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Rotating Contacting Device based Improved Cooling Tower - Concept along with Demonstration Results

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Rotating Contacting Disk-based Improved Cooling Tower - Concept along with Demonstration Results

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ABSTRACT

Cooling towers are widely used in industrial and commercial applications. There are various types of cooling towers with or without fills and with or without mechanical draft. Small to medium capacity cooling towers often use fans to induce airflow through the fill. Water quality and cycles of concentration often dictate the selection of fill and the water distribution setup. Range and approach along with the type of fill govern the airside pressure drop. Using mist and drift eliminators reduce the water required, but they increase the airside pressure drop. These factors dictate the fan power in the Induced Draft Cooling Towers, IDCT, or the height of the hyperboloid towers in the Natural Draft Cooling Towers, NDCT, ultimately affecting the life cycle cost of a cooling tower.

The paper presents a novel modular maintenance-friendly energy-efficiently cooling tower that can be deployed for a wide range of applications and capacities. The textured rotating disk-based contacting media offers excellent wettability; it can be operated over a wide range of L/G ratios from 0.5 to 3 and can handle water with high total dissolved solids, TDS, without scale formation on the disks. A rotating contacting disk, RCD, based cross flow cooling tower is developed and demonstrated in the Heat Pump Laboratory at IIT Bombay. Very high surface densities are possible, in the range of 300 to 400 m^2/m^3. Airside pressure drop through the RCD is typically less than 10 Pa (1 mm H_2O). Also, mist and drift eliminators can be eliminated by judicious design using RCD. These RCD-based cooling towers can also be used with wastewater or seawater. Fouling of the RCD is not an issue as this type of RCD has been operating as effluent concentration and seawater concentration systems in the industry, for more than a year now.

1. INTRODUCTION

Cooling Towers, CT, are widely used in industrial and commercial applications. There are various types of cooling towers with or without fills and with or without mechanical draft. Natural draft cooling towers are often used in power plants and have heat rejection capacity typically above 350 MW. Airflow is induced using hyperboloid towers of 120 to 200 m in height. Small to medium capacity cooling towers often use fans to induce airflow through the fill. Cooling towers with up to several hundred MW heat rejection capacities are also available with water spray-induced airflow.

Water quality and cycles of concentration often dictate the selection of fills and the water distribution setup. Range and approach along with the type of fill govern the airside pressure drop. Using mist and drift eliminators reduce the water required, but they increase the airside pressure drop.

Cooling towers reject heat from air conditioning and refrigeration systems, industrial processes, and power plants. Cooling towers are typically deployed with fills, which increase the interfacial area for heat and mass transfer between the water being cooled and the air used to cool it. Cooling towers without fills have been deployed if water quality is a concern, but this usually increases the size of the tower.

Fills are prone to fouling if the water quality is not good or the water has high TDS. Water quality and cycles of concentration often dictate the selection of fills and the water distribution setup. Surface densities, surface area per unit volume of fill, for low fouling fills are typically in the range of 98 to 155 m^2/m^3, they can serve when the water quality is not very good. If the water quality is good, then the typical fill surface densities are in the range of 102 to 226 m^2/m^3 (*Cross-Fluted Film Fill*, 2022; *Low Fouling Film Fill*, 2022).

High fill surface densities enable the reduction of fill volume deployed for a specific application and thus reduce the footprint and size of the cooling tower. They offer high air side pressure drop per unit depth of the fill. They may be susceptible to fouling. Fouling of fills and clogging of the water distribution headers can lead to maldistribution of water and air, and significantly deteriorate the cooling tower's thermal and hydraulic performance. This further leads to an increased approach, reduced heat rejection capacity, and increased fan/blower power if deployed.

Range and approach along with the type of fill govern the airside pressure drop. The range of the cooling tower is the difference between the temperature of the warm water at the cooling tower inlet, $t_{w.ct.i}$, and the temperature of the cooler water at the cooling tower outlet, $t_{w.ct.o}$. The approach of the cooling tower is the difference between the temperature of the cooler water at the cooling tower outlet, $t_{w.ct.o}$, and the wet-bulb temperature of the ambient air entering the cooling tower $t_{wb.a.ct.i}$.

Spraying of water to enable uniform distribution of water over the fixed/stationary fill generates fine water droplets. Depending on the size of the fine droplets and the air velocity, some of these water droplets may get entrained along with the air streams. Using mist and drift eliminators help reduce this entrainment and the associated water loss, which does not contribute to the cooling of the water. However, they increase the airside pressure drop. These factors dictate the fan power or the height of the hyperboloid tower. Increased airside pressure drop increases fan/blower power increases the operating cost and increased tower height in an NDCT increases the initial and maintenance cost, ultimately affecting the life cycle cost of a cooling tower.

