



Torsional-Couette-Flow HiGee

D.P. Rao^{a,*}, R.C. Mehta^b

^a Process Intensification Consultants, 715, Ushodaya Signature, Deepthi Sri Nagar, Miyapur, Hyderabad, 500049, India

^b Trilok Corporation, Unit no 17, Vaibhav Industrial Estate, Sion Trombay Road, Deonar, Mumbai, 400078, India

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ABSTRACT

We proposed a HiGee fundamentally different from the present-day HiGees. A separated two-phase flow prevails in the proposed HiGee in contrast to an interpenetrated flow in other HiGees. It comprises of a rotating disc placed in the middle of two stationary discs which are enclosed in a casing. The liquid flows as a thin film on both sides of the rotating disc. The gas, fed into the casing of the unit, is in a converging spiral flow, counter current to the liquid flow, through the two narrow channels formed between the rotating disc and stationary discs. We validated the efficacy of the proposed HiGee.

1. Introduction

The quest to downsize the distillation and absorption columns by replacing the gravitational force with a centrifugal force started with the coiling of the wetted wall column around a cone mounted on a turntable way back in 1930 (Podbielniak [1]). It matured into the Rotating Packed Bed (RPB) through various innovations (Pilo and Dahlbeck [2]). The RPB came to be known as HiGee (Ramshaw [3]). Several variants of the RPB have been proposed, and some of the past were rediscovered. These developments have been dealt with elsewhere (Li et al. [4], Rao [5] and Garcia et al. [6]). A brief account of the HiGee evolution and the motivation for the present work are presented below.

We refer as HiGees to those two-phase contactors in which a centrifugal force replaces the gravitational force in bringing contact between the phases. However, we restrict here to the gas-liquid contactors (excludes annular centrifugal extractors, Podbielniak liquid extractors and centrifuges). Given below is a classification of HiGees based on their internals. Fig. 1 shows HiGees with different internals.

1.1. HiGee with monobloc packing

A variety of packings of high specific surface areas, such as a stack of wire-mesh sheets, roll of wire-mesh, metal or plastic foam, beads of various kinds, and 3-D printed rotor have been used. The packing is placed as a monobloc of cylindrical annular bed sandwiched between two side discs that rotate with the bed (see Fig. 1a). It is known that the rotation affords the use of high interfacial packing, enhances a liq-

uid-side coefficient but does not enhance the gas-side mass transfer coefficients with an exception mentioned below (Garcia et al. [6]).

1.2. HiGee with split packing

The liquid, on entry at the inner periphery of RPB as jets or spray of droplets, breaks up into small droplets and filaments. It travels mostly as films in the rest of the bed (Yan et al. [7]). The local mass-transfer coefficients are far higher in the region of about 5 mm deep next to the inner periphery than those over the rest of the bed (Luo et al. [8], Shivhare et al. [9], Guo [10]). Therefore, Chandra et al. [11] have replicated these entrance conditions over the bed by splitting the packing into annular rings of 8 mm thick with a gap of 4–5 mm in between the adjacent rings (see Fig. 1b). Rotating alternate rings in opposite directions, the slip velocity between gas and liquid can be set several times higher than in the HiGee with monobloc packing, which, in turn, enhances the gas-side mass transfer coefficient.

Lin and Jian [14] have presented a HiGee with ‘blade packings’ (see Fig. 1c). Variants of this HiGee have ‘baffles and blades’ and ‘pins’. These offer a low pressure drop; however, they have a low interfacial area.

We refer to the above HiGees with monobloc and split packing as RPBs.

1.3. HiGee with one stationary side disc of rotor

In an RPB, both side discs of the rotor rotate with the packing. Hence, it is difficult to draw the side streams or provide multiple feeds – one of the RPB shortcomings. It is possible to overcome this shortcoming if one of the side discs is kept stationary.

* Corresponding author.

