Environment, Development and Sustainability
https://doi.org/10.1007/s10668-021-01678-5

REVIEW

Condenser cooling technologies for concentrating solar power plants: a review

Tarun Kumar Aseri[1,2] · **Chandan Sharma**[2] · **Tara C. Kandpal**[1]

Received: 16 April 2021 / Accepted: 21 July 2021

Abstract

Selection of condenser cooling technology can affect the financial as well as technical viability of concentrating solar power (CSP) plants. Detailed comparative assessment of three cooling technologies, i.e., wet, dry, and hybrid, is therefore desirable so as to facilitate selection of optimum cooling technology for the plant. Despite the high efficiency of wet cooling technology, considering the fact that the potential plant locations are generally in arid regions suffering from water scarcity, it is imperative to explore and consider other water conserving condenser cooling options. A review and comparison of technical, economic, and environmental aspects of the three condenser cooling technologies for CSP plants have been presented. Adoption of dry or hybrid technology as against wet cooling technology may lead to reduced thermal performance and increased parasitic power requirement resulting in the high cost of electricity generation. However, the same also results in reduced cooling water requirement up to 92% and thus increase the potential of solar thermal power generation considerably as sites in arid areas can also be utilized.

Keywords Concentrating solar power · Condenser cooling technology · Wet cooling · Dry cooling · Hybrid cooling

Nomenclature

Subscripts

eq	Equivalent

Acronyms

ANN	Artificial neural network
COC	Cycle of concentration
CSP	Concentrating solar power
CTR	Central tower receiver
DNI	Direct normal irradiance

✉ Tarun Kumar Aseri
tarunaseri@gmail.com

[1] Department of Energy Science and Engineering, Indian Institute of Technology, Delhi 110016, India

[2] Mechanical Engineering Department, Engineering College, Ajmer, Rajasthan 305025, India

Published online: 06 August 2021

GHG	Greenhouse gas
ITD	Initial temperature difference
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflector
MACC	Modular air-cooled condenser
NTU	Net transfer unit
PM	Particulate matter
PD	Parabolic dish
PTC	Parabolic trough collector
PV	Photovoltaic
TTD	Terminal temperature difference

1 Introduction

Environmental concerns along with the uncertainty regarding the availability and price of fossil fuels during the last few decades have created significant interest in renewable energy-based power generation options (Edenhofer et al., 2015; Frisvold & Marquez, 2013). Solar power generation (both photovoltaic and thermal routes) is being promoted across the globe as an environmentally sustainable renewable energy option (DOE, 2009; Kalogirou, 2004). In solar thermal power generation, the incident solar radiation is first converted into heat, and the same is then utilized in the power cycle to produce electricity (Timilsina et al., 2012). A schematic of a solar thermal power plant with indirect (two-tank) thermal energy storage is shown in Fig. 1. A solar thermal power plant can be divided into three sub-systems, namely solar energy collection sub-system, thermal energy extraction and storage sub-system, and power generation sub-system (Herrmann et al., 2004; Kuravi et al., 2013; Praveen et al., 2018). The solar energy collection system consists of solar concentrators for concentrating the incident solar radiation onto the receiver. Accordingly, solar thermal power plants are also referred to as concentrating solar power (CSP) plants (Trinh et al., 2014). The concentrators used in a CSP plant can be either line focus or point focus (Behar et al., 2013; Desai & Bandyopadhyay, 2017). The line focusing solar collectors include parabolic trough collectors

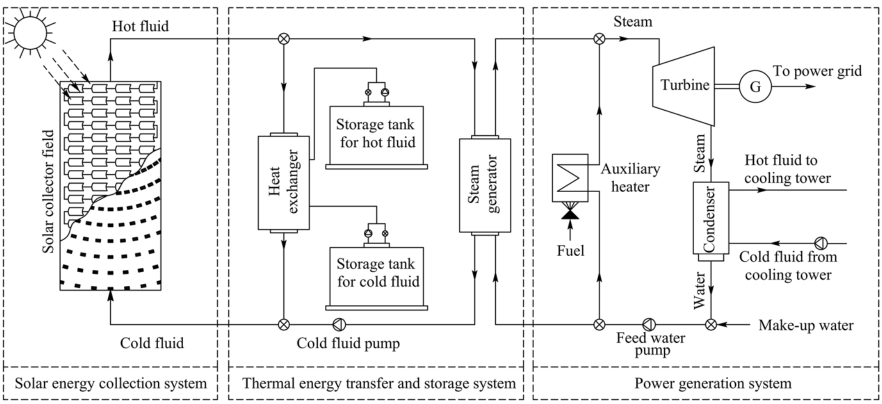

Fig. 1 Schematic of a CSP plant with indirect (two-tanks) thermal energy storage

(PTC) and linear Fresnel reflector (LFR). The point focusing collectors include central tower receiver (CTR) and parabolic dish (PD). Salient features of PTC, LFR and CTR technologies based CSP plants are summarized in Table 1. Due to dual-axis tracking, the point focused CSP systems can achieve relatively higher concentration ratio leading to higher operating temperatures than the line focused (single-axis tracked) concentrators. Around 114 CSP plants (including commercial, demonstration, prototype, research and development type) with a cumulative installed capacity of 6.5GW are reportedly operational at present in different parts of the world (Aqachmar et al., 2019; CSP.guru, 2020; SolarPACES, 2020). Relevant details of some operational and under construction CSP plants are given in Tables 9 and 10, respectively of Appendix 1.

As mentioned earlier, the heat collected by the solar concentrators is utilized to generate steam that can be used directly for power generation or can be stored for use in off sunshine hours (Jegadheeswaran & Pohekar, 2009; Jian et al., 2015; Kuravi et al., 2013; Laing et al., 2006; Xu et al., 2015a, b). The steam is usually expanded in a steam turbine (usually in a Rankine cycle) to produce electricity (Besarati & Goswami, 2017; Stein & Buck, 2017). The exhaust steam from the turbine is fed into a condenser in which the latent heat of vaporization of steam is transferred to the available cooling medium (Holbert & Haverkamp, 2009). Based on the approaches used for cooling the exhaust steam, the condenser cooling technologies can be termed as wet, dry, and hybrid cooling.

High annual direct normal irradiance (DNI), adequate land area, and sufficient water availability are some of the essential requirements for the deployment of CSP plants (Bouhal et al., 2018; Broesamle et al., 2001; Chien & Lior, 2011; Corral et al., 2012; Fluri, 2009; Hinkley et al., 2013; Sharma et al., 2015a, b; Sundaray & Kandpal, 2014). While the first two requirements are more likely to be satisfied in arid regions, sufficient water availability may not be possible due to low rainfalls (Meyer et al., 2012; Xu et al., 2016). This fact can also be observed from Table 2 that summarizes the characteristics (such as annual DNI and rainfall) of few potential locations in the world. In such locations, the CSP plants with wet cooling technology may not be feasible. Hence it is imperative to explore and consider alternative condenser cooling options that are water conserving (Colmenar-Santos, et al., 2014a, b; Macknick et al., 2012; Shirazi, 1972).

One of the possible approaches to reduce the water requirement in CSP plants is the use of dry cooling technology (also referred to as air-cooling system or air-cooled condenser) (Wagner & Kutscher, 2010a). Alternatively, a hybrid cooling technology that partially combines the desirable features and characteristics of both wet and dry cooling technologies could also be considered for CSP plants in arid regions (Hu et al., 2018; Turchi et al., 2010a, b).

In view of the above discussion, the present paper aims to present a detailed review of available literature to examine the suitability of condenser cooling technologies for CSP plants in different climatic zones. Various aspects of condenser cooling technologies, including technical characteristics, water requirements, thermal performance (in terms of energy and exergy), as well as economic and environmental implications have been included in the review.

The organization of the paper is as follows: Sect. 2 presents the classification of three condenser cooling technologies. Detailed comparison of the cooling technologies based on technical characteristics, water requirement, thermal performance, economic and environmental aspects is presented in different sub-section of Sect. 3. Recent advancements reported in the literature for condenser cooling technologies is presented in Sect. 4, followed by conclusion drawn from the study in Sect. 5.

Table 1 Salient features of concentrating solar technologies based power plants (Aseri et al., 2020a; Baharoon et al., 2015; IEA 2010; IRENA 2012; Islam et al., 2018; Purohit & Purohit, 2017; Sharma et al., 2015a, b; Xu et al., 2016)

Characteristic	Unit	LFR	PTC	CTR
Concentrator type	–	line focus	line focus	point focus
Concentration ratio (range)	–	70–80	25–100	300–1000
Maximum cycle temperature (approx. range)	°C	250 – 400	393 – 550	565 – 680
Annual capacity utilization factor-without storage (range)	%	17–22	18–23	20–24
Annual solar-to-electricity conversion efficiency (range)	%	8–12	10–16	20–35
Foot print required (range)	km^2/MW	0.02–0.045	0.025—0.04	0.045 -0.084
Possible power cycle	–	Steam and/or organic Rankine cycle	Steam and/or organic Rankine cycle	Air/supercritical CO_2 Brayton cycle and/or steam/organic Rankine cycle
Heat transfer fluid	–	Water/steam	Synthetic oil, water/steam, molten salt	Water/steam, molten salt, air
Thermal energy storage	–	Direct and indirect 2-tank molten salt storage	Direct and indirect 2-tank molten salt storage	Direct 2-tank molten salt storage

Table 2 Few potential locations across the globe with the availability of annual DNI and annual rainfall

Country	Location	Annual DNI (kWh/m$_2$)	Annual Rainfall (mm)	References
Algeria	Sahara Desert	2661	12	(Boukelia & Mecibah, 2013; NASA, 2020)
Australia	Wheatbelt	2332	337	(Clifton & Boruff, 2010; NASA, 2020)
Chile	Atacama Desert	2814	15	(Corral et al., 2012; NASA, 2020)
China	Qinghai	2329	191	(Li et al., 2014; NASA, 2020; Zhang et al., 2009)
	Xinjiang	2237	125	
India	Barmer	2051	221	(NASA, 2020; Purohit & Purohit, 2017; Ramachandra et al., 2011; Sundaray & Kandpal, 2014)
	Kutch	2037	304	
	Thar desert	2049	189	
Kenya	Marsabit	2307	315	(Gathu et al., 2017)
Mongolia	Gobi Desert	2223	260	(NASA, 2020; Zhang et al., 2009)
Oman	Duqum	2581	34	(Charabi & Gastli, 2010; NASA, 2020)
Pakistan	Quetta	2544	167	(Bhutto et al., 2012; NASA, 2020)
Saudi Arabia	Riyadh	2438	38	(Kassem et al., 2017; NASA, 2020)
	Tabuk	2665	15	
South Africa	Kalahari Desert	2510	386	(NASA, 2020; Zhang et al., 2013)
Turkey	Adana	2329	593	(Kaygusuz, 2011; NASA, 2020)
USA	Mojave Desert	2554	171	(NASA, 2020; Zhang et al., 2013)

2 Condenser cooling technologies

As mentioned earlier, the condenser cooling technologies can be classified as wet, dry, and hybrid types. Each technique can further be divided into different sub-categories as presented in Fig. 2. The details of various condenser cooling technologies are presented in the following sub-sections.

2.1 Wet cooling technologies

Due to high heat capacity and the possibility of re-use, water has been traditionally used as a cooling medium in wet cooling technology. Wet cooling technology requires substantial amount of water (3.5 – 4.0 m^3/MW/h) for condenser cooling (CEA, 2012; Martín & Martín, 2013). The wet cooling technology can be the open-loop type or closed-loop type (Fig. 3). The open-loop wet cooling technology makes use of water from an open-source (such as a river or a lake) in the vicinity of the plant. The water at a relatively lower temperature than the ambient temperature is fed directly into the condenser for cooling and after the use, relatively warmer water is fed back into the source. There may be environmental restrictions on the use of open-loop wet cooling technology due to its adverse effects on the water body owing to the elevated temperature of the return water from the condenser (Kablouti, 2015). The closed-loop wet cooling technology requires evaporative cooling towers to cool the warm water prior to its re-circulation into the system. Majority of the wet-cooled thermal power plants are closed-loop type (CEA, 2012; Martín & Martín, 2013).