Current commercially available technologies serving this market are:

1. ***Natural draft cooling towers with hyperbolic towers*** *typically serve the needs of the thermal power plants*
   a. Heat rejection capacity: above 360 MW (10^5 TR)
   b. CT range, $t_{w.ct.i} - t_{w.ct.o}$: typically designed for 10ºC; usual operating range 9 ºC to 12ºC
   c. CT approach, $t_{w.ct.o} - t_{wb.a.ct.i}$: typically designed for 4 ºC; usual operating range 3ºC to 7ºC
   d. Total air side pressure drop: typically designed for 60 Pa; usual operating range 50 to 75 Pa
   e. Airside pressure drop across the fill: typically designed for 45 Pa; usual operating range 40 to 60 Pa
   f. Material of construction: Structure - RCC, fill/mist eliminator/fan blades - plastic, composites

2. ***Induced draft cooling towers with fans*** *typically serve the needs of small air conditioning and refrigeration systems, process cooling applications, and thermal power plants*
   a. Heat rejection capacity: from less than 35 kW to above 360 kW, with above 360 kW/cell for IDCT of a power plant cooling tower
   b. CT range, $t_{w.ct.i} - t_{w.ct.o}$:
   c. Typically designed for 5.6ºC for AC&R applications; the usual operating range is 3ºC to 7ºC
   d. Typically designed for 10ºC for Power Plant applications; the usual operating range is 9 ºC to 12ºC
   e. CT approach, $t_{w.ct.o} - t_{wb.a.ct.i}$:
   f. typically designed for 2.8ºC for AC&R applications; the usual operating range is 2ºC to 5ºC
   g. typically designed for 4ºC for Power Plant applications; the usual operating range is 3 ºC to 7ºC
   h. Total air side pressure drop: typically design 60 Pa; the usual operating range is 50 to 100 Pa

i. Material of construction: Structure – Reinforced Cement Concrete, RCC, for large and Fiber Reinforced Plastic, FRP, for smaller cooling towers, fill/mist eliminator/fan blades - plastic, composites

Various types of cooling towers, their working, and methodology to evaluate their performance and methodology to design the cooling tower are explained in the "Cooling Towers" (2012). Majumdar *et al.* (1983 P1) explain various mathematical and physical models and Majumdar *et al.* (1983 P2) apply their model to simulate the thermal performance of various natural and mechanical draft cooling towers. Conventional methods recommended by the Cooling Tower Institute, CTI, and the (Kelly, 1976), solve three equations, namely heat balance, Merkel's equation, which expresses the heat transfer to be proportional to the enthalpy difference between saturated water vapour and air and an imperial expression relating overall heat and mass transfer coefficient, Ka, with L/G. Where, L/G is the ratio of water flow rate and the airflow rate.

Some of the shortcomings of the conventional method, although convenient and widely used, are identified as follows:

a. Lack of flexibility to accept empirical input in a general form
b. Simplifying assumptions of Merkel's equation
c. Non-uniformity of flow as air changes direction from the entrance region to the exit region
d. coupling between fluid flow and heat transfer, especially in the natural draft cooling tower, where the amount of airflow through the tower affects the heat and mass transfer between water and air, this, in turn, affects the temperature and moisture inside the cooling tower which determines the density of the air inside the tower which governs the airflow
e. Effect of ambient pressure variation on evaporation.

$$\mathrm{St} = \frac{Nu}{Re\ Pr} = \frac{h}{\rho\ u\ cp} \tag{1}$$

$$\mathrm{St_m} = \frac{Sh}{Re\ Sc} = \frac{hm}{\rho\ u} \tag{2}$$

$$\mathrm{Le_f} = \frac{h}{cp\ hm} \tag{3}$$

$$\mathrm{Le} = \frac{\alpha}{D} = \frac{k}{\rho\ cp\ D} = \frac{Sh}{Pr} \tag{4}$$

(Kloppers & Kröger, 2005) discuss the Lewis factor, $\mathrm{Le_f}$, and its influence on the performance prediction of wet cooling towers. Merkel assumes that this factor is 1, to simplify the governing equation. They have shown that this assumption is acceptable for warm and humid ambient. Lewis factor is defined as the ratio of the heat transfer Stanton number, St, to the mass transfer Stanton number, $\mathrm{St_m}$.

Where h is the heat transfer coefficient and hm is the mass transfer coefficient. Lewis number, Le, is equal to the ratio of Schmidt, Sh, to the Prandtl numbers, Pr. Where α is the thermal diffusivity and D is the diffusion coefficient.

They recommend that the cooling tower performance be evaluated at the same ambient conditions under which the fill performance is tested. The same definition of the Lewis factor must be employed in the fill performance analysis and the subsequent cooling tower performance analysis.

Uniform distribution of water is very important. Misdistribution of water can cause bypassing of air and substantial degradation of the tower performance. One of the commonly observed field situations is that the water spray pattern is not as per the design, the desired uniform distribution. Common reasons are reduced flow due to deposits in the distribution headers and/or clogging of nozzles. This significantly affects the tower's performance concerning approach and range. Regular inspection and maintenance are essential even if it is labour-intensive and costly. The return on this investment is usually very fast.