E-mail addresses: dprao@iitk.ac.in (D.P. Rao); rcmehta1@gmail.com (R.C. Mehta)

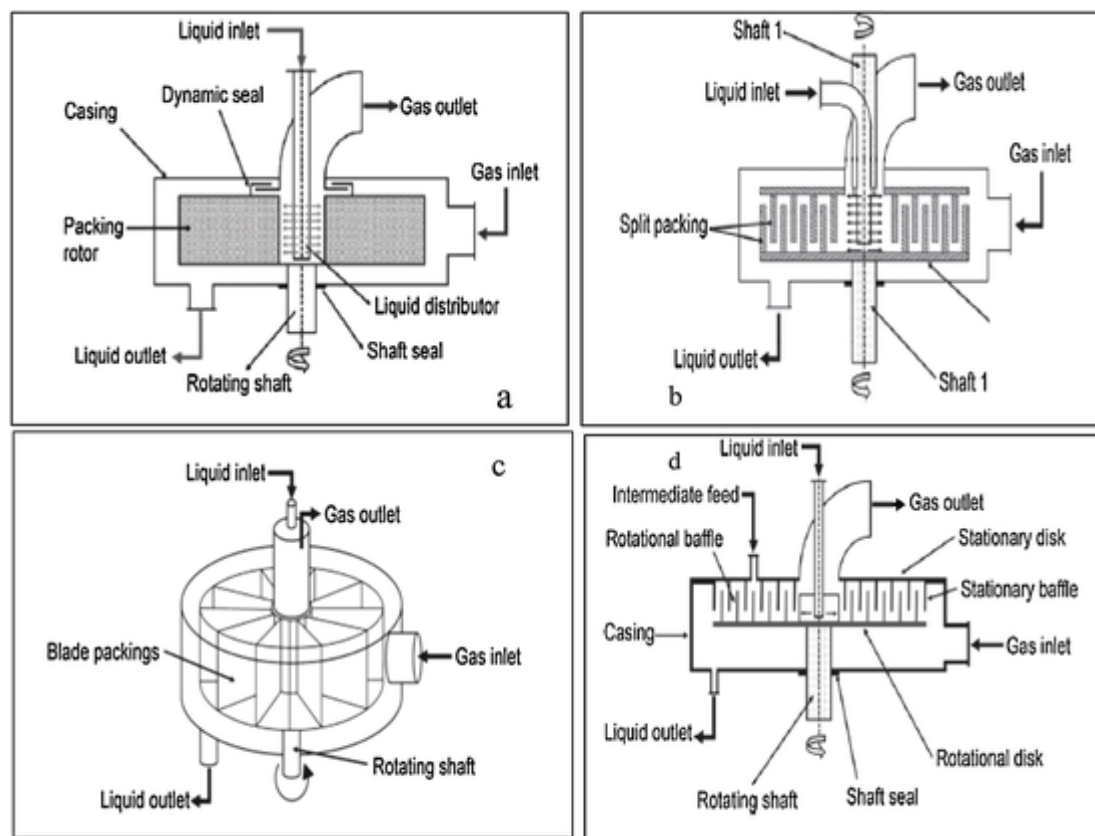


Fig. 1. Different HiGees (compiled from figures presented by Garcia et al. [6]).

Yu et al. [12] proposed a zigzag HiGee (named after the flow paths of phases) using circular rings fixed on top and bottom discs (see Fig. 1d). The upper disc is kept stationary. The stationary disc, besides allowing multiple feeds and side streams, also permits delivery of liquid feed by gravity (Wang et al. [13]). These, in turn, facilitate setting multiple units on a single shaft. The feature of setting one of the side discs as stationary is a significant development in HiGee technology. Several variants of the zigzag HiGee are available. These have no packed bed *per se*. Garcia et al. [6] have presented a comprehensive account of these HiGees. We refer to the RPBs and zigzag HiGees collectively as HiGees.

1.4. Limitations of HiGees

The geometry (doughnut shape) of the bed adversely affects HiGee's performance. Neumann et al. [15] aptly treat the RPB as a truncated, inverted, cylindrical cone in which both the flow area and interfacial area increase along with the height. Variation in flow area leads to a significant decrease in radial velocities of the gas and liquid along the radius, which, in turn, adversely affect the allowable throughputs (due to flooding) and local mass transfer coefficients. Further, there is little control over the residence times or the mass transfer coefficients of individual phases in the HiGees as well as conventional columns. As mentioned earlier, the rotating side discs pose difficulties in introducing multiple feeds and withdrawal of side stream and in employing multiple beds or stages needed in distillation.