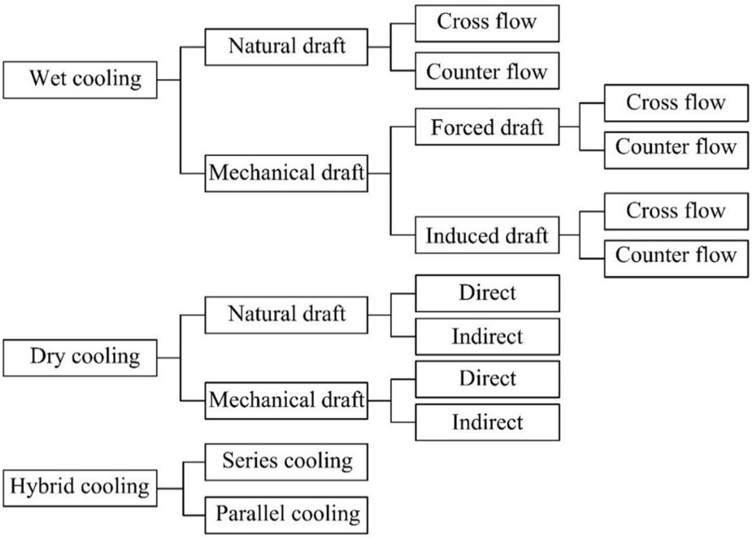

Fig. 2 Classification of condenser cooling technologies

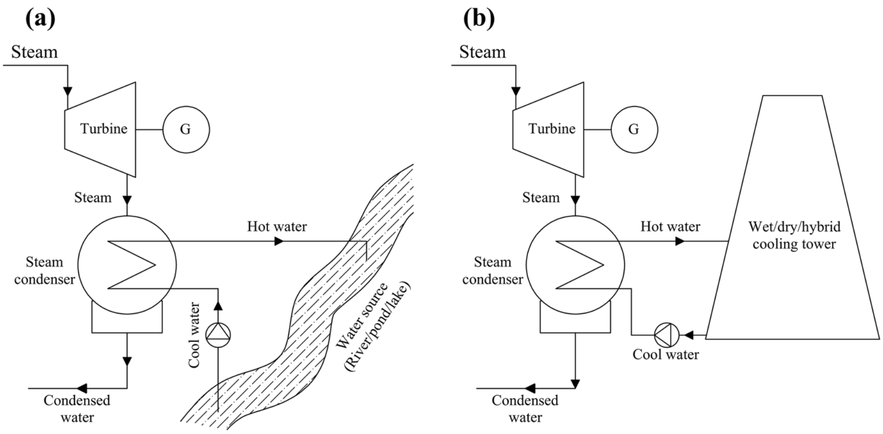

Fig. 3 Type of wet cooling technology **a** open-loop and **b** close-loop

The cooling tower in a closed-loop type wet-cooled technology can be based on (a) mechanical draft (forced or induced) and (b) natural draft (Fig. 4). In the case of the mechanical draft-based cooling tower, the hot water enters from the top of the tower in the form of a spray (using nozzles) and flows downwards through the tower. The fill is utilized to enhance heat and mass transfer by providing large contact surface area and enough contact time for water and air within the limited area of the wet cooling tower. Based on the location of fans deployed (at top or bottom) to draw the ambient air, the tower can be termed as induced draft or forced draft. Ambient air is drawn into the tower with the help of fans and flows in a counter or cross-current manner to the water stream and based

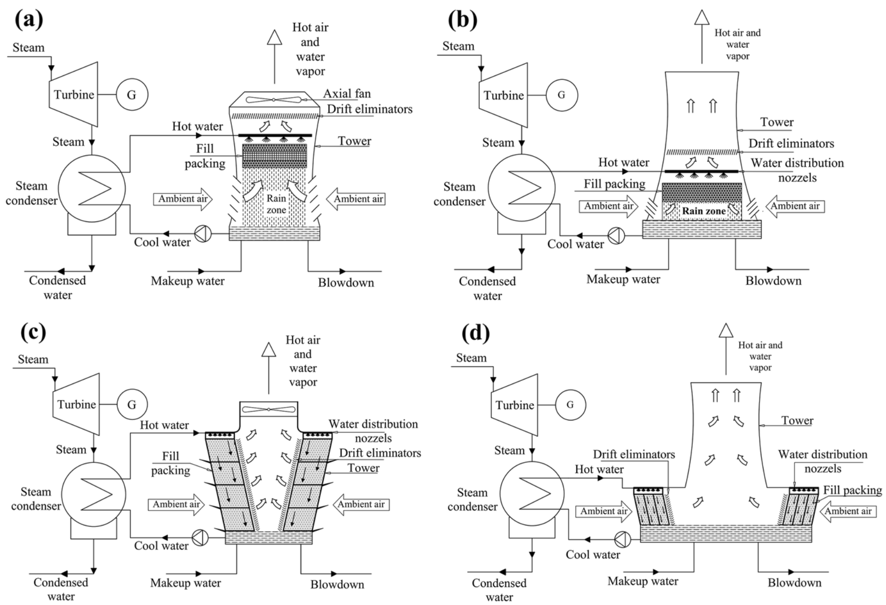

Fig. 4 Schematics of closed-loop **a** counterflow mechanical (induced) draft and **b** counterflow natural draft, **c** crossflow mechanical (induced) draft and **d** crossflow natural draft wet cooling technologies

on this flow direction, the tower may also be classified as counterflow type or crossflow type. However, the natural draft cooling towers do not use fans and make use of the buoyancy effect of the heated air, generated due to the hyperbolic shaped structure of the cooling tower (Basu & Debnath, 2015). Figure 4 shows schematics of closed-loop wet cooling technologies involving mechanical and natural draft type systems with counterflow and crossflow arrangements. Since in the wet cooling technology, the cooling process is governed by many factors that include thermodynamic properties of the surrounding air, the heat rejection process inside the cooling tower occurs in two modes: (i) sensible heat mode and (ii) latent heat mode (Duan et al., 2012; Rubio-castro et al., 2011). The latent heat of vaporization accounts for 80–90% of the total heat removal from the system (Colmenar-Santos, et al., 2014a, b).

2.2 Dry cooling technologies

In this type of cooling, the warm water and the ambient air do not have direct contact with each other (as in wet cooling). Since there is no loss/evaporation of water in the dry cooling approach, the same is suitable for arid regions (Hooman et al., 2017). Dry cooling technology is expected to be relatively less expensive to maintain as compared to wet cooling technology since the requirement of chemical additives for water treatment is substantially reduced (Chou, 1973; González-Roubaud et al., 2017; Kutscher & Costenaro, 2002). Increasing restrictions (through environmental legislations) on thermal pollution caused by open-loop wet cooling, blow-down pollution, fogging and icing with the use of wet cooling towers have further necessitated the need for considering deployment of dry cooling technology (Hu & Englesson, 1977; Tyagi et al., 2012).

A dry-cooled heat exchanger usually consists of several finned tubes arranged in a row of A-frame (or delta) configuration, and each row consists of numerous cells. Each cell has several bundles of finned tubes arranged in parallel (Yang et al., 2011a). In dry cooling, heat is rejected to the surroundings by convection via extended or finned surfaces or tubes (Turchi et al., 2010a, b; Xiao et al., 2016). The dry cooling technologies can be classified as natural draft or forced draft and further into direct and indirect types (Duniam et al., 2018; Preez & Kröger, 1995; Vosough et al., 2011). Schematics of three forced draft A-frame type (direct and indirect type) and two natural draft indirect dry cooling technologies (crossflow and counterflow) are presented in Fig. 5. In the direct forced draft dry cooling technology (Fig. 5a), the steam exhaust from the turbine enters directly into the steam header through large pipes and flows down through the array of finned tubes (Zhang et al., 2015). The heat is rejected directly to the surroundings and hence no cooling water is needed. The direct dry-cooled technology does not require a separate surface condenser. However, the requirement of large header pipes and large capacity vacuum pumps limits its suitability for small capacity thermal power plants.

In an indirect forced draft dry cooling technology, two heat-exchangers operate simultaneously in series, as shown in Figs. 5b, c. The exhaust steam from the turbine is condensed in the non-contact type heat exchanger (Fig. 5b) or direct contact type heat exchanger (Fig. 5c) with the help of continued supply of cold water from the dry-cooled towers. The natural draft cooling tower does not require active fans like force draft cooling towers and works on the principle of buoyancy effect. The natural draft cooling tower can have counterflow (Fig. 5d) and crossflow (Fig. 5e) configurations.

The terminal temperature difference (TTD), defined as the temperature difference between the steam inlet temperature and outlet temperature of condensed water at the condenser, is used to assess the effectiveness of a condenser cooling technology. TTD plays a vital role in lowering the condenser pressure and subsequently, the efficiency of the power cycle of the plant. A direct contact type condenser system is capable of achieving very low TTD (~0.5 ºC) as compared to non-contact type surface condenser (~3–4 ºC) due to thermodynamic

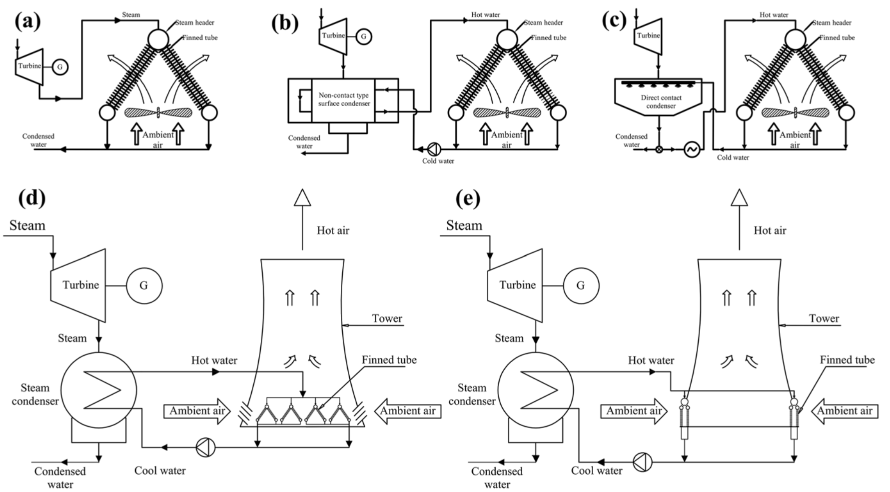

Fig. 5 Types of dry cooling technologies: **a** direct type forced draft, **b** indirect type forced draft with non-contact type surface condenser, **c** indirect type forced draft with direct-contact type surface condenser, **d** indirect type counterflow natural draft **e** indirect type crossflow natural draft cooling tower

irreversibility involved (Balogh & Szabo, 2005). Such irreversibility (essentially due to additional heat exchanger) is likely to increase turbine back-pressure resulting in reduced power cycle efficiency (Stallings, 2012). Moreover, the capital cost as well as the cost of operation and maintenance also increases. In the direct contact type condenser, as shown in Fig. 5(c), the exhaust steam is condensed by the spray of cold water received from the dry-cooled condenser.

While the thermal performance of wet-cooled plants depends on wet bulb temperature and moisture content of the ambient air, the performance of dry-cooled plants depends on several factors including dry bulb temperature of the ambient air. Thus, the year-round variation in dry bulb temperature significantly affects the performance of a dry-cooled condenser (Conradie & Kröger, 1996; Kashani et al., 2013; Kröger, 2004a, b; Kuppan, 2000; Duniam et al., 2018; SPX, 2013; Wei et al., 2017; Xi et al., 2014). On days with relatively higher ambient temperatures, the condenser temperature is comparatively higher, resulting in higher condenser pressure and lower turbine efficiency, consequently leading to lower net electricity generation (Gao et al., 2010; Kong et al., 2017; Su et al., 1999; Xia, et al., 2017; Zhao et al., 2015a, b; Zou & He, 2015).

