Units
N*p* =Number of ideal stages
R=Reflux Ratio
r=Radius of RPB, m
r_1 =Inner radius of RPB, m
r_2 =Outer radius of RPB, m
S=Distillation factor
x=Mole fraction of component in liquid
X=Mole fraction in liquid phase
xf = Feed concentration
xD =Distillate concentration
y=Mole fraction of component in vapour
y*=Equilibrium values of corresponding y
Y=Mole fraction in vapor phase

Greek Letters

Ɛ=Porosity of the packing
ρ=Density, *kg/m3*
C_p =Molar specific heat, kJ/mol K

Introduction

Distillation is one of the most energy intensive processes in chemical industries. Substantial amount of energy is utilized in crude oil processing due to high heat demand. On the other hand tallness of conventional distillation columns is also a great hindrance. Exploiting the energy efficient columns and improving the process are the only possible solutions. Process intensification is one such strategy to enhance the process performance and to reduce the size of the columns while maintaining the quality.

The technology of utilizing the centrifugal force to enhance the gas-liquid mass transfer was introduced by Colin Ramshaw [1] A torus shaped Rotating Packed Bed (RPB) generates a centrifugal force hundred times larger than the gravitation force. The high gravity (HIGEE) rotating packed bed facilitates packing with larger surface area and effective contact of gas-liquid results in enhanced mass transfer coefficients. This in turn reduces the size of the columns up to 10 fold.

Different HiGee Systems: Mono Block Packing

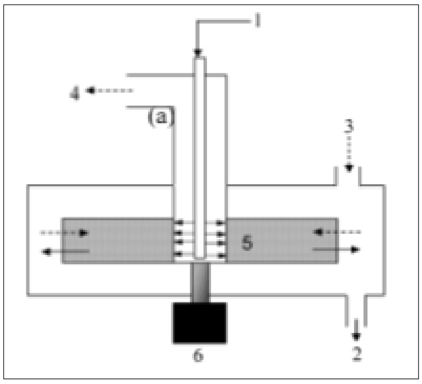

Figure 1: HiGee with Monoblock Packing, 1. Liquid in, 2. Liquid out, 3. Vapor in, 4. Vapor out, 5. Packing, 6. Motor

This is the most commonly used HiGee in which the rotor is attached to the motor shaft in vertical direction (Figure 1). Rotor can have a variety of packing materials like wire mesh, metal foam, plastic beads and discs. The specific surface area of these packing materials is ranged in between 750-5000 m^2/m^3. Liquid enters from the top of the rotor and reaches the liquid distributor installed at the eye of the rotor. Liquid flows as a thin film over the surface of the packing under the influence of rigorous centrifugal field. Whereas the gas enters into the casing and flows in counter direction to the liquid and emerges out from the eye of the rotor. Due to the high centrifugal force, the liquid droplets flow vigorously through the packing which increases the gas-liquid interfacial area and a wide range of flow rates are used due to less possibility of flooding. Therefore, an enhancement in liquid side mass transfer is observed and a significant reduction in the volume is achieved in RPB as compared with conventional packed beds. However the commercial applications of rotating packed bed of this sort were limited. D.P. Rao explained the reasons after carefully examining the gas-liquid flow through the packing. Gas attaches to the packing surface and rotates like a solid body along with the rotor and hence the angular slip velocity between the gas and packing is very less. Due to this reason, there has been no significant enhancement in the gas side mass transfer coefficient [1,2].