It is not difficult to visualise how to set one of the side discs stationary for both monobloc and split packing to overcome the above-mentioned limitations. Luo et al. [16] have set the top discs fixed in the studies on distillation in a two-bed RPB unit. Mehta and Rao [17] disclosed the methods for (a) setting one of the discs stationary for monobloc and split packing, (b) decreasing the porosity and increasing interfacial area of the packing along the radius to overcome the ad-

verse effect of the 'conical bed' mentioned earlier, and (c) demisting of the gas leaving the RPB.

We proposed here a novel torsional-Couette-flow HiGee and validated its proof-of-concept.

2. Torsional-Couette-flow HiGee

2.1. Basic unit

We present below a basic unit of the torsional-Couette-flow HiGee. Fig. 2 shows a sketch of the basic torsional-Couette-flow HiGee. It is essentially an assembly of a rotating disc set in between two stationary discs. This assembly is housed in a casing.

The rotating disc has trapezoidal slots around the shaft for the gas to flow from the bottom channel into the gas outlet. The liquid is fed just after the slots as a film flow onto both sides of the rotating disc. It flows radially outward due to centrifugal force as a thin film over both sides of the disc. It leaves the rim as a thin sheet of droplets. These droplets form a film on the casing wall, which flows down to the bottom of the casing. The channel height may be chosen between 2–20 mm depending upon the system characteristics.

The gas, fed into the casing, flows through the annular channels, formed between stationary disc and the liquid film over the rotating disc, to the gas outlet located at the centre. Note the openings in the rotating disc next to the shaft. The gas from the bottom channel goes through these openings into the gas outlet. The gas acquires tangential velocity in the annular channels due to the torsional stresses induced due to the rotating and stationary discs. This flow is known as torsional-Couette flow and hence the name torsional-Couette-flow HiGee. We refer to it as Couette-flow HiGee for brevity. The sum of the radial velocity (due to through flow) and tangential velocity (due to the tor-

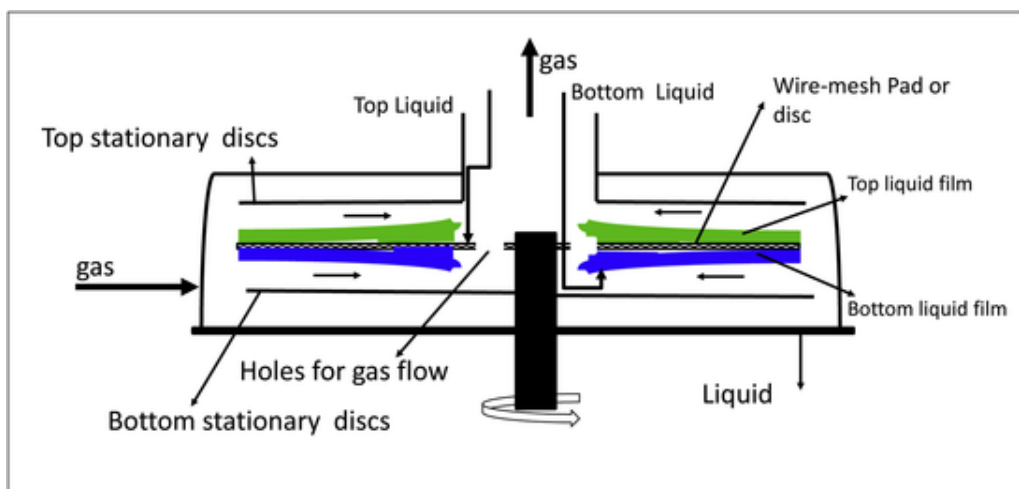


Fig. 2. Basic torsional-Couette-flow HiGeeTop.

sional stress) leads to a converging spiral flow inside the annular channels.

A grooved or perforated disc could be used in place of the plain (rotating) disc to enhance the liquid-side mass-transfer coefficient. Further, a metal-foam disc, wire-mesh pad or 3-D printed metal or plastic foam disc of about 2–5 cm thick could be used in place of the plain disc to enhance the interfacial area. Hereafter, we refer to these also as discs.

The distinguishing features of the basic unit, which sets apart from other HiGees, are the nature of the two-phase flow and two stationary side discs in contrast to one with the zigzag HiGee and none with the RPB.