2.3 Hybrid (wet/dry) cooling technologies

The hybrid cooling technology reduces water consumption significantly as compared to that of wet cooling plants, whereas the extent of reduction in electricity output is also much lower as compared to that with dry cooling plants (Rezaei et al., 2010). Hybrid cooling technologies can be divided into two broad categories: series type (plume abatement) and parallel type (water conservation). In the series type hybrid cooling technology (Fig. 6a), the steam first enters the dry cooling section where it loses its heat to the incoming ambient dry air, and then it enters the wet cooling section (Barigozzi et al., 2011). On the other hand, in the parallel cooling hybrid technology (Fig. 6b), there are separate sections for dry and wet cooling (Poullikkas et al., 2011). However, the dry cooling section remains the primary heat rejection section to be used for majority of the time. The percentage of hybridization represents the operational hours of the dry cooling technology as a fraction of the total annual operating hours of the plant (Golkar et al., 2019). The stand-alone operation of either wet cooling tower or dry cooling tower is possible only in parallel type hybrid cooling technology. In other words, on days with comparatively higher ambient temperature, the performance of the plant can be enhanced by routing a major fraction of the steam leaving the turbine to the wet cooling tower. By reducing the load on the dry-cooled condenser, the wet cooling tower can bring the value of condensate water temperature more closer to the design value to achieve design operating conditions of the power cycle (Delgado, 2012; Pistocchini et al., 2011). However, due to the involvement of both wet and dry cooling technologies, hybrid cooling technology has double thermal irreversibility and is relatively more expensive (Sarker et al., 2009). The same also leads to lower plant performance (though better than dry cooling technology alone) and higher parasitic consumption (but lower than dry cooling technology) as compared to a wet-cooled CSP plant (Heyns, 2008; Owen et al., 2017; Timur et al., 2012).

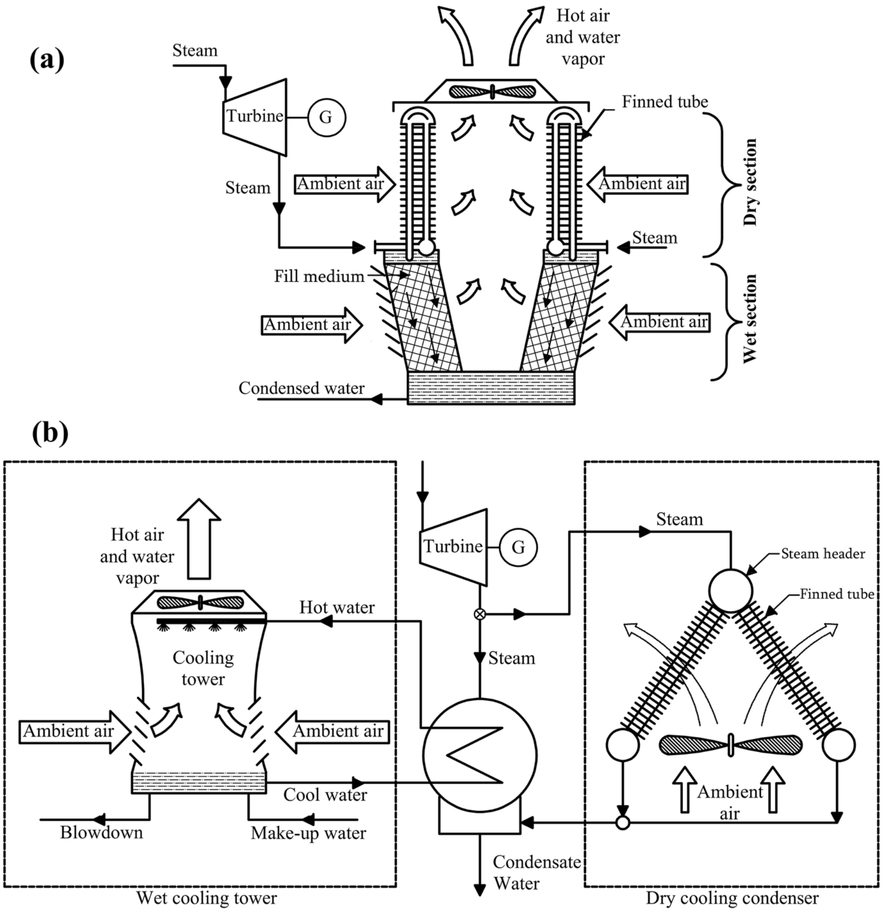

Fig. 6 Schematics of hybrid cooling technologies **a** Series cooling (plume abatement) and **b** parallel cooling (water conservation)

3 Comparison of condenser cooling technologies

The condenser cooling technologies (i.e., wet, dry, and hybrid) have variety of design, construction, operational, and performance related differences (Guerras & Martín, 2020). A comparison of different condenser cooling technologies on above-mentioned aspects as reported in the literature is presented in the following sections.

3.1 Technical characteristics

The suitability of a condenser cooling technology for CSP plants at any location primarily depends on the required temperature of cooling water (in the condenser) and availability of water (Palenzuela et al., 2013). Other factors that are significant in selecting an appropriate cooling technology include operational parameters of the power block, cost of operation and maintenance, parasitic energy consumption etc. (Carter & Campbell, 2009). Further, the PM_{10} pollution associated with wet cooling towers and high noise of fans of dry cooling condensers are typical environmental issues that also need to be considered before selecting a cooling technology (WorleyParsons, 2008). It is worth mentioning that PM_{10} are particulate matter having diameter less than or equal to 10 μm and the same can be inhaled by humans leading to adverse health impacts.

A comparison of some of the relevant technical characteristics of cooling technologies is presented in Table 3. While comparing the cooling technologies, the wet cooling technology has been assumed as the base case owing to its relatively superior thermodynamic performance. The positive (+) sign shows the additional requirement of that parameter/component as against its value in the base case, and the negative (-) sign indicates a correspondingly reduced requirement of that parameter/component. The details of different components required in wet, dry, and hybrid cooling technologies are presented in Table 4. A hybrid cooling technology requires relatively larger infrastructure as it comprises of components of both wet and dry cooling technologies. Unlike wet cooled plants, the dry cooled plants do not require waterside infrastructure and other related components such as water supply network, evaporation ponds, storage ponds, large treatment plants for condenser cooling water. As a consequence, for the dry-cooled plants, capital and operation and maintenance costs of these components are not involved (Fares and Abderafi 2018). However, dry cooling technology requires much larger amounts of steel and aluminum, thus increasing the cost of the system. Selection of a condenser cooling option for CSP plants requires consideration of variety of technical parameters (Tables 3 and 4) (Asdrubali et al., 2015; Lechón et al., 2008).

3.2 Water requirement

The water requirement of a power plant primarily depends on the type of condenser cooling technology used, plant design, quality of available water, and ambient conditions (Fares and Abderafi 2018). In wet cooling technology, evaporation, drift, and blowdown affect the water requirement. The range of water consumption in different cooling technologies i.e., closed-loop wet, open-loop (once-through) wet, hybrid (wet and dry), and dry type for coal-based, natural gas-based, and CSP based thermal power plants is shown in Fig. 7. Significantly large range of reported amounts of water requirement can be attributed to the variation in plant capacity, location of plant (hot, moderate or cold region), operating temperature (sub-critical, critical or super-critical) of power cycle, source and quality of water (surface water or groundwater) (Hashemi et al., 2021; He et al., 2014a, b; Kong et al., 2018; Kopac & Hilalci, 2007; Ma et al., 2015; Ming et al., 2012; Papaefthimiou et al., 2012; Valencia, 2011; Yang, et al., 2012a, b, c). It is worth mentioning that a CSP plant requires additional water for mirror washing and dust suppression (of solar field) (Hirbodi et al., 2020; Sharma et al., 2018). The water requirement in a dry-cooled CSP plant is for auxiliary purposes such as cleaning of cooling tower (finned tubes), steam cycle makeup, washing of mirrors in the solar field besides potable and service use (Boukelia et al., 2020). The water requirement of hybrid cooling technology depends on the mode of operation (i.e., series or parallel cooling).

A typical breakup of water requirement for different activities in coal-based plants and CSP plants is presented in Table 5. It may be noted that steam condensing in wet cooling technology consumes more than 80% of the total water required in conventional and CSP plants primarily due to continuous evaporation of water in the cooling tower (Pieve &

Table 3 Comparison between technical characteristics of wet, dry, and hybrid cooling technologies

Parameter	Type of condenser cooling technology			Reference(s)
	Wet	Dry	Hybrid	
Water consumption	Base case	(-)95 to (-)97%	(-)50 to (-)80%	(Bustamante et al. 2016a; Turchi, 2010, 2010a, b; Turchi et al., 2010a, b)
Electricity output	Base case	(-)4.0% to (-)10%	(-)3% to (-)5%	
Operation and Maintenance Cost	Base case	(-)2%	(+)8%	(Klein, 2013; Klein & Rubin, 2013)
Land use	Base case	(+)10 to (+)13%	(+)20%	
Parasitic load	Base case	(+)4 to (+)6 times base case	Up to (+)4 to (+)6 times base case	(Hawlader & Liu, 2002)
Evaporation losses	83% of make-up water	None	Same as the base case	(Burkhardt III et al. 2011)
Blowdown losses	13% of make-up water	None	Same as the base case	
Drift losses	4% of make-up water	None	Same as the base case	
Sludge generation	Yes	None	Yes	(DiFilippo & Maulbetsch, 2003)
PM_{10} emission	Yes	None	Yes	(EPRI, 2002)
Plume	Visible plume	None	None	(Chou, 1973; EPRI, 2002)
Noise level	Low	High	High	(EPRI, 2002; Mills et al., 2012; Poullikkas et al., 2011)
GHG emissions	Base case	(+)8 to(+)10%	(+)8 to (+)10%	(Burkhardt III et al. 2011; Whitaker et al., 2013)

Table 4 Hardware comparison between different cooling technologies for thermal power plants (NETL, 2011; Turchi, 2010, 2010a, b; Wolfe, 2007)

Component(s)	Type of condenser cooling technology			Remark (s)
	Wet	Dry	Hybrid	
Condensate tank	×	√	√	Needed indirect dry-cooled condenser
Tower basin	√	×	√	–
Steam surface condenser	√	√	√	Needed in indirect dry-cooled condenser
Steam duct support	×	√	√	
Cleaning system	√	√	√	For circulating water system in wet cooling For finned tube surfaces in dry cooling
Large-sized fan	×	√	√	–
Water supply/intake structure	√	×	√	–
Cooling water treatment/ blowdown discharge	√	×	√	–
Large water storage pond(s)	√	×	√	Relatively smaller size needed in a hybrid cooling technology
Drift eliminator	√	×	√	Required only in parallel mode of hybrid cooling technology

Salvadori, 2011). The activities such as sludge removal, coal dust suppression, and cleaning of electrostatic precipitators that require water in coal thermal power plants are not applicable for CSP plants (Weinrebe et al., 2014). To avoid scaling and corrosion of condenser tubes, cooling water containing dissolved solids is to be replaced with fresh makeup water. In coal thermal power plants, the blowdown water is likely to be used for the disposal of ash hence the same is not considered as water consumptive activity (CEA, 2012).

It is worth mentioning that the performance and plant output of the dry-cooled CSP plant is considerably lower than a wet-cooled plant. However, the same can be compensated by deploying additional solar collector field so as to generate nominal power output (Yilmazoglu, 2016; Zeyghami & Khalili, 2015). It is also worth mentioning that such an increase in the solar field would essentially require a relatively higher amount of water for washing of mirrors and steam-cycle make-up in the dry-cooled plants (Table 5) (Aseri et al., 2020b; DOE, 2006).