Some of the challenges in using commercially available technologies have been the limited availability of good quality water to run the cooling towers and the high fan and pump power consumption. Reducing the environmental impact of cooling tower effluent being discharged from the basin, and entrainment of water droplets and microbiological contaminants in the air are additional concerns. Increasing the reliability of the cooling towers while reducing the maintenance and life cycle cost of the installation has always been the driving force for new developments.

Thus, there is a need to develop cooling towers that can address the gaps in technologies available for deployment concerning lower initial and operating cost, modular nature to optimally utilize the available free spaces, lightweight, and ability to use seawater and treated wastewater, while minimizing the approach, air and waterside pressure drops.

2. DESCRIPTION OF THE CROSSFLOW COOLING TOWER USING RCD

A novel Rotating Contacting Disk, RCD, based on Crossflow Cooling Tower, CF_CT, is developed in the Heat Pump Laboratory at IIT Bombay, HPL_IITB. This modular cooling tower is simple to integrate and easy to maintain. Figure 1 shows the sectional view of a 42-rotor-induced draft crossflow cooling tower. It has seven rotors stacked one above the other on each face of the six-sided CT. Effective wetting is achieved over a wide range of water irrigation rates due to the presence of crisscross groves on the disk surface, which are porous. As air passes parallel to the disk surface, the pressure drop is less. Typically, less than 10 Pa at an air face velocity of 1.5 m/s.

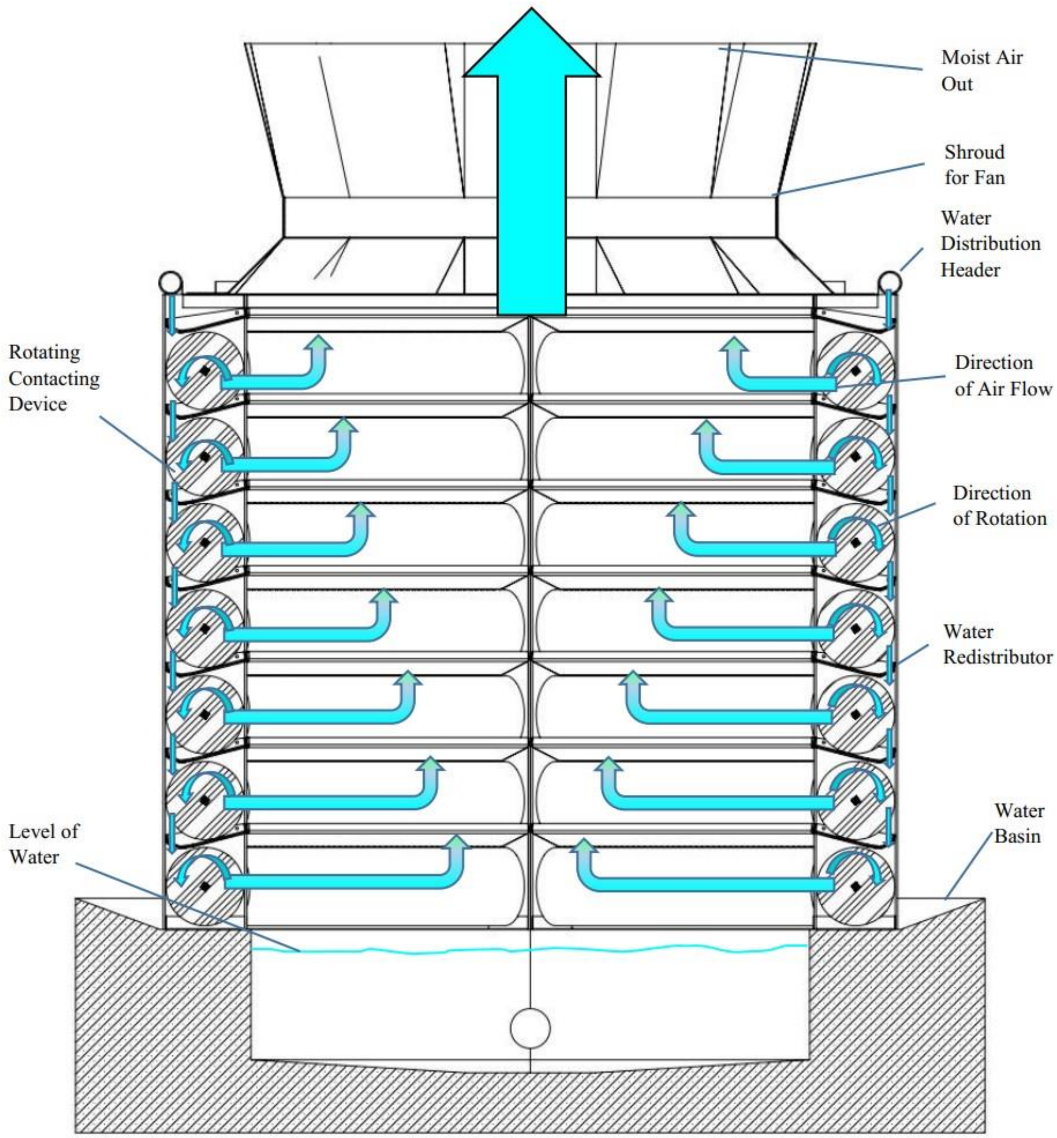

Figure 1: Sectional view of CT with 42 rotors; with 7 high rotor assemblies on each of the six sides