A separated flow of the phases prevails in the proposed HiGee, whereas an interpenetrated flow prevails in all present-day HiGees except for the one with spiral microchannel [18]. A minor adjustment of the height of channel and bell-shaped stationary discs near the gas outlet eliminates the flooding over a wide range of throughputs. The pressure drop can be set as low as required since the separated flow prevails in the unit. The contact of the phases for separation or reaction takes place in the annular channels and to a minor extent in the casing.

2.2. Variants of the basic unit

In the Couette-flow HiGee, there are two stationary side discs. These stationary discs afford flexibility to accommodate multiple feeds, withdrawal of side streams and to provide turbulent promoters. The latter is a unique feature of the torsional-Couette flow HiGee. Its modifications — to suit to the characteristics of mixture to be processed like gas-side or liquid-side controlled mass transfer, reaction kinetics, and the ratio of gas and liquid flow rates— lead to several variants. Application of these to process large volumes as in CO₂ capture, dehydration of natural gas and for replacing dividing-wall column are presented elsewhere (Mehta and Rao [19]).

Spinning-disc technology exploits film flow of liquid to intensify the rates of mass transfer, reaction and mixing. The proposed HiGee exploits further the geometry of narrow annular channels formed about the spinning disc by the stationary discs or domes to intensifies the rate of gas-side mass transfer and to control of the residence time of gas. The proposed HiGee is akin to an RPB, a spinning disc ‘reactor’ (Reay et al. [20]) or a ‘rotor-stator reactor’ (Visscher et al. [21]).

3. Efficacy of proposed HiGee

The assessment of the efficacy of Couette-flow HiGees for different application is in order. The experimental data of the liquid-side mass-transfer coefficient are available for the spinning disc. Depending

on the end use of water, the oxygen content of water needs to be reduced from 7000 ppb (parts per billion by mass) to a range of 50 - 5 ppb. Presented below is the evaluation of the performance of the basic unit (Fig. 2) for deoxygenation of water using nitrogen as the sweep gas.

3.1. Efficacy of basic unit

Koerfer [22] reported that mass-transfer coefficients for deoxygenation of water for plain, grooved and perforated discs of radius of 30 cm spinning in the range of 100 and 600 rpm (revolutions per minute) and water flow rate of 0.3 - 0.9 L/s (see Figure 5.9, page 141, Reay et al. [20]). The mass-transfer coefficient with a perforated disc is about 5–10 times higher than the coefficients with plain and grooved discs. Therefore, we selected a perforated disc for the basic unit for the evaluation. The perforations are of 1.5 mm diameter with an open area of 30 %, like the one used by Koerfer [22]. The average mass-transfer coefficient (over the radius) is 0.007 m/s.

We sized the basic unit using the above data considering the water is flowing both sides of the disc. We considered the water is non-volatile. The differential mass balance of the film on one of the discs is

$$-Ldx = k_l(2\pi r dr) \rho (x - x^*) \quad (1)$$

where

L = liquid flow rate kg/s

x = mass fraction of oxygen in water

x^* = mass fraction of oxygen in water in equilibrium with gas phase

k_l = mass-transfer coefficient on liquid side m/s

r = radius m

ρ = density of water kg/m³

Assuming the gas phase is pure nitrogen, we have set x^* to be zero. Taking the k_l is constant over the radius, integration of Eq. 1 yields

$$r_o^2 - r_i^2 = \frac{L}{\pi \rho k_l} \ln \left\{ \frac{x_i}{x_o} \right\} \quad (2)$$

where subscripts i and o stands for inner radius and outer radius of the disc respectively. The inner radius is set as 20 cm. We found from Eq. 2 the outer radius to be 0.54 m for 2 kg/s (173 t /day) feed.

Trilok corporation has built a HiGee with a rotor with a split packing of foam metal of specific interfacial area 1700 m²/m³. A run for deoxygenation of water was made (more on this later). Table 1 compares the sizes and performance of the HiGees. The above basic unit with a perforated disk is approximately equivalent to a rotor of an RPB with packing width of 18 cm. The proposed HiGee would be far easier to fabricate and lighter than the split-packing HiGee. Admittedly such

Table 1
Comparison of performance of Couette-flow and split-packing HiGee.