3.3 Thermal performance of condenser cooling technologies

The power output and consequently the efficiency of a thermal power plant is also governed by the operating temperature and pressure conditions of the condenser (Damerau et al., 2011; Delgado & Herzog, 2012; Deng & Boehm, 2011; Fthenakis et al., 2010; Wolfe et al., 2009; Xia et al., 2017). The effect of ambient wind direction and speed on the thermal performance of the cooling tower has been investigated by the researchers (Bender et al., 1996a, b; Derksen et al., 1996; Gao et al., 2008; Wang & Li, 2011). Some factors that decide the condenser operating temperature (or turbine backpressure) include ambient temperature of the location and the approach, cooling range and TTD of cooling towers (Fig. 8) (Tang et al., 2013). The approach of the cooling tower is the temperature difference between the circulating water at the condenser inlet (or cooling tower outlet) and the

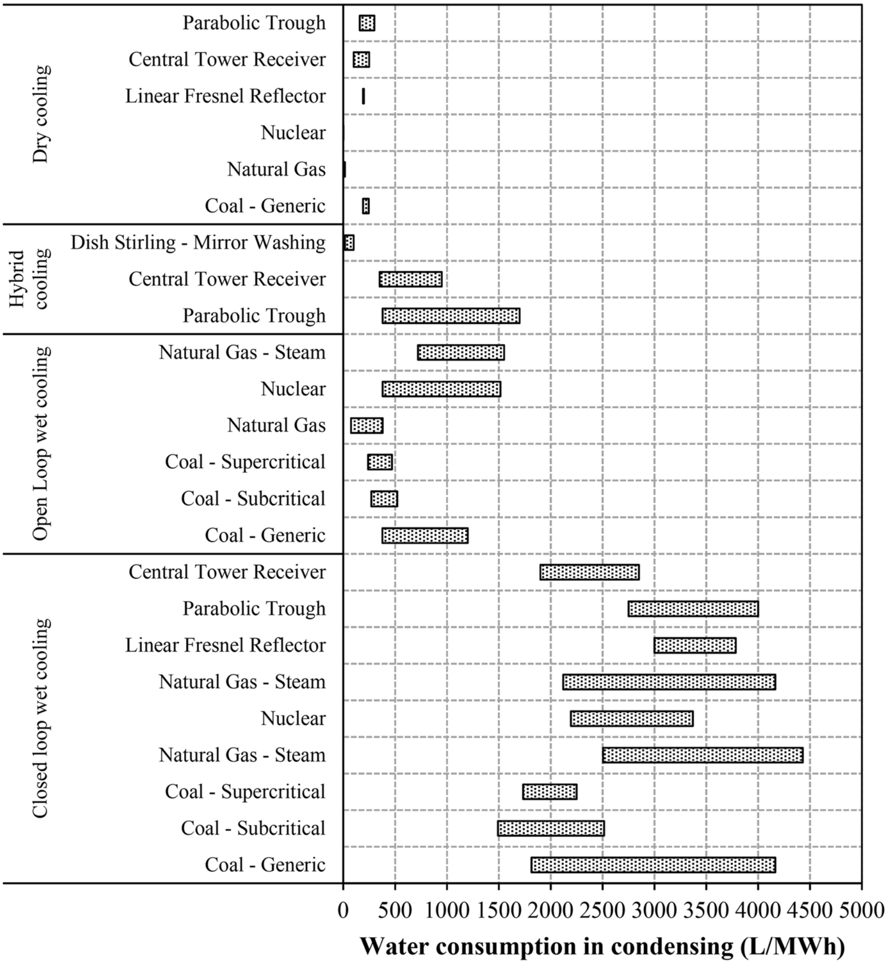

Fig.7 Water consumption in different cooling technologies (Ali & Kumar, 2016; Carter & Campbell, 2009; CEA, 2012; Cohen et al., 1999; Dawson & Schlyter, 2012; DOE, 2006; IT Power, 2011; Macknick et al., 2012; Meldrum et al., 2013; NETL, 2011; Poullikkas et al., 2013a; Purohit et al., 2013; Sharma et al., 2015a, b; TCEL, 2014; Turchi, 2010, a, b;Turchi et al., 2010a, b; DOE 2009; WorleyParsons et al. 2008)

wet-bulb temperature (for wet cooling technology) or dry bulb temperature (for dry cooling technology) of the surrounding. The cooling range of any cooling tower is the temperature gain by circulating cooling water across the condenser or in other words, the temperature difference between hot water inlet and cold-water outlet of the cooling tower under design conditions. The sum of TTD, approach, and cooling range is termed as initial temperature difference (ITD) (Mittelman & Epstein, 2010). To obtain better performance from a cooling tower, the range should be high, and the value of the approach, ITD, and TTD should be low(Baker et al., 2014; O'Donovan & Grimes, 2014; Poullikkas et al., 2013a, b, c; Wagner & Kutscher, 2010b). The design values of ITD govern the size (or surface area) of cooling system and the same can be optimized by economic and performance analysis between the primary energy source, cost of cooling technology, parasitic load and net

Table 5 Break-up of water requirement in different activities of coal thermal and PTC based CSP plants (CEA, 2012; TCEL, 2014; Turchi, 2010, 2010a, b)

Activity	Coal thermal power plant	PTC based CSP plant	
	Wet cooling (litre/MWh)	Wet cooling (litre/MWh)	Dry cooling (litre/MWh)
Steam condensing	3450	3465	–
Blowdown	70	68	–
Steam-cycle make-up	40	39	56
Cleaning of cooling tower	–	–	9
Mirror washing	–	119	129
Clarified sludge	110	–	–
Coal dust suppression	70	–	–
Electrostatic precipitator cleaning	5	–	–
Raw water loss due to evaporation	139	139	–
Potable and service water	250	250	250
Total water requirement	4134	4080	444

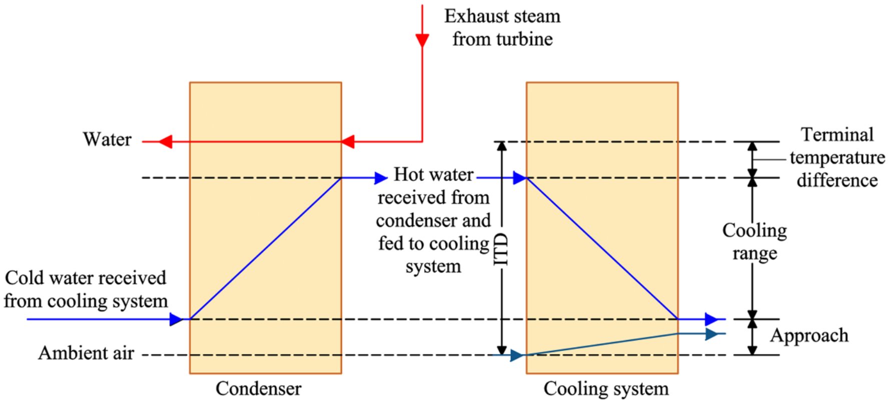

Fig. 8 Temperature terminologies used in close-loop condenser cooling technology

power output from the power plant (Bustamante et al., 2016). In case of dry-cooled heat exchanger based cooling technologies, larger the surface area (and/or more airflow rate), smaller the ITD and consequently lower condensing temperature. On the other hand, the increased surface area implies an increase in capital and operational costs (Wilber & Maulbetsch, 2005). Though to achieve lower condenser pressure, smaller ITD is desirable, the same is expected to increase the number of cells resulting in higher parasitic load (Kelly 2006; Village, 2006).

3.3.1 Thermal performance of wet cooling technologies

Investigations on the thermal performance of wet cooling technologies have been reported in the literature (Khan et al., 2004; Lemouari et al., 2007; Muangnoi et al., 2008; Zheng et al., 2012). A preliminary thermodynamic investigation of a wet cooling tower was undertaken by Walker et al. (1923). In 1925, a numerical model was proposed by Merkel (Merkel, 1925) to evaluate the thermal performance of a counter-flow type wet cooling tower. Since then, this model has been widely used with few modifications by the researchers for analysing the thermal performance of the wet cooling towers (Baker & Shryock, 1961; Guo et al., 2017; Mesarovic, 1973; Osterle, 1991; Spangemaher, 1958; Stabat & Marchio, 2004; Xia et al., 2011). The Merkel theory (Merkel, 1925) was relatively simple and is based on several assumptions such as (a) the loss of water mass due to evaporation is negligible, (b) the air exiting the tower is fully saturated with water vapor, and (c) the Lewis number (Le_f) is equal to the unity (Kloppers & Kröger, 2005a, b, c; Kloppers & Kröger, 2004). The Lewis number is the ratio of thermal diffusivity to mass diffusivity and is used to characterize fluid flows (water and air in a cooling tower) for correlating heat and mass transfer between fluids (Lewis, 1922; Yarin, 2012). However, the predicted performance of cooling towers using Merkel theory was observed to be less reliable and less accurate (Gudmundsson, 2012; Ibrahim et al., 1995; Kloppers & Kröger, 2005a; Lucas et al., 2009; Papaefthimiou et al., 2006; Wu et al., 2010). Apart from these observations, the Merkel theory is still in practice and used by several researchers to predict the thermal performance of wet cooling towers (Chen et al., 2020; Wei et al., 2020; Zhang et al., 2020).

The other proposed models for analysing the thermal performance are (a) ε-NTU model (Jaber & Webb, 1989) and (b) Poppe model (Poppe & Rogener, 1991). These models take into account the rate of change of air temperature, water temperature, humidity ratio and water mass flow rate along the height of the cooling tower to estimate its overall thermal effectiveness. The detailed procedure to solve governing equations of the Merkel, ε-NTU and Poppe methods was presented by Kloppers and Kröger (2005b) for wet cooling tower. Recently, the artificial neural networks (ANN) approach has also been applied with a reasonably high degree of accuracy to predict the thermal performance of wet cooling towers (Abbassi & Bahar, 2005; Gao et al., 2009; Hosoz et al., 2007; Islamoglu, 2005; Qi et al., 2008; Wu et al., 2018). It is reported that the ANN approach is appropriate to model and solve complex problems using input and output variables without taking into account complex thermodynamic correlations (Anderson, 1995; Samarasinghe, 2006; Song et al., 2021; Wu et al., 2011; Xu et al., 2015a, b).

Many researchers have presented numerical and experimental analyses to investigate the thermal performance and heat and mass transfer mechanism of wet cooling technology (Bernier, 1994; Bernier & Braun, 1995; Braun et al., 1989; Cortinovis et al., 2009; Fisenko & Petruchik, 2005; Fisenko et al., 2004; Goshayshi & Missenden, 2000; Goshayshi et al., 1999; Hajidavalloo et al., 2010; Haussler & Karl-Marx-Stadt, 1977; Inazumi & Kageyama, 1975; Lucas et al., 2009; Martín & Martín, 2017; Naik et al., 2017; Xuan et al., , 2012a, b; Zhao et al., 2016). Numerical studies have investigated the interaction between water and air (Al-Waked & Behnia, 2006; Dessouky et al., 1997; Gan et al., 2001; Goodarzi & Ramezanpour, 2014; Khan & Zubair, 2001; Klimanek & Białecki, 2009; Klimanek et al., 2015), whereas the experimental studies emphasized the interaction between falling water film, fill packing geometry, water–air interaction, and rising air stream inside the cooling tower (Heidarinejad et al., 2009; Khalifa, 2015; Kim et al., 2011). In a wet cooling tower, the amount of heat transferred (heat lost by the hot water stream and the heat gained by air stream) is characterized by tower characteristic number, i.e., Merkel number (Me_M) and the ratio of mass flow rates of hot water received from the condenser and that of the ambient air stream (liquid-to-air mass flowrate ratio, L/G) (Lemouari et al., 2007). Under the given set of operating conditions, Merkel number correlates the cooling tower design and operating parameters to the amount of heat (sensible and latent) that could be removed

(Dessouky et al., 1997; Khan et al., 2004; Kloppers & Kröger, 2003). With an increase in L/G ratio, Merkel number decreases leading to lower performance of the cooling tower (El-Dessouky, 1993).

To ensure quality standards of cooling towers for wet cooling technology, the technical guidelines for testing and rating of thermal performance of open-loop and close-loop wet cooling towers (natural and mechanical) have been developed by International Organization for Standardization, Switzerland in 2014 and published as ISO 16,345:2014(ISO, 2014). Cooling Technology Institute (CTI, 2016), a USA based organization has also developed a standard namely CTI Standard 201 for testing and rating wet cooling towers on various characteristics including thermal performance, sound test, drift emissions, plume abatement etc.

Exergy analysis has also been undertaken by the researchers to compare the thermal performance of different condenser cooling technologies (Ataei et al., 2008; Ghazani et al., 2017; Wepfer et al., 1979). Muangnoi et al. (2007) compared experimental results with analytical results to predict the exergy performance of a counterflow wet cooling tower. The study provides a systematic approach to predict the exergy of water and air along the tower height considering the effects of inlet dry bulb temperature and relative humidity. Qureshi and Zubair (2007) have performed a parametric study to estimate the exergy efficiency and exergy destruction as a function of wet bulb temperature of inlet air for a counter-flow wet cooling tower.