HiGee with Split Packing

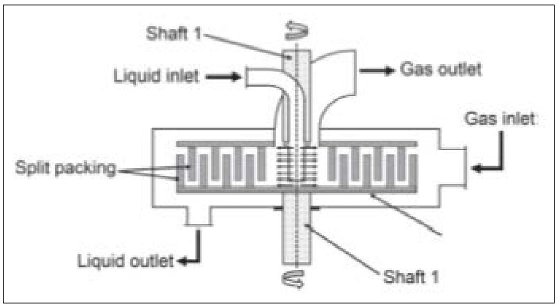

Figure 2: Split packing HiGee

To overcome the limitations of RPB with mono block packing, Chandra et al. proposed split packing suitable for the processes like distillation in which the mass transfer controlling resistance is in gas phase. As shown in the figure 2, the packing (metal foam or wire mesh) is split into annular rings with gaps provided in between them. One set of packing is attached to one plate and the other being attached to the other plate. These two plates rotate in co-current or counter direction with the help of two separate motors. Due to the high interfacial area, turbulence and better liquid distribution within the packing, higher gas side volumetric mass transfer coefficients are achieved than conventional rotating packed beds [3,4]. It is evident that the repeated liquid redistribution through the packing allows better usage of available surface area for mass transfer. However, the middle feed entry is difficult as both the plates are in rotation.

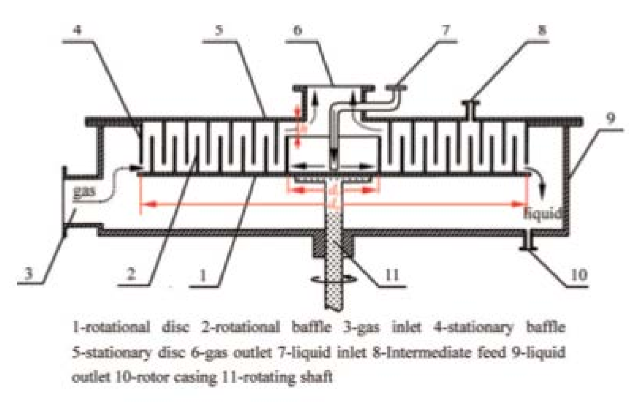

Figure 3: Rotating Zig-Zag Bed HiGee

In spite of having numerous advantages, rotating packed beds have some disadvantages such as incapable continuous distillation operations, multi-rotor configuration and the short residence time. Rotating zig-zag bed (RZB) is a unique gas liquid contactor [5]. which combines a rotating disc and a stationary disc. As shown in the figure 3, the concentric circular sheets are attached on to the rotating and stationary discs which act as rotating and stationary baffles respectively. These baffles were arranged alternatively on either of the discs with a 15 mm clearance between them. Gas enters the casing and flows through the packing due to the pressure difference then leaves from the eye of the rotor whereas the liquid is fed into the casing from the centre of the top stationary disc. The clearance between the concentric baffles helps the gas and liquid to flow in a zig-zag path hence the name. Some of the intriguing aspects of RZB include the elimination of one dynamic seal as the top disc is stationary. And the provision for intermediate feed is easily achieved for the obvious reason. In RZB, the liquid distribution is high due to the centrifugal force and it flows in the form of droplets.

Experimental Setup and Methodology

Figure 4: Rotating Packed Bed

The rotating packed bed for carrying out distillation in this study is shown in figure 4. The experiments were carried out using variety of packing materials like Rasching rings, ceramic beads and wire mesh which were arranged in a rotor placed inside a glass casing. Feed mixture was taken in a round bottom flask which has a provision of heating mantle. The rotor is made of stainless steel perforated mesh with an outer diameter of 15.2cm, inner diameter of 15.0cm and a height of 4cm. Vapor rises from this flask and enters radially from the outer periphery of rotor into the packing and exits from the eye of the rotor. A condenser is placed on top of the rotor to condense the vapors emerging out of the rotor eye. Condensed liquid in the form of reflux comes back to the rotor through the eye and distributes evenly on the packing with the help of a liquid distributor attached to the shaft. This unique way of distributing the liquid on to the packing helps the vapor and liquid to interact in counter current fashion. Even distribution of liquid droplets enables the creation of thinner liquid films, consequently enhances the mass transfer performance.

The liquid droplets from the outeredges of the casing settle at the bottom of the casing and drains through the provision made and reaches the reboiler flask. The rotor inside the casing was driven by a motor attached to the rotor by a shaft. A rotational speed of about 300 to 1200 rpm was varied in this study to evaluate the mass transfer performance. The experiments were carried out using methanol-water, acetone-water and ethanol-water system using three different packing materials viz. Rasching rings, glass beads and stainless steel wire mesh. The packing characteristics were highlighted in table 1. In all the above mentioned cases the total reflux condition was maintained. And the feed composition for acetone-water system with glass bead packing was taken as 15% v/v. The composition of the obtained distillate at the rotor outlet and reflux liquid were measured after achieving the steady state. These liquid samples were analyzed using a Refractometer at room temperature. The compact structure of Rotating packed bed HiGee allows the system to reach the steady state in a short span of about 30 min.