	Couette-flow HiGee	Split packing HiGee
Rotor	Perforated disc	Metal-foam packing
Water flow rate, kg/s	2 (172.8 ton/day)	0.55
O ₂ in feed water, PPM	6.74	6.74
O ₂ in water at outlet, PPB	20	14.7
Rotations, RPM	600	600
Inner radius of rotor, m	0.1	0.06
Outer radius of rotor, m	0.54	0.29
Axial height, m	--	0.05

a comparison is not rigorous; however, it gives a qualitative measure. A rigorous comparison should also include pressure drop, the power needed, compactness and ease of fabrication.



Plate 1. Rotating disc attached to shaft.



Plate 2. Torsional-Couette-flow HiGee.

The above calculations show that a HiGee with a few multiple discs may suffice for many large-scale applications. Such a unit is compact and easy to fabricate compared to a HiGee with split packing.

The radius of the plain disc (with no perforations) was calculated by integrating Eq. 1 using Euler's method with Δr of 0.1 m and k_f , estimated for laminar film flow. It was found to be unwieldy 6.3 m.

The performance of the proposed HiGee for a case where the gas-side resistance is controlling the mass transfer is of interest. Unfortunately, the efficacy could not be evaluated as the gas-side mass-transfer coefficients for these HiGee configurations are not available.

3.2. Experimental validation

Experimental runs of exploratory nature were conducted to validate the proof-of-concept for deoxygenation of water. Plate 1 shows the rotating disc with one layer woven wire mesh topped with an expanded metal mesh. Plate 2 shows the basic unit used (built by Trilok corporation) for the experiments. It had a provision for single rotating disc and two stationary discs. The channel heights could be set between 2–8 mm.

The radius of the perforated disc was of 0.19 m. The disc had holes (on triangular pitch) of 2 mm in diameter and open area 30 %. The radius of the casing was 0.25 m in radius and height of 0.01 m. The channel height was set at 4 mm. A variable speed drive was used to rotate the disc. The runs were carried out with perforated disc as well as with the disc covered one or two layers of woven wire mesh and expanded metal, which contributed an additional interfacial area for mass transfer and promoted turbulence in the gas flow. Water at room temperature (24–40 °C) and pure nitrogen as the sweep gas were used. The oxygen content of the inlet water was monitored using an oxygen meter of range 0–20 PPM (HACH USA/ SC200 controller with LDO sensor) and of the outlet water using a meter of range 0–2000 PPB (HACH USA/ Model- K1100 sensor with 410 controllers) and the pressure across the HiGee measured using Rosemount differential pressure transmitter (Model No.3051CD0AIAM5BADFH2L4D4Q4).

3.2.1. Liquid distributor

The liquid should be fed as a uniform (in angular direction) film on either side of the rotating disc before it enters the gap between the rotating disc and the stationary disc. If the liquid spills over as string

of drops or threads into the gap, there would be churning of the liquid in the gap accompanied an increase in the liquid holdup. These would, in turn, lead to a sharp rise in power consumption by the motor—a good indicator of improper feeding of liquid.

We have employed a liquid distributor along with a rotameter to introduce water on the top side of the disc. A similar distributor with another rotameter was used for the bottom side. The latter has a provision for the gas to flow through the rotating disc to the gas outlet. The water could be fed either on the top or bottom or both sides of the disc.

We have examined the flow visually using water mixed with potassium permanganate. The casing and the stationary discs were removed to gain access to the rotating disc. When the solution was fed only on the bottom, the top side was found to be wet; but no film flow observed. The perforations were filled with the solution. Similar was the case with feed on the top side. Recall the diameter of perforations

was 2 mm. The nature of flow would be different for larger perforations. We have carried out also deoxygenation of water with the three modes of feed at top, bottom and both sides.

Table 2 presents the data. The performances with the three modes are nearly the same. The performance in terms of mass-transfer coefficients was slightly lower with feed at the bottom side compared with feed on the top side. The same is the case with power consumption. This difference could be attributed to the variation in the liquid distributors. In rest of the experiments, the water was fed equally onto the top and bottom side of the disc.

3.2.2. Effect of rpm

Table 3 presents the performance of deoxygenation of water variation with rpm. In addition to the oxygen content in the inlet and outlet water, the power consumed, also listed are the calculated mass-trans-

Table 2

Performance of Couette-flow HiGee with feed on bottom or top or both sides.