It was observed that most of the studies dealt with the effect of design and thermodynamic parameters such as water to air mass flow rate ratio, ambient conditions, type of packing material, water spray conditions etc. on the outlet water temperature and the thermal effectiveness/ behavior of the cooling tower. It has been observed that with the increase in contact time between water and air, increase in packing layer (or density), decrease in ambient temperature (in winters), the performance of wet cooling towers is likely to enhance.

3.3.2 Thermal performance of dry cooling technologies

Several studies have investigated experimentally and numerically the thermal performance of dry cooling tower considering the effect of surrounding wind characteristics, physical size of tower, nearby building structures, and plume recirculation (Al-waked, 2010; Al-Waked & Behnia, 2004; Borghei & Khoshkhoo, 2010; Bredell et al., 2006; Chen et al., 2016a, 2016b; Ghasemi et al., 2016; Gu et al., 2015, 2016; Lu et al., 2016; Reshadatjoo et al., 2011; Seifi et al., 2018; Yang et al., 2011b, 2013; Zhao et al., 2015a, b; Zhou et al., 2018). It has been reported that in order to assess thermodynamics performance, the flow pattern of ambient wind and its visualization is necessary, and the same can be accomplished by using iterative procedures or numerical simulations (Goodarzi, 2010; Lin et al., 2020; Wu et al., 2014; Yang et al., 2012a, b, c; Yanget al., 2012a, b, c; Zhai & Fu, 2006). The effect of the height to diameter ratio of the tower on its thermal performance is also studied using computational fluid dynamics (Liao et al., 2015). The study observed that for the same heat transfer surface area, the performance of a tower with lower height to diameter ratio is relatively better than a tower with higher height to diameter ratio under high wind speeds (15 – 20 m/s).

The effects of crosswinds on the performance of an indirect natural draft dry-cooled condenser have been analyzed by (Li et al., 2017a, b, c). Another study suggested that increasing the wind-wall height and accelerating the rotational speed of the fans near the edge of dry-cooled heat exchanger reduces the exhaust plume recirculation, effectively leading to enhanced heat transfer (Liu et al., 2009). The effect of wind speed and wind direction on the flow field near the direct type dry-cooled condenser platform has also been tested experimentally based on wind tunnel simulation (Gu et al., 2007). It is reported that the plume re-circulation caused by interference from nearby buildings and structures could significantly reduce the performance of dry-cooled condenser. However, by raising the height of the platform, recirculation can be reduced by 30% for wind speeds between 4 and 10 m/s. The effect of cross-flow wind on intake flow of air has also been studied by researchers (He et al., 2014a, b; Hotchkiss et al., 2006; Meyer, 2005). Zhang and Chen (2015) measured the thermo-flow characteristics of direct dry-cooled condenser using windbreak mesh by considering variation in ambient wind velocity. By installing rectangular type windbreak mesh below the platform, and nearby steel supporting structure of condenser, the volumetric effectiveness of fan improves due to protective effect. Yang et al. (2010) have presented the effect of back pressure on the performance of a direct type dry-cooled condenser under different wind conditions. It is observed that a significant reduction in re-circulation of the exhaust plume is possible by extending windscreen, using flow guiding devices and by increasing peripheral edge of a dry-cooled condenser. The results show that using the above mentioned measures, a reduction of the order of 1–6-5.0 kPa in back pressure of the turbine could be achieved.

For the sizing and designing of dry cooling technology, the selection of appropriate mathematical expressions and empirical correlations for non-dimensional numbers is critically important (Kumar et al., 2015; Zheng et al., 2015). The choice of design parameters and material to be used for finned tube heat exchanger is based on the fluid temperature, fouling and cleanability, nature of environment, and cost. Flow parameters govern the convection mode of heat transfer on either side of finned tubes and the same is characterized by Reynolds number, bulk mean temperature of the fluid, and overall heat transfer coefficient (Çengel & Ghajar, 2015). The operational performance of a dry cooling technology can be estimated by a non-dimensional number termed as Colburn factor (Moore et al., 2014a, b), whereas the heat transfer performance is characterized by the Nusselt number and friction factor (Lu et al., 2015). While the value of the Reynolds number helps to define the flow regimes of the fluid (water/steam) inside of the finned tubes, Colburn factor, Nusselt number and friction factor usually denote heat, momentum, and mass transfer for finned tubes of dry-cooled condenser (Kim & Bullard, 2002; Pongsoi et al., 2013; Ryu & Lee, 2015; Wen & Ho, 2009; Wongwises & Chokeman, 2005). The detailed design of dry-cooled heat exchangers and cooling towers has also been reported (Kloppers and Kröger, 2004a, b; Kloppers & Kröger, 2004).

To ensure the quality standards of dry-cooled heat exchangers likely to be used in petrochemical industries, the International Organization for Standardization, Switzerland has developed technical guidelines for design, fabrication, inspection and testing in the year 2000 (ISO 13,706). The latest applicable revision for the same is ISO 13,706:2011 and the same is applicable for horizontal finned tube bundle heat exchanger also. The basic concept can also be used for dry-cooled heat exchanger for different orientations of bundled tubes (ISO, 2011).

The natural draft dry cooling system is gathering considerable attention due to no active power consumption involved. Several studies have been reported considering effect and characteristics of ambient wind on thermo-flow performance of natural draft dry cooling tower (Al-Waked & Behnia, 2004; Goodarzi, 2010; Goodarzi & Keimanesh, 2013). Chen et al. (2016b) have investigated the effect of windbreakers (exterior and interior) on thermal performance of natural draft tower considering different ambient wind conditions. The study suggested that the exterior windbreakers are relatively more effective than the interior wind breaker and help in reducing turbine back pressure. Lu et al., (2013 and 2014) have studied small (15 m) natural draft dry cooling towers without windbreakers with prevalent unfavourable behaviour of crosswind (with different directions and attack angles) and proposed that installing windbreakers against the zero and sixty degree angle of wind, the negative impact turns into positive and enhances thermo-flow performance. The Khi Solar One' plant installed in South Africa and operational since 2015 is one of its kind as it integrates receiver tower on to a natural draft air-cooled condenser (Yang et al., 2017).

Though several studies have been reported that deal with the exergy analysis of dry-cooled power plants including coal (Al-Soud & Hrayshat, 2009; Kotas, 1980), geothermal (DiPippo, 2004; Kamel Hooman, 2010; Kanoglu & Bolatturk, 2008; Kanoğlu & Çengel, 1999; Walraven et al., 2015; Yari, 2010), cogeneration (Colpan & Yeşin, 2006)) plants, limited literature is available for solar thermal power plants with dry-cooling technology. Blanco-Marigorta et al. (2011) presented an exergetic comparison for a 50 MW CSP plant with wet-cooled and dry-cooled condenser. The study estimated that at a condenser pressure of 0.063 bar, the exergy destruction in the wet-cooled condenser is only 1.7% whereas the same for dry-cooled condenser is more than 7%. Another study (Habl et al., 2012) with same kind of plant configuration has assessed energy, exergy, and exergo-economic analysis for wet and dry-cooled CSP plants. From an energetic point of view, the study estimated that output of the plant with dry-cooled condenser is 2.54 MW lower than that with wet-cooled plant due to three times more parasitic load in dry-cooled condenser. The study also estimated the exergy efficiency for a plant with wet cooling and dry cooling as 79.8% and 74.5% respectively. Component wise energy loss and exergy destruction for dry-cooled condensers have been estimated by Aljundi (2009) under varying ambient temperatures from 10 to 45 °C. The study observed that two-thirds of the fuel energy is lost to the environment via condenser. However, exergy destruction is more in boiler (77%) followed by turbine (13%), and dry-cooled condenser (9%).

3.3.3 Thermal performance of hybrid cooling technology

Hybrid cooling technology comprises characteristics of both wet cooling, and dry cooling technologies, and individual performance of wet and dry cooling technologies are also applicable for hybrid cooling technology. Therefore, the percentage of hybridization of wet and dry cooling technologies depends on design parameters, the methodology adopted to use cooling system to save envisaged annual condenser cooling water requirement. Wagner and Kutscher (2010a)have assessed the performance of hybrid-cooled (parallel type) CSP plants and compared the results with the traditional wet-cooled CSP plant. The study has considered 85% and 50% hybridization of dry cooling technology. The study concluded that with 85% hybridization, the plant would generate 2.33% less electricity with a saving of 85% in the cooling water requirements. On the other hand, with 50% hybridization, there is only 1.67% performance penalty in terms of electricity produced and the reduction in water requirements is 52% as compared to the wet-cooled CSP plant. Similarly, Asfand et al. (2020) have evaluated thermodynamic performance and water consumption of a CSP plant with hybrid cooling in different configurations of wet-dry systems (series, parallel, series–parallel and parallel-series). The study suggested that in comparison to wet-cooled based plant, 50% and 30% water can be saved with series–parallel and parallel operating hybridization of a wet-dry cooling systems based plant. The performance of series and parallel type hybrid cooling systems was experimentally evaluated by Rezaei et al. (2010).

The study identified that series type hybrid cooling system performs better in summer than the parallel type hybrid cooling system.Effects of variations in ambient temperature and relative humidity on the thermodynamic performance of fossil fuel based thermal power plant with wet, dry and hybrid cooling systems have been investigated by Hu et al. (2018). Authors reported that the thermal performance of the cooling systems is more dependent on ambient temperature than the relative humidity. The study concluded that hybrid cooling system can not operate above and below certain value of ambient temperature and relative humidity of the surrounding. Sarker et al. (2009) have experimentally investigated the performance of the hybrid cooling system with finned tubes and found that the cooling capacity was 22% and 260%higher as compared to wet and dry cooling systems with bare tubes.Asvapoositkul and Kuansathan (2014) have proposed a computational approach to predict the performance of series type hybrid cooling tower and concluded that rate of air flow through the cooling tower has a major role and the same needs to optimized to enhance the performance. Nourani et al. (2019)have carried out comparative study between wet and hybrid cooling technology based refinery and thermal power plant and concluded that the hybridization up to 44% of dry colling tower with wet cooling tower can save water by 38%.

The thermal performance of hybrid cooling system depends on various factors includes liquid-to-air flow rate ratio, surrounding ambient conditions, type of hybridization (series or parallel) and seasons (winter and summer). It has been observed from the literature that under controlled conditions, hybrid cooling system can save significant amount of water in winter seasonby shifting more fraction of total cooling load towards dry cooling tower to acquire benefits of lower ambient temperatue. It is also worth mentioning that the capital as well as operating costs of hybrid cooling systems are relatively higher than the individual wet or dry cooling systems.

3.4 Economic considerations

Installation of dry or hybrid cooling technologies in place of wet cooling technology results in lower plant efficiency and a higher cost of electricity delivery (Aseri et al., 2020c; J. Hinkley et al., 2011). However, the extent of these penalties significantly depends on the ambient design conditions of the CSP plant (Baweja & Bartaria, 2013; Henry & Diemuodeke, 2021; Margolis et al., 2012; Musi et al., 2017; Patnode, 2006). Table 6 presents a comparison of the cooling options in terms of overall plant performance, capital cost, and levelized cost of electricity (LCOE) for PTC and CTR based CSP plants as reported in the literature. The dry and hybrid cooling options for PTC and CTR based plants have been compared with wet cooled PTC and CTR based plants. It is observed that a dry-cooled PTC based plant would deliver 3–10% less annual electricity output and would cost 4% to 10% more than a wet-cooled plant resulting in 2% to19% increase in LCOE. It was also observed that due to large differences in operating temperature of power cycle (560ºC for CTR based plants and 391ºC for PTC based plants), the reduction in net electricity output for CTR based plants is less as compared to PTC based plants (Sau et al., 2016).