Figure 2: Single 300 mm diameter Polypropylene, PP, disks each weighing about 64 g

2.1 Features of the Novel Rotating Contacting Disk-based Cooling Towers

1. Simple Construction: easy to integrate, install and maintain
    a. Disks rotated using water flow without the use of drive motors
2. Versatile Design: operable over a very wide range of L/G ratios
    a. Flooding is avoided even at very high water flow rates
    b. Wetting of the textured rotating contacting disk surface is assured at low water flows
3. Novel Modular Design: hence no upper limit for capacity
4. Low Carryover: as the liquid is not sprayed, carryover is almost non-existent
5. High Mass Transfer Coefficients: mass exchanger can be optimized by suitably selecting the geometry and texture of the rotating disk
6. Energy-Efficient Operation: air/gas side pressure drops can be as low as 10 Pa, thereby reducing fan power and low pump head of ~3 m
7. Material of Construction: MOC is predominantly plastic and composites
    a. Disks made of Polypropylene PP, Polycarbonate PC, Stainless Steel SS304, 316, 316L, Aluminium, Mild Steel MS, etc. according to fluid type e.g. corrosive, erosive, fouling, catalytic activity, etc.
8. Easy to Maintain: can be cleaned using clean-in-place using Jet Cleaning

3. THEORETICAL ANALYSIS OF RCD-BASED COOLING TOWER

The theoretical analysis of the RCD-based cross flow-cooling tower is performed considering each RCD rotor to bring ambient air in contact with the water irrigated on the rotor. Water is irrigated on the rotor away from the center of rotation of the disk rotor. The distributor is provided with holes of 3 to 9 mm holes at a close pitch of 5 to 12.7 mm. The size and number of the holes in the water distributor depend on the volume flow rate of water and water quality.

Off-center loading of water on the disk creates an unbalanced force and this turns the disk rotor. The crisscross texturing of the PP disks ensures that both the faces of each disk remain wet. The velocity of the water jet typically varies between 0.25 to 1.0 m/s and the speed of rotation of the disk rotor varies between 15 to 60 rpm. Suitable adopting the procedure recommended in the (“Ch 40 Cooling Towers,” 2012; Fulkerson, 2009) for a crossflow cooling tower performed modelling of the RCD-based crossflow CT. The details about the state points in and out of each of the seven rotors are summarized in Table 1.

Table 1: CD-based Crossflow Cooling Tower without Fan - Specifications along with Test Data

Rotating Contacting Disks based Cooling Tower: *Heat and Mass Balance Across Rotors*

L/G	0.776		L/G ratio
cp_w	4.18	kJ/kg.K	specific heat of water
$n_{rcd.ric\ daf}$	7		number of rotors in a column
$n_{rcd.s}$	6		number of rotor columns
h_{rs}	0.33	mm	height of RCD
w_{rs}	1.22	mm	width of RCD
ε_{rcd}	0.8		effectiveness
BPE	0.02	°C	Boiling Point Elevation of Water/Effluent

Nomenclature

$t_{w.ct.i}$	temperature of water at cooling tower inlet, °C
$t_{db.a.ct.i}$	drybulb temperature of air at cooling tower inlet, °C
dt_w	change in water temperature, °C
$h_{ct.w.i}$	enthalpy of water at cooling tower inlet, kJ/kg
$dh_{a.ct}$	change in enthalpy of air in the cooling tower, kJ/kg
$w_{ct.a.i}$	**kg of moist air/ kg of dry air**
$\vartheta_{ct.a.i}$	**m^3/kg of dry air**
$v_{ct.a.i}$	**m/s velocity of air at CT/RCD Frontal Area**

Water Inlet: $mf_{w.total}$ **16.81 kg/s 60,500 kg/h**

Mumbai Weather Data for Evaporation @ 1% Reliability, ASHRAE 2013

Air Inlet: $mf_{a.tot}$ 78,000 kg/h; $mf_{a.tot}$ **21.67 kg/s**; $volf_{a.tot}$ **71,428 m^3/h**