$r_o = 19 \text{ cm}$, $r_i = 5 \text{ cm}$											
Run no.	Disc type	rpm	Water flow rate, lpm			N ₂ Flow rate, lpm	ΔP mBar	Inlet O ₂ , ppb	Outlet O ₂ , ppb	Power, W	Mass Trans. Coeff. m/s
			Bottom	top	Total						
1	Perforated	1400	1	0	1	40	3.53	4230	5	90	0.0005
2		1400	5	0	5	40	4.01	4480	43	132	0.0019
3		1400	10	0	10	40	4.2	4740	371	194	0.0021
4		1400	15	0	15	40	4.13	4730	467	200	0.0028
5		1400	0	1	1	40	3.93	4580	4	108	0.0006
6		1400	0	5	5	40	3.89	4620	25	153	0.0021
7		1400	0	10	10	40	4.03	5040	100	205	0.0032
8		1400	0	15	15	40	4.46	5100	125	226	0.0045
9		1400	3	3	6	40	1.11	3840	125	144	0.0024
10		1400	5	5	10	40	4.97	4740	97	190	0.0032

Table 3

Effect of rpm on performance of Couette-flow HiGee.

Run No.	Disc type	rpm	Water flow rate lpm	N ₂ Flow lpm	ΔP mbar	Inlet O ₂ , ppb	Outlet O ₂ , ppb	Power, W	Mass Trans. Coeff. m/s	Radius for 20 ppb, cm	Radius for 5 ppb, cm
$r_o = 19 \text{ cm}$, $r_i = 5 \text{ cm}$											
1	Perforated	800	2	40	0.05	3310	26.0	43	0.00142	0.195	0.220
2		1000	2	40	0.05	3440	15.6	68	0.00159	0.186	0.209
3		1200	2	40	0.40	3540	9.3	90	0.00175	0.177	0.200
4		1400	2	40	0.80	3690	6.4	120	0.00187	0.172	0.194

Table 4

Effect of type of disc on performance of Couette-flow HiGee ($r_o = 19 \text{ cm}$, $r_i = 5 \text{ cm}$).

Set	Disc type	rpm	Water flow rate LPM	N ₂ Flow LPM	ΔP mbar	Inlet O ₂ , ppb	Outlet O ₂ , ppb	Power, W	Mass Trans. Coeff. m/s	Radius for 20 ppb, cm	Radius for 5 ppb, cm
Effect of type of disc											
1	Perforated	1400	2	40	0.7-0.8	3690	6.3	120	0.00195	0.182	0.192
	Woven 1	1400	2	40	3.55	4902	31.9	154	0.00176	0.194	0.204
	Woven 2	1400	2	40	9.26	2190	20.4	204	0.00170	0.190	0.201
2	Perforated	1400	10	40	4.97	4740	97.2	190	0.00793	0.203	0.215
	Woven 1	1400	10	40	3.38	4960	66.6	292	0.00824	0.200	0.211
	Woven 2	1400	10	40	9.27	2980	5.5	444	0.00970	0.180	0.191

Table 5
Effect of flow rates on performance of Couette-flow HiGee ($r_o = 19$ cm, $r_i = 5$ cm).

Set	Disc type	rpm	Water flow rate lpm	N2 Flow lpm	ΔP mbar	Inlet O2, ppb	Outlet O2,ppb	Power, W	Mass Trans. Coeff. m/s	Radius for 20 ppb,cm	Radius for 5 ppb, cm
Lower flow rate											
1	Perforated	1400	4	40	1.10	3840	12.4	144	0.00372	0.186	0.197
		1400	6	40	1.36	4120	31.8	155	0.00519	0.194	0.204
		1400	8	40	5.00	4600	72.1	179	0.00650	0.201	0.212
2	Woven 1	1400	10	40	4.97	4740	97.1	190	0.00793	0.203	0.215
		1400	4	40	3.38	3430	3.7	190	0.00404	0.178	0.188
		1400	6	40	3.3	3430	6.3	218	0.00582	0.182	0.192
3	Woven 2	1400	8	40	2.94	3430.00	14.3	235	0.00728	0.187	0.198
		1400	4	40	9.32	2210	11.5	248	0.00715	0.186	0.196
		1400	6	40	9.22	2240	8.9	321	0.01097	0.184	0.194
		1400	8	40	8.96	2380	8.2	394	0.01479	0.183	0.194
		1400	10	40	8.87	2600	8.6	442	0.01854	0.184	0.194
Higher flow rates											
4	Perforated	1400	20	60	0.983	5270	268	286	0.01453	0.213	0.225
		1400	30	60	0.24	5220	336	321	0.02127	0.216	0.228
		1400	38	60	1.6	5230	342	350	0.02690	0.216	0.228
5	Woven 1	1400	40	40	5.94	1970	149	683	0.02788	0.209	0.221
		1400	50	60	6.83	1920	150	741	0.03475	0.209	0.222
		1400	60	60	7.67	2300	121	818	0.04344	0.207	0.219
6	Woven 2	1400	30	60	1.85	3200	36.8	360	0.05014	0.195	0.206
		1400	50	60	1.91	2900	60.1	528	0.07924	0.199	0.211
		1400	70.5	60	6.06	2900	59.9	850	0.11176	0.199	0.211
Rotating packed bed, ro = 30 cm, ri = 6 cm, axial width = 5 cm											
7	RPB	1000	33	33	5.57	4640	6.3	1094			
		600	33	33	2.18	4640	14.1	674			