Efforts have also been made to assess the techno-economic feasibility of wet-cooled and dry-cooled CSP plants in different parts of the world (Anders et al., 2005; DOE and EPRI 1997; Kelly 2006; Moser et al., 2014). Turchi (2010, 2010a, b) presented a detailed comparison of PTC based wet and dry-cooled CSP plants using System Advisor Model simulation tool developed by National Renewable Energy Laboratory, USA. It was observed that by replacing wet cooling with dry cooling technology, the cost of the plant increases

Table 6 Comparison of dry-cooled and hybrid-cooled plants with wet-cooled plant

Solar concentrating technology	Dry-cooled	Hybrid-cooled	Reference(s)
(A)Relative reduction in net annual electricity delivery (%) with respect to wet-cooled plant			
Parabolic trough collector	3 – 10	1 – 4	(Anders et al., 2005; Bustamante et al., 2016; DOE, 2009; DOE and EPRI 1997; Ikhlef & Larbi, 2020; Kelly & Kelly, 2006; Liqreina & Qoaider, 2014; Moser et al., 2014; Poullikkas et al., 2013a; Trabelsi et al., 2018)
Central tower receiver	1 – 3	1 – 3	(DOE, 2009; Poullikkas et al., 2013a)
(B) Relative increment in capital cost (%) with respect to wet-cooled plant			
Parabolic trough collector	4 – 12	2 – 3	(Aseri et al., 2021; DOE, 2009; IEA 2010; Kibaara et al., 2012; Andreas Poullikkas et al., 2013a; Turchi, 2010, 2010a, b)
Central tower receiver	1 – 5	2 – 5	(DOE, 2009; Poullikkas et al., 2013a)
(C) Relative increment in the levelized cost of electricity (LCOE) (%) with respect to wet-cooled plant			
Parabolic trough collector	2 – 20	8	(Anders et al., 2005; Aseri et al., 2021; DOE, 2009; DOE and EPRI 1997; IEA 2010; B. Kelly & Kelly, 2006; Kibaara et al., 2012; Liqreina & Qoaider, 2014; Moser et al., 2014; Andreas Poullikkas et al., 2013a; Turchi, 2010, 2010a, b; Vogel & Kalb, 2010)
Central tower receiver	2 – 8	5	(DOE, 2009; Poullikkas et al., 2013a; Vogel & Kalb, 2010)

by 10%, and LCOE increases by 7%. Liqreina and Qoaider (2014) studied the competitiveness of dry cooling in comparison to wet cooling in the arid zone of the Middle East and North Africa using Greenius software developed by the German Aerospace Centre (DLR), Germany. The study reported that the energy yield is reduced by 10.2% and LCOE is increased by 14.8% with the adoption of dry cooling. It is worth mentioning that there is significant difference in the reported LCOE of wet-cooled and dry-cooled plants for the two studies mentioned above. The reason for the same can be attributed to the fact that the nominal capacities, technical assumptions and financial parameters for the two studies are significantly different. Further, both the studies have used different simulation tools for the analysis.

The financial viability of selected cooling technology in CSP plants would also depend on the price of water in the area where the plant is proposed. The effect of the cost of water on LCOE for a PTC based plant with wet cooling and indirect dry cooling has been analyzed by Dersch and Richter (2007). Turchi et al., (2010a, b) presented an analysis of a PTC based plant located in Las Vegas, Nevada, USA. The study observed that the overall increment in capital cost (for a plant without storage) is only 4.2% and 6.9%, respectively for dry and hybrid-cooled plants. A lower increment in the capital cost of dry and hybrid plants is due to the fact that the cooling water storage pond and water treatment plant that are essential for a wet-cooled plant are not required in dry-cooled plant and only partially required in the hybrid-cooled plant. Moreover, the increment in capital cost would further reduce to 2.2% and 3.7% respectively, for dry and hybrid-cooled plants with six hours of storage capacity. The authors also reported that LCOE is increased by 8.1% for dry-cooled plant and 6.4% for the hybrid-cooled plant without thermal energy storage. In addition, the inclusion of thermal energy storage in the dry or hybrid cooling plant can reduce the overall penalty of LCOE considerably (8.1% to 6.3% for dry-cooled and 6.4% to 3.2% for hybrid cooled plants) as compared to wet-cooled plants.

3.5 Environmental considerations

Studies on life cycle assessment and $CO_{2\text{-eq}}$ emissions mitigation potential of power plants have also been reported in the literature (Burkhardt III et al. 2011; Corona et al., 2014; Heath et al., 2009; Lechón et al., 2008; Viebahn et al., 2011). Table 7 summarises the life cycle GHG emissions ($gCO_{2\text{-eq}}$/kWh) of different technologies used for electricity generation. As expected, the life cycle GHG emissions of renewable energy-based electricity generation options are significantly lower than those based on fossil fuel. However, environmental impacts of the solar field on humans and wildlife (such as glaring, killing of birds, etc.) may also need consideration (Ho et al., 2015). The other likely adverse effects of CSP plants on the environment arise from the use of hazardous materials, hydraulic fluids (coolants, lubricants, thermal oils and/or molten-salts) etc. (Hondo, 2005; Kommalapati et al., 2017; Xu et al., 2016).

The choice of condenser cooling technology may also have its implications. Cooling technologies may have adverse effects on nature (air, water, and land) and human health. For example, fine water droplets, visible plume formation, noise pollution, and humid environment would affect the ecology in the vicinity of the cooling towers (Richter, 2011). Moreover, the return of water into nearby lake or river at an elevated temperature in open-loop cooling technology is also a source of potential environmental hazard and could adversely affect the aquatic life and ecosystem (Bailey, 2012). As a consequence

Table 7 Reported lifecycle GHG emissions for different electricity generation options

Technology	Life cycle GHG emissions ($gCO_{2\text{-eq}}$/kWh)	Reference(s)
Conventional thermal power plants		
Coal	975.2–1001	(Hondo, 2005; Whitaker et al., 2013)
LNG	518—607	(Hondo, 2005)
Natural gas—combined cycle	480	(Whitaker et al., 2013)
Nuclear	22—24	(Hondo, 2005)
Renewable energy-based power plants		
Amorphous PV	16–50	(Sherwani et al., 2010)
Central tower receiver dry-cooled	32—42	(Whitaker et al., 2013)
Crystalline silicon PV	44—53	(Hondo, 2005; Whitaker et al., 2013)
Geothermal	15	(Hondo, 2005)
Hydro	11	(Hondo, 2005)
Parabolic trough dry-cooled	28	(Burkhardt III et al., 2012; Kommalapati et al., 2017)
Parabolic trough wet-cooled	26	(Kommalapati et al., 2017)(Burkhardt III et al. 2011)
Parabolic dish	24	(Kommalapati et al., 2017)
poly-crystalline PV	10—54	(Sherwani et al., 2010)
Solar chimney	34	(Kommalapati et al., 2017)
Wind	11—29	(Hondo, 2005; Whitaker et al., 2013)

the same may not be legally allowed in several countries. Bloemkolk and Schaaf (1996) have reported that suction of live organisms (microorganisms, fish, etc.) with the cooling water is also observed.

Consumption of water for a long time for condenser cooling may also affect local hydrology and eco-system (Carter & Campbell, 2009; Hernandez et al., 2014). As mentioned earlier, evaporation, blowdown, and drift in wet cooling towers leads to water loss, and evaporation accounts for significant loss of water (Uzgoren & Timur, 2015). The water loss due to blowdown is driven by the cycle of concentration (COC) in the cooling tower, which is defined as the ratio of the concentration of dissolved solids in the blowdown water and make-up water. The value of COC essentially defines the frequency of replacement of the circulating water in the cooling technologies with fresh (makeup) water. (Frayne, 2010; Pan et al., 2018). The same is a potential environmental hazard and is also likely to increase the operational cost as additional treatment of water is required to maintain the desired cooling water quality. Blowdown rates are set so as to limit the accumulation of impurities in the circulating water within prescribed limits (Kumar, 2017). Cooling tower operated at higher COC reduces blowdown losses but results in increased accumulation of impurities in the cooling water (Rubio-castro et al., 2011).

The water droplets (PM_{10} and $PM_{2.5}$) that leave the cooling tower are considered as drift loss. The drift losses are relatively small, but the water droplets may contain impurities of circulating water at significantly higher concentrations (Lamnatou & Chemisana, 2017). The droplet completely evaporates, but the contaminants remain in the atmosphere as fine particulate matter (PM_{10}), thus adversely affecting ambient air quality (Abbey et al., 1995; DiFilippo & Maulbetsch, 2003). A plume of water vapor emitted from the wet cooling tower is also considered a visible disturbance (Asvapoositkul & Kuansathan, 2014; Backer & William, 2003; Deng & Boehm, 2011).

A wet cooling tower may also suffer from 'Legionnaires disease' due to the formation of legionella bacteria in the water storage pond and inside the tower (Bentham & Broadbent, 1993; Lucas et al., 2012; Naik & Muthukumar, 2017; Ruiz et al., 2016). Humans are likely to inhale legionella in the form of aerosol-sized droplets of water that contain these bacteria in the surroundings of the cooling tower. The dry cooling technologies do not suffer from such a problem (Micheletti et al., 2002). Large numbers of cooling fans used in dry cooling technologies contribute to noise pollution (Bustamante et al., 2016). Noise levels depend on the size and types of fans used in the cooling systems. The use of ultra low-noise fans can significantly reduce noise pollution though the cost of cooling technology will increase (EPRI, 2002).

Life cycle GHG emissions and cumulative energy demand of dry-cooled plants are expected to be higher as compared to wet-cooled plants. The use of more energy-intensive materials, increased number of solar collectors, and correspondingly increased amount of heat transfer fluid contribute to relatively higher GHG emissions from dry cooled power plants (Burkhardt III et al. 2011). On the other hand, for a wet-cooled plant, the consumptions of significant amounts of water and the requirement of a large waterside structure contribute to GHG emissions. Out of a total value of GHG emissions, 1.35 $gCO_{2\text{-eq}}$ per kWh (0.30 $gCO_{2\text{-eq}}$ per m^3) may be attributed to water consumption in wet-cooled plants (M. Martín, 2015; Whitaker et al., 2013). Overall, the GHG emissions were observed to be 5% less for the wet-cooled plant as compared to the dry-cooled plant (M. Martín, 2015).

Comparing the three condenser cooling technologies on technical, economic and environmental aspects, it is observed that before deployment of thermal power plant, a location specific study is required considering long term resource availability. Preliminary observations suggest that the performance and cost of wet-cooled condenser technology are more favorable than the other condenser cooling options but at the same time it requires around 50–90% more water for cooling. Additionally, the environmental issues associated with wet-cooling technology are to be taken into consideration. From the viewpoint of solar thermal power plants, since these plants are likely to be installed in arid regions where adequate water may not be available for wet cooling technology, dry cooling is likely to replace wet cooling technology. Though presently the capital cost of dry cooled plant is higher and their electricity output is lower as compared to wet cooled plants, continuous efforts towards technological improvements along with cost reduction possibilities is likely to make dry-cooling technology more competitive in future as compared to wet cooling technology.

4 Recent advances in condenser cooling technologies

Significant efforts are being made to improve the efficiency of cooling technologies used in power plants. Several parameters have been identified (such as reduced water requirement and lower condenser temperature) that are expected to provide better efficiency and performance of these cooling technologies. Besides these, few advanced designs have also been proposed for wet, dry, and hybrid cooling technologies. For example, in wet cooling plants, modifications in the design parameters of wet cooling tower (such as range, approach, water-to-air flow rate ratio (L/G), etc.) are expected to vary the ratio of sensible to latent heat, resulting in reduction in evaporation losses (Fares and Abderafi 2018). Similarly, for dry cooling plants, methods have been proposed to achieve lower ITD (or lower condenser temperature) by improving the air-side heat transfer coefficient without increasing size of the condenser and parasitic load. The details of few advances in cooling technologies are presented in the following paragraphs.

4.1 Advances in wet cooling technology

The reduction in condenser pressure and water requirement in a cooling tower are two key areas of research to achieve better thermal performance. Several components of wet cooling towers such as drift eliminator and packing fill are likely to have scope for improvement. Design of an efficient drift eliminator can significantly reduce the amount of water losses that are carried by saturated air to the environment in the form of PM_{10} emission. However, it also tends to increase the pressure loss of air stream resulting in an imbalance of water to airflow ratio leading to increase in parasitic power requirements (Velandia et al., 2016). Based on shape, material and number of passes of the air stream, various kinds of drift eliminators have been tested and reported (Ruiz et al., 2017). Results show that a drift eliminator keeps drift losses typically in the range of 0.002% to 0.005%. Recently, Brentwood Industries, Inc, USA has developed a drift eliminator named as "CFUltra" that is expected to reduce drift losses up to 0.00025% (Brentwood, 2020). SPX Cooling Technologies, Inc. USA (Mortensen, 2009) has developed Air2Air™, a water conservation system, to recover water vapor in the wet-cooled tower. It is expected that with the use of Air2Air™ technology, around 10% to 15% water can be recovered depending on the local climate.