		$t_{w.ct.i}$	$h_{w.ct.i}$	$mf_{w.1,1}$		H&ME @ Effectiveness 80%		
$mf_{a.1}$	3.095	42.0	175.6	16.806	$dh_{a.ct.1,1}$	56.38		
$t_{db.a.ct.i}$	30.9				$t_{db.a.ct.1,1.o}$	37.44		
$t_{wb.a.ct.i}$	27.4				$t_{wb.a.ct.1,1.o}$	37.04	Q.w.1	174.49 kW
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,1.o}$	*97.40*	Q.a.1	174.49 kW
$w_{a.ct.i}$	0.0217		1,1		$w_{a.ct.1,1.o}$	0.04101	m.w.evp	262 kg/h
					$dw_{a.ct.1,1.o}$	0.01930		
$t_{dp.a.ct.i}$	26.3				$t_{dp.a.ct.1,1.o}$	36.96		
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.1.o}$	0.9370		
$h_{a.ct.i}$	86.58	3.11	38.90	162.6	$h_{a.ct.1,1.o}$	143.0		
$v_{a.ct.i}$	1.14	dt_w	$t_{w.ct.1,1.o}$	$h_{w.ct.1,1.o}$	$dh_{w.ct.1,1}$	10.38		
$mf_{a.2}$	3.095	2.48	39.52	165.2	$dh_{a.ct.1,2}$	45.03		
$t_{db.a.ct.i}$	30.9				$t_{db.a.ct.1,2.o}$	*35.77*		
$t_{ct.a.wb.i}$	27.4				$t_{wb.a.ct.1,2.o}$	35.40	Q.w.2	139.37 kW
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,2.o}$	*97.53*	Q.a.2	139.37 kW
$w_{a.ct.i}$	0.0217		1,2		$w_{a.ct.1,2.o}$	0.03727	m.w.evp	209 kg/h
					$dw_{a.ct.1,2.o}$	0.01556		
$t_{da.ct.i}$	26.3				$t_{dp.a.ct.1,2.o}$	35.32		
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.2.o}$	0.9267		
$h_{a.ct.i}$	86.58	2.48	37.04	154.8	$h_{a.ct.1,2.o}$	131.6		
$v_{a.ct.i}$	1.14	dt_w	$t_{w.ct.2,1}$	$h_{ct.w.2,1}$	$dh_{w.ct.1,2}$	8.29		
$mf_{a.3}$	3.095	1.98	37.53	156.9	$dh_{a.ct.1,3}$	36.58		
$t_{db.a.ct.i}$	30.9				$t_{db.a.ct.1,3.o}$	*34.63*		
$t_{ct.a.wb.i}$	27.4				$t_{wb.a.ct.1,3.o}$	34.11	Q.w.3	113.24 kW
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,3.o}$	*96.49*	Q.a.3	113.24 kW
$w_{a.ct.i}$	0.0217		1,3		$w_{a.ct.1,3.o}$	0.03448	m.w.evp	170 kg/h
					$dw_{a.ct.1,3.o}$	0.01277		
$t_{da.ct.i}$	26.3				$t_{dp.a.ct.1,3.o}$	33.99		
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.3.o}$	0.9193		
$h_{a.ct.i}$	86.58	2.02	35.52	148.5	$h_{a.ct.1,3.o}$	123.2		
$v_{a.ct.i}$	1.14	dt_w	$t_{w.ct.3,1}$	$h_{ct.w.3,1}$	$dh_{w.ct.1,3}$	6.74		
$mf_{a.4}$	3.095	1.61	35.92	150.1	$dh_{a.ct.1,4}$	30.05		
$t_{db.a.ct.i}$	30.9				$t_{db.a.ct.1,4.o}$	*33.57*		
$t_{ct.a.wb.i}$	27.4				$t_{wb.a.ct.1,4.o}$	33.03	Q.w.4	93.01 kW
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,4.o}$	*96.35*	Q.a.4	93.01 kW
$w_{a.ct.i}$	0.0217		1,4		$w_{a.ct.1,4.o}$	0.03235	m.w.evp	140 kg/h
					$dw_{a.ct.1,4.o}$	0.01064		
$t_{da.ct.i}$	26.3				$t_{dp.a.ct.1,4.o}$	32.91		
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.4.o}$	0.9132		
$h_{a.ct.i}$	86.58	1.66	34.27	143.2	$h_{a.ct.1,4.o}$	116.63		
$v_{a.ct.i}$	1.14	dt_w	$t_{w.ct.4,1}$	$h_{ct.w.4,1}$	$dh_{w.ct.1,4}$	5.53		
$mf_{a.5}$	3.095	1.32	34.60	144.6	$dh_{a.ct.1,5}$	24.96		
$t_{db.a.ct.i}$	30.9				$t_{db.a.ct.1,5.o}$	*32.75*		
$t_{ct.a.wb.i}$	27.4				$t_{wb.a.ct.1,5.o}$	32.16	Q.w.5	77.27 kW
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,5.o}$	*95.95*	Q.a.5	77.27 kW
$w_{a.ct.i}$	0.0217		1,5		$w_{a.ct.1,5.o}$	0.03069	m.w.evp	116 kg/h
					$dw_{a.ct.1,5.o}$	0.00898		
$t_{da.ct.i}$	26.3				$t_{dp.a.ct.1,5.o}$	32.02		
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.5.o}$	0.9084		
$h_{a.ct.i}$	86.58	1.38	33.22	138.9	$h_{a.ct.1,5.o}$	111.5		