Table 1: Packing Characteristics

Packing	Rasching rings	Ceramic beads	Wire mesh
Material	Plastic	Ceramic	Stainless steel
Specific surface area(m^2/m^3)	200-500	500-800	1200-1800
Void fraction (ε)	0.4-0.5	0.5-0.7	0.95-0.98
Packing factor(1/m)	50-100	150-200	150-200

Modeling Equations

In conventional distillation columns the vapor liquid flow in axial direction and the mass flow rates are assumed to be constant. Whereas in rotating packed beds the flow is in radial direction leading to the varying rates. In conventional packed bed distillation columns the mass transfer takes place only in packing whereas in Higee distillation there is an additional area exists between casing and rotor. However, very few have reported the models explaining the mass transfer in Higee distillation columns. The modeling equations used for Higee distillation are often written over a differential volume with a radial length (dR) and surface area ($2\pi rz$) and the film theory, penetration theory and surface renewal theory are commonly used to describe the mass transfer in Higee contactors [6]. Liu et. al presented a design equation for the overall gas mass transfer coefficient using the material balance over a differential volume and the transfer unit concept [7].

$$\frac{G_m}{z\,K_G a p_t}\,\frac{ln\left[(1-S)\frac{Y_1-H_C X_2}{Y_2-H_C X_2}+S\right]}{S-1} = \pi(r_2^2 - r_1^2) \quad (1)$$

Where G_m being the molar flow rate of the gas, H_c is the Henry's law constant, Y, X are the mole fractions of gas and liquid respectively. S is the distillation factor defined as the $H_c\ G_m/L_m$. As in the case of conventional columns the parameters such as HTU-NTU are used for the design [8]. Considering the fluid flow in radial direction, Area Transfer Unit ($\mathrm{ATU}=\frac{G_m}{z\,K_G a p_t}$) was introduced by singh et al, which is similar to the Height of Transfer Unit (HTU) in conventional distillation columns [9]. Equation 1 was proposed by Lin et. al based on the assumption of the gas-liquid flow rates were constant during the operation and the flow resembles the equimolar countercurrent diffusion and it can be applied only to the systems governed by Henry's law. But in the current work the liquid composition keep on changes and depends on the operating conditions of the system, hence this law can't be applied. For this reason an empirical equation was derived.

$$K_{ya} = G\,\frac{1}{\pi h(r_2^2-r_1^2)}\,\frac{y_2-y_1}{y_2-mx} \quad (2)$$

Where K_{ya} is the overall gas side mass transfer coefficient, G is the vapor flow rate. r_2, r_1 are the outer and inner radii of the packing respectively.

Pressure Drop

Pressure drop in rotating packed beds are two types dry pressure drop and wet pressure drop. The former is responsible for the interaction of gas with packing material in the absence of liquid flow. It is characterized by the drag force of gas on walls of the packed bed and the frictional force within the packing. While the wet pressure drop on the other hand is all about the gas liquid interaction within the packing. The effect of rotational speed is minimal when compared with wet pressure drop. However the total pressure drop varies with the geometry of the rotor, gas liquid flow rates and rotational speed. Moreover the overall pressure drop is attributed to the loss of flow momentum due to the resistance caused by the packing material.

A gauge pressure was installed on the rotor to investigate the change in pressure with change in rotational speed during the experiments. As shown in the figure 5, as the rpm increases the pressure inside the rotor was increased for the wire mesh packing. This might be due to the centrifugal forces within the rotor and the increased drag force.