To reduce the evaporation losses and to increase the water–air contact area, Electric Power Research Institute, USA, has developed a 'dew point cooling tower' that helps in lowering cooling water outlet temperature and integrates plume abatement by modifying the flow path arrangement of air (Kozlov & Glanville, 2014). With this approach, water and parasitic power requirements are reported to be reduced by 45% and 74%, respectively (Glanville et al., 2011).

Fill or packing media in the wet cooling towers is another crucial component that has received significant attention of researchers and has been studied to assess the heat transfer performance of wet cooling towers (Lemouari & Boumaza, 2010; Lemouari et al., 2011; Smrekar, et al., 2011a, b; Smrekar, et al., 2011a, b). The packing media/fill is a porous/corrugated material and is used to enhance heat and mass transfer by providing large contact surface area and enough contact time for water and air within the limited space of the wet cooling tower. Based on the function, the fills can be broadly classified as splash, film, and trickle type (He, et al., 2015a, b; Khater, 2014). Splash fill is intended to break the large size water droplets into smaller water droplets while film fill converts thick water film into thin films, and trickle fill changes large water streams into small streams (Heet al., 2015a, b).

Several researchers have studied the thermal performance of mechanical draft wet cooling tower using addition of nanofluids in the inlet water so as to improve the heat removal phenomenon (Imani-Mofrad et al., 2016, 2018; Xie et al., 2017). Experimentally, the effects of carbon nanotubes and nanoporous graphene based nanofluids mixed with inlet water in the mechanical wet cooling tower have been investigated for thermal performance (Askari et al., 2016). Results show that under design conditions such as inlet water temperature (45ºC) and L/G ratio (1.37), the range of cooling tower can be enhanced by 40% with carbon nanotubes and 67% with nanoporous graphene nanofluids. It was also found that with these nanofluid the water consumption is also reduced up to 19%. A rotational splash type fill in mechanical draft counterflow wet cooling tower is experimentally evaluated by Amini et al. (2020) using aluminium oxide and copper oxide as nanofluid with distilled water as base fluid. The study found that the performance of tower under design conditions can be improved up to 11% and 5% by adding 0.1% (by weight) of aluminium oxide and copper oxide as nanofluid, respectively. It was observed that the thermal performance of tower can be improved with the use of nanofluid, and it depends on thermal and rheological properties of nanofluid alongwith operating conditions of the cooling tower. Recently, effects of zinc oxide as nanoparticles with three packing media on the thermal performance of wet cooling tower have been experimentally investigated by Rahmati (2021). In comparison to distilled water, authors have found that with increased layer of packing media (or density) along with addition of nanofluids by 0.1% (by weight), the cooling efficiency of tower can be increased by 11.1% under design conditions.

The thermodynamic performance of the wet cooling tower is also governed by water and airflow rates. Excessive water flow blocks the opening of the fill media and consequently restricts the flow of incoming air. On the other hand, reduced water flow leaves the fill media partially dry, causing a reduction in the performance of the cooling tower (Lemouari et al., 2009; SCT, 2020). Therefore, the cooling efficiency provided by the manufacturer under standard specific conditions for selected fill/packing media is applicable for cooling towers.

4.2 Advances in dry cooling technology

The performance of a dry cooling technology depends on the air-side convective heat transfer coefficient. Several advanced techniques have been reported to achieve lower condenser temperatures by improving the air-side heat transfer coefficient (Deziani et al., 2017). These include wetting of fins (Kröger, 2004a), spraying water on incoming dry ambient air (Xuan et al., 2012b) and introducing wetted media at the air inlet section (He, et al., 2015a, b). All these techniques are expected to increase the water content in the incoming air leading to enhanced sensible and latent heat transfer. Experiments and numerical studies dealing with different relevant aspects such as different finned-tube configurations, spray water density, air velocity, the pressure drop across the bank of tubes, etc. have also been reported in the literature (Dreyer et al., 1992; Kosky, 1976; Mednick & Colver, 1969; Pawlowski & Siwoń, 1988; Wen-Jei & Clark, 1975; Wilson & Jones, 1978).

Effect of different shapes of fins such as plain (Bhuiyan et al., 2013, 2014), wavy (Bhuiyan et al., 2015), corrugated louvers (Moosavi et al., 2021), offset strip (Kim et al., 2020), perforated (Bhambere et al., 2019), spiral (Kiatpachai et al., 2015) on the thermo-hydraulic performance of dry-cooled heat exchangers has also been evaluated by researchers. Bošnjakovic and Muhic (2020) have evaluated heat transfer performance using perforated star-shaped finned-tube. Author found that with these types of fins, the mass of fins can be reduced up to 17.6% and heat transfer can be increased up to 11.3%. Effect of circular and elliptical fins have been estimated to optimize the shape of finned-tube bundle (Nemati et al., 2020). The study found that with combination of circular fins at entrance region and elliptical fins at middle region can reduce pressure drop and fin weight up to 31% and 23%, respectively. A numerical comparison of thermal performances of finned tube annuli with various types of fin shapes have been presented by Kim (2021). The study concluded that the fin with variable thickness provides improved thermal performance as compared to the fins of other shapes considered.

Studies show that spraying of water on the bank of finned tubes enhances thermal performance by 5 to 16 times in comparison to dry cooling without wetting of fins (Dreyer et al., 1992; Kosky, 1976). Water droplets are introduced in a controlled manner in the incoming dry air by appropriate spray technique to achieve the lowest possible ambient temperature (i.e., wet bulb) by taking the heat of vaporization from the incoming dry air (Dreyer et al., 1992; Kosky, 1976). The performance of dry cooling tower by considering different types of nozzles for water spray, effect of water density, effect of droplet size, variation in air–water flow rate, and change in interfacing time between water and air also been estimated (Campbell, 2013; Sun et al., 2017a, b, c; Sun, et al., 2017a, b, c; Sun, Guan, Gurgenci, Li, et al., 2017a, b, c; Zhang et al., 2014). By pre-cooling of inlet air, the cooling performance can be reportedly enhanced in the range of 15% to 20% leading to a reduction in the parasitic load and consequently increase in the plant output by 2% to 4% (Alkhedhair et al., 2015, 2016; Sadafi et al., 2015).

The wet media refers to the cooling pad, packages, and fills with corrugated and porous material that can hold the water while allowing the incoming air to pass through. The principle of wet media is similar to the pre-cooling of air in the desert (evaporative) coolers. Studies pertaining to the use of cellulose medium (He et al., 2014a, b), munter media (He et al., 2013), and trickle media (He et al., 2015a, b) for pre-cooling of inlet air for natural draft dry cooling tower have also been reported. It is also noted that (i) the performance of the cooling tower cannot be improved significantly by pre-cooling of inlet air below a specific temperature (ii) there is always a trade-off between achievable cooling potential and pressure drop imposed by the use of wet media (He et al., 2015a, b).

Use of flutter reeds mechanism is another technique to increase vorticity so as to enhance the air-side heat transfer coefficient (Hidalgo et al., 2015; Li et al., 2019). Flutter reeds are flag like structure that deform due to body force imparted by the flow of fluid and the same are classified as active and passive types (Hidalgo et al., 2010, 2015). The effects of flutter reeds on the air-cooled power plant efficiency have been evaluated experimentally by Mahvi et al. (2021). Considering specific optimized parameters for pitch of fin, length of fin and air flow rate, it was reported that though the power plant efficiency is slightly lowered (0.89%) with the use of flutter reeds, the same reduces significant amount of surface area of heat exchanger that leads to reduction in capital cost.

An air-cooled condenser equipped with the latest electronics actuating devices named as a modular air-cooled condenser (MACC) has also been developed (Moore, et al., 2014a, b). The sensors embedded in MACC detect the changes in ambient conditions and accordingly control the fan speed for optimal power output from the turbine (Moore, et al., 2014a, b). Several different configurations of MACC have been tested for techno-economic feasibility by (Poullikkas et al., 2012, 2013b, c). From these studies, it was inferred that MACC could become a cost-competitive alternative to wet or dry-cooled condenser technologies. However, with MACC, the plant output increases up to a certain point by increasing fan speed and afterwards plant output is offset by the power consumption of fans (O'Donovan et al., 2013). Hence, it is essential to identify optimal operating parameters and configuration in order to achieve increased power output and the lowest unit cost of electricity from the plant (Muñoz et al., 2012).

Recently, Camba and Petrakopoulou (2020) have numerically investigated that with the use of earth-tube (PVC pipe) heat exchangers installed 3 m below ground level, the temperature of ambient air before feeding it to dry-cooled heat exchanger of CSP plant can be reduced from 35ºC to 25.13ºC. The decrease of air temperature definitely increases the performance of dry cooled heat exchanger. However, considering the cost of pipe, trenching and parasitic power required to pump the air through PVC pipe will affect the economics of the cost of electricity delivered from the CSP plant.

Considering above mentioned advancements in the field of condenser cooling technologies, it seems that efforts toward promising significant technological improvements have already been initiated. Further, for wet cooling technology, the techniques to improve liquid–air interaction, ways to reduce the drift emissions are also required reduce parasitic power requirement, and ease of operation and maintenance. In case of dry-cooling technology, more efforts are required to obtain finned-tube heat exchanger having minimum fin area pressure drop across the finned-tube rows for enhanced heat transfer and reduction in parasitic power requirements.

5 Conclusions

Availability of the required quantity and quality of water may be a formidable challenge in most of the locations with high annual availability of DNI. The reported values of water requirement for condenser cooling in concentrating solar power (CSP) plants is higher than other electricity generation options besides the incremental water requirement for mirror cleaning etc. Alternative water conservative condenser cooling options such as dry or hybrid for CSP plants, especially for arid/desert regions are therefore necessary. The alternative cooling options could have a variety of design, operational, performance and economics related differences in comparison to the plants with wet cooling. A detailed comparison of three condenser cooling technologies on various attributes is summarised in Table 8. Though the wet cooling technology provides most favourable attributes that are responsible for lower cost of electricity delivered from the plant, the same may not be feasible in arid regions due to inadequate availability of water. Additionally, being a relatively

Table 8 Attribute wise comparison of condenser cooling technologies

Attribute	Condenser cooling technology		
	Wet	Hybrid	Dry
Thermal performance	High	Medium	Low
Water consumption	High	Medium	Low
Parasitic power requirement	Low	Medium	High
Power block efficiency	High	Medium	Low
Capital cost requirement	Low	High	Medium
Operating and maintenance requirements	High	High	Low
Environmental emissions	Low	High	Medium
Suitability in arid zone	Low	Medium	High
Potential of performance improvement	Low	Medium	High
Potential of cost reduction	Low	Medium	High
LCOE	Low	Medium	High

more mature technology, the potential for likely performance improvement and capital cost reduction is lower for wet cooling technology as compared to the dry cooling technology. On the other hand, adopting dry cooling in the plants require a relatively much larger heat exchanger along with large capacity fans thus increasing both the capital investment as well as auxiliary power requirement. Another impact of adopting dry cooling in a CSP plant is the reduction in the gross electricity output due to reduced power cycle efficiency (as the condenser operates at a high temperature). As cumulative impact of these penalties, the LCOE delivered by dry-cooled CSP plants may increase considerably. With the use of hybrid-cooled technology, such adverse implications (in terms of performance and LCOE) are likely to be lower than that for dry-cooled plants. From the perspective of environmental sustainability, the dry cooling and hybrid cooling options for CSP plants also have several associated adverse impacts as they are more material-intensive than the wet cooling technology. The need for adopting dry cooling is likely to adversely affect the financial attractiveness of CSP plants against other solar based electricity generation options. However, as most of the locations suitable for CSP generation are likely to be in arid areas, dry cooling and hybrid cooling could be only water conserving feasible options to opt for. Thus, there is a need to explore and investigate opportunities for capital cost reduction and performance improvement to improve the techno-economic feasibility of plants with alternative condenser cooling options.

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Appendix 1

See Tables 9 and 10.