Table 1: CD-based Crossflow Cooling Tower without Fan - Specifications along with Test Data (continued)

$v_{a.ct.i}$	1.14	**dt_w**	**$t_{w.ct.5,1}$**	**$h_{ct.w.5,1}$**	**$dh_{w.ct.1,5}$**	**4.60**		
$mf_{a.6}$	**3.095**	**1.10**	**33.50**	**140.0**	**$dh_{a.ct.1,6}$**	**20.70**		
$t_{db.a.ct.i}$	**30.9**				**$t_{db.a.ct.1,6.o}$**	***31.98***		
$t_{ct.a.wb.i}$	**27.4**				**$t_{wb.a.ct.1,6.o}$**	32.42	**Q.w.6**	**64.07 kW**
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,6.o}$	***96.09***	**Q.a.6**	**64.07 kW**
$w_{a.ct.i}$	0.0217		**1,6**		$w_{a.ct.1,6.o}$	**0.02937**	**m.w.evp**	**96 kg/h**
					$dw_{a.ct.1,6.o}$	**0.00766**		
$t_{d.a.ct.i}$	26.3				**$t_{dp.a.ct.1,6.o}$**	**31.50**		
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.6.o}$	0.9043		
$h_{a.ct.i}$	86.58	**1.14**	32.36	135.2	**$h_{a.ct.1,6.o}$**	**107.3**		
$v_{a.ct.i}$	1.14	**dt_w**	**$t_{w.ct.6,1}$**	**$h_{ct.w.6,1}$**	**$dh_{w.ct.1,6}$**	**3.81**		
$mf_{a.7}$	**3.095**	**0.91**	**32.58**	**136.2**	**$dh_{a.ct.1,7}$**	**17.43**		
$t_{db.a.ct.i}$	**30.9**				**$t_{db.a.ct.1,7.o}$**	***31.48***		
$t_{ct.a.wb.i}$	**27.4**				**$t_{wb.a.ct.1,7.o}$**	30.82	**Q.w.7**	**53.95 kW**
$rh_{a.ct.i}$	76.4				$rh_{a.ct.1,7.o}$	***95.37***	**Q.a.7**	**53.95 kW**
$w_{a.ct.i}$	0.0217		**1,7**		$w_{a.ct.1,7.o}$	**0.02829**	**m.w.evp**	**81 kg/h**
					$dw_{a.ct.1,7.o}$	**0.00658**		
$t_{d.a.ct.i}$	26.3				**$t_{dp.a.ct.1,7.o}$**	**30.65**	**m.w.evp**	**1,073 kg/h**
$\vartheta_{a.ct.i}$	0.891				$\vartheta_{a.ct.1.7.o}$	0.9013		
$h_{a.ct.i}$	86.58	**0.96**	31.62	132.2	**$h_{a.ct.1,7.o}$**	**104.0**	**Q.a**	**862.9 kW**
$v_{a.ct.i}$	1.14	**dt_w**	**$t_{w.ct.7,1}$**	**$h_{ct.w.7,1}$**	**$dh_{w.ct.1,7}$**	**3.21**	**Q.w**	**715.4 kW**
		0.77	**31.82**	**133.0**			**Q.a**	**715.4 kW**

The RCD-based crossflow CT of 200 TR was deployed in the field after a smaller configuration was tested in the Heat Pump Laboratory at IIT Bombay, HPL_IITB. Hot water was supplied to the distributor header and various parameters were measured. Table 1 list the specifications of the RCD-based crossflow CT along with the measurement data and the calculated CT performance parameters.

4. RESULTS

As can be seen from Table 2, for field data with a water inlet temperature of 42ºC and flow rate of 60,500 kg/h, when the ambient dry bulb temperature was 30.9ºC and wet bulb temperature was 27.4ºC, the water was cooled to 31.8ºC. A range of 10.2ºC and an approach of 4.4ºC. The heat duty handled by the crossflow cooling tower with 42 rotors of 330 mm rotor assembly was 715.4 kWth (~200 TR). The error in measuring the range and approach is +0.2ºC and that in determining the heat duty is +6%.

The surface density of the RCD-based CT without a fan is 64.3 m^2/m^3 with a disk pitch of 4.5 mm.