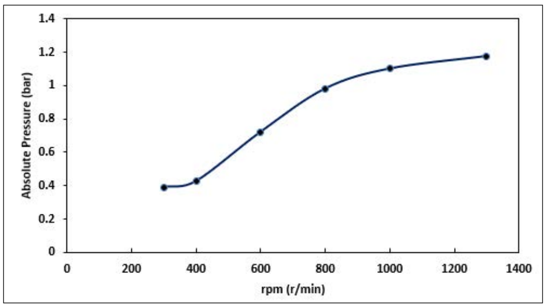

Figure 5: Effect of Rotational Speed on Pressure inside the Rotor

Flooding is another most important aspect in rotating packed beds; it depends on the orientation of the rotor, pressure drop inside the rotor and gas liquid flow rates [10]. As the centrifugal acceleration increases, the flooding capacity can be maximized.

Results and Discussions

A shown in the figure 6, the effect of mass transfer coefficient is plotted against the rpm for the acetone water system. For the initial rotational speeds for the wire mesh packing the rotational effect is very less on the mass transfer till 900 rpm. This is may be due to the thick liquid film and the low dispersion at lower speeds. As the rotational speed increased beyond 900, there is a significant enhancement in the mass transfer coefficient. The trend is observed because the fine liquid drops are formed and increased surface renewal. This in turn helps the liquid and gas to have high interfacial area available for mass transfer. This leads to the better dispersion of liquid onto the rotor and achieves perfect interaction with the gas. Although, greater the rotational speed, higher the energy requirement. Whereas for the ceramic beads with the same feed concentration as wire mesh packing, the rotational speed shows limited improvement in the mass transfer coefficient. Because of the fact that the ceramic beads have the very less void fraction and a thick liquid film formed in the rotor which has higher mass transfer resistance in comparison with the wire mesh packing.

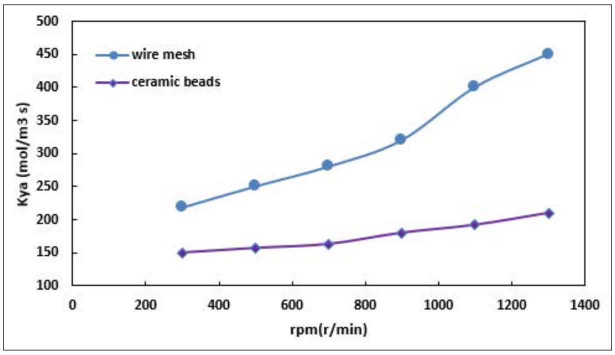

Figure 6: Effect of rpm on Mass Transfer Coefficient mol/m^3 s

Area transfer unit (ATU) on the other hand is one of the key parameters to assess the mass transfer efficiency. ATU quantifies the effective interfacial area per unit volume of the packed bed. ATU is affected by liquid, gas flow rates and the rotational speed. As shown in figure 7, the effect of rotational speed on ATU has been plotted. It is clearly evident that the increase in rpm leads to the decrease in ATU for wire mesh packing. As the mass transfer efficiency increased with increase in rotational speed, the ATU is decreased. For the initial stages, the rpm has a drastic effect on ATU for the wire mesh packing. After the rotational speed of 900, the effect was minimal. For the same initial feed condition, there is no much change observed in ATU for the ceramic beads packing.

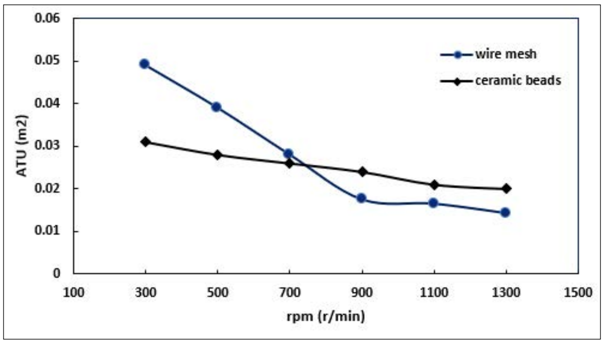

Figure 7: Effect of Rotational Speed on Area transfer Unit

Figure 8 illustrates the effect of rotational speed on Height equivalent to Theoretical Plates (HETP). HETP is also a vital metric in determining the mass transfer efficiency in rotating packed beds. It is observed that the increase in rpm, HETP decreases significantly for wire mesh packing. The rapid decreasing in HETP was observed from 700 rpm to 900 rpm for the wire mesh packing and a slight decrease was thereafter. For ceramic beads, the HETP values decreased with increasing rpm but at a slower pace. This is due to the fact that, the enhancement of mass transfer was very low in this type of packing.