Note that 70 lpm (100 T/day) of water with an oxygen content of 5 ppb would be adequate for a medium-size boiler. This need can be met with the proposed HiGee having one disc with 2-layers of woven-mesh covered with an expanded metal of 0.22 m radius (see set 7, last row).

fer coefficients. Most industrial applications require water with oxygen content in the range of 20 to 5 ppb. Therefore, the disc radii calculated to obtain desorption of oxygen content to 20 ppb and 5 ppb using Eq. 2, assuming k_f was constant.

The oxygen content in outlet water decreased with an increase in rpm. The power consumption, as expected, increased with rpm. With an increase in rpm, the mass-transfer coefficient increased as the residence of water decreased in line with the penetration theory.

3.2.3. Effect of type of disc

Table 4 shows the performance of the proposed HiGee with different types of discs. Set 1 indicates that the perforated disc performed better than the discs layered with woven mesh for a water flow rate of 2 lpm. However, Set 2 shows that the 2-layered disc performed better than the other two for a water flow rate of 10 lpm. Perhaps, the wetted area increased with an increase in flow rate for the 2-layer disc.

3.2.4. Effect of liquid flow rate

Sets 1 and 2 in Table 5 show that the oxygen content of the outlet water increased with flow rate for the perforated and 1-layered discs, whereas Set 3 shows that the oxygen content decreased for the 2-layered disc. Perhaps, the wetted area increased with an increase in flow rate for the 2-layer disc.

Sets 4, 5 and 6 indicate that the 2-layered discs performed better than the perforated and 1-layered disc at high flow rates. The mass-transfer coefficients for the former were a few times higher than the latter two, which may be attributed to a higher irrigated surface area of the woven wire mesh.

The last two columns in Tables 4 and 5 show the radii of discs required to attain the oxygen content of 20 and 5 ppb are not significantly different for three discs. Therefore, the perforated disc is prefer-

able over the others as it is relatively easy to fabricate and maintain compared to the discs with layers of woven mesh.

Consider Set 7. It presents the performance of an RPB with a rotor with wire-mesh packing. The rotor dimensions were 29 cm outer radius, 6 cm inner radius and 5 cm the axial width. Set 4 shows deoxygenation achieved was 5 ppb with a single perforated disc of radius 23 cm. Though the water and nitrogen flow rates are not the same, they show a single disc is roughly equivalent to the RPB mentioned above. The construction of the latter is relatively simple than the former. We may infer the proposed HiGee is superior to the RPB.

These are preliminary qualitative observations. Detailed studies are needed to quantify the effects of various parameters.

4. Summary

We have presented a novel torsional-Couette flow HiGee and its variants. It is only HiGee, besides the RPB with split packing, which enables to set high tangential slip velocity to enhance gas-side mass-transfer coefficient. The preliminary theoretical and experimental performance of the proposed HiGee for deaeration of water has been presented. It is hoped that the ideas presented in our study will stimulate further research in the adoption of Couette-flow HiGee for various other applications.

Declaration of Competing Interest

As per the competing interest: The authors jointly filed patent application for the new HiGee. We are in the business of supplying the HiGees for various applications.

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