The frontal velocity of the air through the rotor assembly is about 0.375 m/s, with an airflow of 0.333 kg/s through a frontal area of 0.759 m^2. If a fan is deployed to circulate air across the rotors, the frontal velocity of air can be increased to 1.2 m/s. Keeping the L/G ratio around 1 would mean that the water flow rate can be increased 3 times or be increased to 3,600 kg/h. This will substantially increase the heat duty. Reducing the L/G ratio can help reduce the approach. An approach of 4ºC should be easily possible with the fan or tower-aided airflow across the rotors when the range is about 10ºC, the typical design condition for power or process industry applications.

There is no limit to scaling this novel RCD_CT to serve small or large capacity needs. CT from less than 3.52 kW to 1760 kW heat duties can be conceived and implemented.

RCD-based cooling towers can benefit power plants and large cooling tower users in the power and process industry. The airside pressure drop across the RCD will be 3 to 6 times lower, as compared to that of the conventional fill in an NDCT. This will substantially reduce the tower height, the time, and the cost of its erection. Also, mist and drift eliminators can be eliminated by judiciously designing the RCD CTs.

A 704 kW RCD-based cooling tower with a 1.5 kW fan is recently commissioned in the industry. Preliminary results look promising as the fan power saving is expected to be about 5 kW (Rane & Rane, 2019; Rane & Saini, 2017).

Table 2: RCD based Crossflow Cooling Tower with Fan - Specifications along with Field Data

Parameter	Parameter	Value	Units
Number of sides	n_{sid}	**6**	
Number of rotors per side	n_{rot}	**7**	
Pitch of disk assembly	$pitch_{dsk}$	5	mm
Length of rotor assembly (rotor assembly including end plugs)	$l_{rot.asm}$	**1.22**	**m**
Number of disks per rotor	$n_{dsk.rot}$	**244**	
Diameter of disk	d_{dsk}	**300**	**mm**
Thickness of disk (gross including corrugations)	t_{dsk}	2.1	mm
Clear gap between adjoining disks	$gap_{dsk.clr}$	2.9	mm
Vertical pitch between rotors	$pitch_{rot.v}$	330	mm
Total height of rotor assembly (rotor assembly including distribution header)	$h_{rot.tot}$	**2.31**	**m**
Height fan with diffuser	h_{fwd}	0.96	m
Total height of CT (assembly from fan with diffuser to base)	$h_{ct.tot}$	4.05	m
Contact area offered by a disk (both sides of one disk)	$A_{s,dsk}$	0.141	m^2
Total number of disks	$n_{dsk.ct}$	10,248	
Contact area offered by disks in a rotor	$A_{hme,dsk.rot}$	34.5	m^2
Contact area offered by all the disks in the CT	$A_{hme,dsk.tot}$	**1449**	$\mathbf{m^2}$
Surface density	$\mathbf{Ad_{dsk.rot}}$	**400**	$\mathbf{m^2/m^3}$
Frontal area (air flows across all the rotors through this area)	$A_{fr,ct}$	**16.9**	$\mathbf{m^2}$
Volume of CT (3.1 m x 2.9 m x 2.5 m)	vol_{ct}	22.5	m^3
Foot Print of CT (3.1 m x 2.9 m)	$A_{fr,ct}$	5.8	m^2
Mass of water retained by the disk (varies with water flow)	$m_{w.ret.dsk}$	0.011	kg
Mass of water retained by the all the disk in CT (varies with water flow)	$m_{w.ret.dsk.ct}$	112.7	kg
Thickness of water film on the disk (varies with water flow)	thk_{film}	0.078	mm
Dry bulb temperature of air at inlet to the CT	$t_{db.a.ct.i}$	30.9	°C
Wet bulb temperature of air at inlet to the CT	$t_{wb.a.ct.i}$	27.4	°C
Temperature of water at CT inlet (into the distributor header above 1st rotor)	$\mathbf{t_{w.ct.i}}$	**42.0**	**°C**
Temperature of water at CT outlet (in the basin below the 7th rotor)	$\mathbf{t_{w.ct.o}}$	**31.8**	**°C**
Water flow rate	$\mathbf{mf_{w.ct}}$	**16.81**	**kg/s**
Airflow rate (varies with water flow and wind velocity)	$\mathbf{mf_{a.ct}}$	**21.7**	**kg/s**
Range	$\mathbf{dt_{range}}$	**10.2**	**°C**
Approach	$\mathbf{dt_{app}}$	**4.4**	**°C**
Heat load	Q_{ct}	***715.4***	***kW***
Heat load per unit disk surface area	Q_{Act}	***0.49***	***kW/m²***
Heat load per unit CT foot print	Q_{Afp}	***123.2***	***kW/m²***
Heat load per unit CT volume	Q_{volct}	***31.8***	***kW/m³***

Seawater-based cooling towers have been deployed. Scaling has not become an issue with RCD. The reliability of the RCD-based wastewater vaporizers has already been demonstrated for multiple years in the Indian industries.