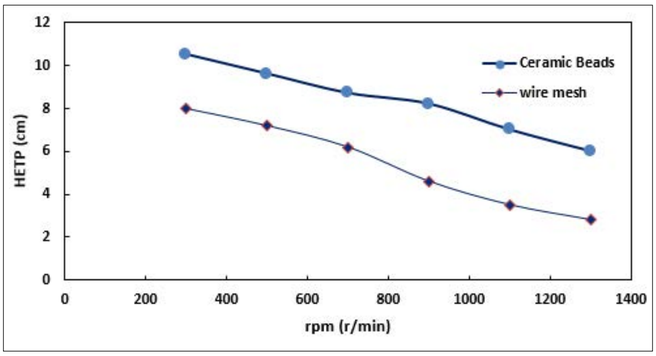

Figure 8: Effect of Rotational Speed on HETP

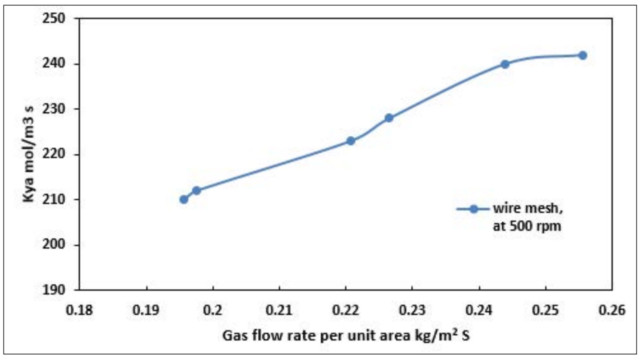

Figure 9: The Variation of Mass Transfer Coefficient with Gas Flow Rate

The effect of gas flow rates on mass transfer performance has shown in figure 9. It can be imperative that the increase in gas flow rate per unit area increases the mass transfer coefficients. The study has been conducted for acetone water system with 15 % v/v feed ratio, with wire mesh packing and at a constant rotational speed of 500. It can be observed from the graph that there was sharp increase in mass transfer coefficient till the gas flow rate of 0.24 kg/m2 s. beyond that it has shown less effect due to the decrease in the gas to liquid ratio.

Conclusions

The effectiveness of packing with two different packing materials for acetone water system has been investigated in this study. For a 15% v/v mixture of acetone-water mixture, the mass transfer performance of the rotating packed bed was observed by changing the parameters like gas flow rates and rotational speed. It is evident that the mass transfer inside the rotor highly depends on the packing characteristics and the centrifugal acceleration. High porous structures with maximum interfacial area give a great facility for gas and liquid to interact. The mass transfer coefficient for acetone-water system with wire mesh packing has shown an increasing trend with rotational speed due to the obvious reason of tiny liquid particles. But for the ceramic beads, there was slight effect on mass transfer coefficient with rotational speed for the same system and conditions of 15% feed mixture and at a gas flow rate of 0.19 kg/m^{2}s.

The packing efficiency was measured in terms of area transfer unit in this study. It is concluded that the centrifugal acceleration has a huge effect on it. As the rotational speed increased, the ATU for the acetone water system at 15% v/v feed mixture with wire mesh packing has been decreased significantly till the rpm of 900. However the same has not been observed for ceramic beads at the same conditions.

The height equivalent to theoretical plates attributes decreased with increasing the rotational speed for both the packing materials at same experimental conditions. It was observed that the wire mesh packing seems to have higher mass transfer capacity in comparison with the other packing. This was due to its high interfacial area and low resistance to the gas-liquid flow offered inside the packing. The HETP for the rotating packed beds was almost 6 times less than that of conventional columns. The gas flow rate per unit area was increased to check the mass transfer efficiency for the wire mesh packing. The mass transfer coefficient was increased with increase in gas flow rate at a constant rpm of 500. It was evident that this study contributes to significantly advancing the industrial applications of rotating packed beds.

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