5. CONCLUSIONS

A novel rotating contacting disk, RCD, based cross flow cooling tower is developed and demonstrated in the Heat Pump Laboratory at IIT Bombay. Very high surface densities are possible, in the range of 150 to 300 m^2/m^3. Airside pressure drop through the RCD is typically less than 10 Pa (1 mm H2O) for an air velocity of 1.5 m/s. This modular cooling tower has been demonstrated to operate well with and without a fan. Deploying a fan can significantly improve performance. Airflow can be enhanced 2 to 3 times, and area density can be increased by using a mechanical draft.

A prototype consisting of seven rotors, stacked in a vertical column, is developed. Theoretical analysis, along with experimental data, is presented for a crossflow CT using 300-diameter PP disks. This type of cooling tower can handle a range of 12.5^{o}C within 2.4 m height. As the total height of the cooling tower is less, and the pressure drop across the water distributor is typically less than 50 mm H2O, the pumping power required is lower than most conventional cooling towers.

Tower height in an NDCT, its cost, and erection time can be substantially reduced due to a 3 to 6 times lower pressure drop across the RCD-based fill compared to the conventional fill in an NDCT.

NOMENCLATURE

A	Area	(m^2)
D	diffusion coefficient	($m^2.s^{-1}$)
D	Diameter	(m)
Dt	difference in temperature	(^{o}C)
Ka	overall heat and mass transfer coefficient	(-)
L	Length	(m)
L/G	liquid to gas ratio	(-)
Mf	mass flowrate	($kg.s^{-1}$)
Q	heat load	(kW)
Abbreviations		
CF	Cross Flow	(-)
CT	Cooling Tower	(-)
CTI	Cooling Tower Institute	(-)
FRP	Fibre Reinforced Plastic	(-)
HPL_IITB	Heat Pump Laboratory at IIT Bombay	(-)
IDCT	Induced Draft Cooling Towers	(-)
NDCT	Natural Draft Cooling Towers	(-)
RCC	Reinforced Cement Concrete	(-)
TDS	Total Dissolved Solids	(-)
Dimensionless numbers		
Le	Lewis number, $h / (\rho c_p D)$, or Sc / Pr, or α / D	
Le_f	Lewis factor, $h / (c_p h_m)$	
Pr	Prandtl number, $(c_p \mu) / k$	
St	Stanton number, $h / (\rho \mu c_p)$	
St_m	mass transfer Stanton number, $(h m) / (\rho \mu)$	
Greek symbols		
Α	thermal diffusivity, $k / (\rho c_p)$	
Μ	dynamic viscosity	

Subscripts

A	air
App	approach
Asm	assembly
Ct	cooling tower total
Db	dry bulb
Dsk	disk
Fp	footprint
fwd	fan with diffuser
hme	heat and mass exchange
i	inlet
o	outlet
p	pitch
ret	retained
rot	rotor
s	surface
t	temperature
th	thermal
tot	total
vol	volume
w	water
wb	wet bulb

REFERENCES

Cooling Towers. (2012). In *ASHRAE Handbook HVAC Systems and Equipment* (pp. 40.1-40.23).

Cross-Fluted Film Fill. (n.d.). Brentwood. https://www.brentwoodindustries.com/cooling-tower/accupac-counterflow-film-fill-media/

Fulkerson, R. (2009). Crossflow Cooling Tower Performance Calculations. *CTI Journal*, *30*(1), 33–41.

Kelly, N. W. (1976). *Kelly's Handbook of Crossflow Cooling Tower Performance*. Kansas City, Mo. : Neil W. Kelly & Associates, 1976.

Kloppers, J. C., & Kröger, D. G. (2005). The Lewis factor and its influence on the performance prediction of wet-cooling towers. *International Journal of Thermal Sciences*, *44*(9), 879–884. https://doi.org/10.1016/j.ijthermalsci.2005.03.006

Low Fouling Film Fill. (n.d.). Brentwood. https://www.brentwoodindustries.com/cooling-tower/low-fouling-film-fill/

Majumdar, A. K., Singhal, A. K., Reilly, H. E., & Bartz, J. A. (1983 P2). Numerical modeling of wet cooling towers-Part 2: Application to natural and mechanical draft towers. *ASME Journal of Heat Transfer*, *105*(4), 736–743. https://doi.org/10.1115/1.3245656

Majumdar, A. K., Singhal, A. K., & Spalding, D. B. (1983 P1). Numerical Modeling of Wet Cooling Towers-Part 1: Mathematical and Physical Models. *ASME Journal of Heat Transfer*, *105*(4), 728–735. https://doi.org/https://doi.org/10.1115/1.3245655

Rane, M. V, & Rane, A. M. (2019). Efficient Cooling Tower using Rotating Contacting Device. *Air Conditioning and Refrigeration Journal*, *22*(4), 32–40.

Rane, M. V, & Saini, S. K. (2017). *Rotating Contacting Disks based Mass and Heat Exchangers* (Indian Patent Application No. 201721029712).

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