Table 9 Summary of operational CSP plants in the world (as of December 2020) (Aqachmar et al., 2019; CSP.guru, 2020; SolarPACES, 2020)

Name of Plant, Location, Country	Nominal Capacity (MW)	Type of CSP Technology	Annual DNI (kWh/m^2)	Annual Rainfall (mm)	Cooling technology
Alvarado—I (La Risca), Alvarado, Badajoz, Spain	50	PTC	2197	701	Wet
Andasol-1, Aldiere, Granada, Spain	50	PTC	2212	529	Wet
Andasol-2, Aldeirey La Calahorra, Granada, Spain	50	PTC	2128	489	Wet
Andasol-3, Aldeire, Granada, Spain	50	PTC	2128	489	Wet
Arcosol 50 (Valle 1), San Josédel Valle, Cádiz, Spain	50	PTC	2194	573	Wet
Arenales, Morón de la Frontera, Seville, Spain	50	PTC	2270	610	Wet
Aste 1A, Alcázar de San Juan, Ciudad Real, Spain	50	PTC	2037	533	Wet
Aste 1B, Alcázar de San Juan, Ciudad Real, Spain	50	PTC	2037	533	Wet
Astexol II, Olivenza, Badajoz, Spain	50	PTC	2139	730	Wet
Bokpoort, Globershoop, South Africa	50	PTC	2719	256	Dry
Borges Termosolar, Les Borges Blanques, Lleida, Spain	25	PTC	1902	566	Wet
Caceres, Valdeobispo, Caceres, Spain	50	PTC	2044	715	Wet
Casablanca, Talarrubias, Badajoz, Spain	50	PTC	2179	646	Wet
Crescent Dunes, Nevada, United States	110	CTR	2526	329	Hybrid
Dacheng, Dunhuang, China	50	LFR	2000	37	Dry
Delingha Solar Thermal Power Project, Qinghai, China	50	PTC	2307	263	Dry
Dhursar, Rajasthan, India	125	LFR	2059	383	Wet
Enerstar, Villena, Alicante, Spain	50	PTC	1931	482	Wet
Extresol-1, Torre de Miguel Sesmero, Badajoz, Spain	50	PTC	2190	701	Wet
Extresol-2, Torre de Miguel Sesmero, Badajoz, Spain	50	PTC	2190	701	Wet
Extresol-3, Torre de Miguel Sesmero, Badajoz, Spain	50	PTC	2190	701	Wet
GemasolarThermosolar Plant, Spain	19.9	CTR	2285	610	Wet
Genesis Solar Energy Project, California, United States	250	PTC	2453	164	Dry
Godawari Solar Project, Naukh, Rajasthan, India	50	PTC	2044	365	Wet
Guzmán, Palma del Río, Córdoba, Spain	50	PTC	2270	610	Wet
Hami, China	50	CTR	1920	34	Dry

Table 9 (continued)

Name of Plant, Location, Country	Nominal Capacity (MW)	Type of CSP Technology	Annual DNI (kWh/m^2)	Annual Rainfall (mm)	Cooling technology
Helioenergy 1, Écija, Sevilla, Spain	50	PTC	2285	610	Wet
Helioenergy 2, Écija, Sevilla, Spain	50	PTC	2285	610	Wet
Helios I, Puerto Lápice, Ciudad Real, Spain	50	PTC	2037	533	Wet
Helios II, Puerto Lápice, Ciudad Real, Spain	50	PTC	2037	533	Wet
Holaniku at Keahole Point, Hawaii, United States	2	PTC	2639	989	Wet
Ibersol Ciudad Real (Puertollano), Spain	50	PTC	2223	529	Wet
Ivanpah SEGS, Primm, NV, California, United States	392	CTR	2559	190	Dry
Jemalong, New South Wales, Australia	1.1	CTR	2143	679	Dry
KaXu Solar One, Northern Cape, South Africa	100	PTC	2628	44	Dry
Khi Solar One, Upington, Northern Cape, South Africa	50	CTR	2708	256	Dry (Natural draft)
La Africana, Posadas, Córdoba, Spain	50	PTC	2292	610	Wet
La Dehesa (Samcasol 2), La Garrovilla, Badajoz, Spain	50	PTC	2201	701	Wet
La Florida (Samcasol 1), Badajoz, Badajoz, Spain	50	PTC	2194	701	Wet
Lebrija 1 (LE-1), Lebrija, Sevilla, Spain	50	PTC	2245	661	Wet
Liddell Power Station, New South Walles, Australia	9	LFR	1584	1858	Dry
LunengHaixi, China	50	CTR	1945	609	Dry
Majadas I, Majadas de Tiétar, Cáceres, Spain	50	PTC	2205	646	Wet
Manchasol-1 (MS-1), Ciudad Real, Spain	50	PTC	2037	533	Wet
Manchasol-2 (MS-2), Ciudad Real, Spain	50	PTC	2037	533	Wet
Megha Solar Plant, Andhra Pradesh, India	50	PTC	1763	1128	Wet
Mojave Solar Project, California, United States	250	PTC	2588	215	Wet
Morón, Morón de la Frontera, Seville, Spain	50	PTC	2270	610	Wet
Nevada Solar One, Boulder City, Nevada, United States	75	PTC	2540	204	Wet
Noor I, Ouarzazate, Morocco	160	PTC	2748	168	Wet
Noor II, Ouarzazate, Morocco	200	PTC	2748	168	Dry

Table 9 (continued)

Name of Plant, Location, Country	Nominal Capacity (MW)	Type of CSP Technology	Annual DNI (kWh/m^2)	Annual Rainfall (mm)	Cooling technology
Noor III, Ouarzazate, Morocco	150	CTR	2748	168	Dry
Olivenza 1, Olivenza, Badajoz, Spain	50	PTC	2577	558	Wet
Orellana, Orellana, Badajoz, Spain	50	PTC	2300	518	Wet
Palma del Río I, Palma del Río, Córdoba, Spain	50	PTC	2289	610	Wet
Palma del Río II, Palma del Río, Córdoba, Spain	50	PTC	2289	610	Wet
Planta Solar 10, Sevilla, Sanlúcar la Mayor, Spain	11	CTR	2259	661	Wet
Planta Solar 20, Sevilla, Sanlúcar la Mayor, Spain	20	CTR	2259	661	Wet
Puerto Errado 2, Calasparra, Murcia, Spain	30	LFR	1916	467	Dry
Qinghai,Gonghe, China	50	CTR	1920	321	Dry
Saguaro, Red Rock (Arizona), Southwest, United States	1.35	PTC	2478	281	Wet
SEGS I, Daggett, California, United States	13.8	PTC	2504	179	Wet
SEGS II, Daggett, California, United States	33	PTC	2504	179	Wet
SEGS III, Kramer Junction, United States	33	PTC	2588	215	Wet
SEGS IV, Kramer Junction, United States	33	PTC	2588	215	Wet
SEGS V, Kramer Junction, United States	33	PTC	2588	215	Wet
SEGS VI, Kramer Junction, United States	35	PTC	2588	215	Wet
SEGS VII, Kramer Junction, United States	35	PTC	2588	215	Wet
SEGS VIII, Harper Dry Lake, United States	89	PTC	2588	215	Wet
SEGS IX, Harper Dry Lake, United States	89	PTC	2592	215	Wet
Shams 1, Madinat Zayed, Southwest of Abu Dhabi, UAE	100	PTC	2544	84	Dry
Shouhang Dunhuang Phase II, Jiuquan Shi, China	100	CTR	2000	37	Dry
Sierra SunTower, California, United States	5	CTR	2588	248	Wet
Solaben 1, Logrosán, Cáceres, Spain	50	PTC	2179	646	Wet
Solaben 2, Logrosán, Cáceres, Spain	50	PTC	2179	646	Wet
Solaben 3, Logrosán, Cáceres, Spain	50	PTC	2179	646	Wet

Table 9 (continued)

Name of Plant, Location, Country	Nominal Capacity (MW)	Type of CSP Technology	Annual DNI (kWh/m^2)	Annual Rainfall (mm)	Cooling technology
Solaben 6, Logrosán, Cáceres, Spain	50	PTC	2179	646	Wet
Solacor 1, El Carpio, Córdoba, Spain	50	PTC	2245	548	Wet
Solacor 2, El Carpio, Córdoba, Spain	50	PTC	2245	548	Wet
Solana, Arizona, Gila Bend, United States	280	PTC	2467	226	Wet
Solnova 1, Sevilla, Sanlúcar la Mayor, Spain	50	PTC	2259	661	Wet
Solnova 3, Sevilla, Sanlúcar la Mayor, Spain	50	PTC	2259	661	Wet
Solnova 4, Sevilla, Sanlúcar la Mayor, Spain	50	PTC	2259	661	Wet
Stillwater GeoSolar Hybrid Plant, Nevada, United States	17	PTC	2427	336	Dry
SunCan Dunhuang – I, China	10	CTR	2403	176	Wet
Supcon, Delingha, Qinghai, China	50	CTR	2405	175	Dry
Termesol 50 (Valle 2), San José del Valle, Cádiz, Spain	50	PTC	2194	573	Wet
Termosol 1, Navalvillar de Pela, Badajoz, Spain	50	PTC	2179	646	Wet
Thai Solar Energy 1, Kanchanaburi Province, Thailand	5	PTC	1643	1559	Wet
Termosol 2, Navalvillar de Pela, Badajoz, Spain	50	PTC	2179	646	Wet
Urat Middle Banner, China	100	PTC	2170	200	Dry
Xina Solar One, Northern Cape Province, South Africa	100	PTC	2738	186	Dry

Table 10 Summary of CSP projects under construction in the world (as of December 2020) (Aqachmar et al., 2019; CSP.guru, 2020; SolarPACES, 2020)

Name of Plant, Location, Country	Nominal Capacity (MW)	Type of CSP technology	Annual DNI (kWh/m²)	Annual Rainfall (mm)	Cooling technology
Abhijeet Solar Project, Phalodi, Rajasthan, India	50	PTC	2084	263	Wet
Agua Prieta II, Agua Prieta, Sonora, Mexico	14	PTC	2537	321	Dry
Ashalim 2, Ashalim, Negev Desert, Israel	110	PTC	2482	131	Wet
Ashalim Plot B, Ashalim, Negev Desert, Israel	121	CTR	2482	131	Dry
Diwakar, Askandra, Rajasthan, India	100	PTC	2044	296	Wet
DLR—Algeria CSP tower pilot plant, Boughzoul, Algeria	7	CTR	2037	361	–
Golmud, Qinghai, China	200	CTR	2158	43	Dry
Gujarat Solar One, Kutch, Gujarat, India	25	PTC	2015	434	Wet
HelioFocus China Orion Project, China	60	PD	2267	237	–
Helios Power, Larnaca, Cyprus	50.76	PD	2584	449	–
Hidden Hills SEGS, Inyo County, United States	500	CTR	2559	226	–
Kogan Creek Solar Boost (Hybrid), Queensland, Australia	44	LFR	2362	770	Dry
KVK Energy Solar Project, Askandra, Rajasthan, India	100	PTC	2044	296	Wet
Llo Solar Thermal Project, PyrénéesOrientales, France	9	LFR	1657	777	Dry
Maximus Dish project, Florina, Greece	75	PD	1694	748	Wet
Mazara Solar, Sicily, Italy	50	CTR	1891	606	–
MINOS CSP tower, Crete, Greece	50	CTR	2460	471	–
Palen SEGS, California, Riverside County, United States	500	CTR	2340	164	Dry
Pedro de Valdivia, Maria Elena, Antofagasta, Chile	360	PTC	2800	84	Dry
Planta Solar Cerro Dominador, Chile	110	CTR	2789	84	Dry
PTC50 Alvarado, Badajoz, Alvarado, Spain	50	CTR	2194	701	–
RayspowerYumen, China	50	PTC	1800	90	Dry
Redstone, Postmasburg, South Africa	100	CTR	2727	383	Dry
Rice Solar Energy Project, Rice, California, United States	150	CTR	2482	183	Dry
SunCan Dunhuang – II, China	100	CTR	2403	176	Dry

Table 10 (continued)

Name of Plant, Location, Country	Nominal Capacity (MW)	Type of CSP technology	Annual DNI (kWh/m^2)	Annual Rainfall (mm)	Cooling technology
TuNur, Qibili, Tunisia	2000	CTR	2310	157	–
Yumen, China	50	CTR	1800	90	Dry

(-) Data are not available

Acknowledgements The first author (Tarun Kumar Aseri) sincerely acknowledges the Department of Technical Education, Government of State of Rajasthan, and the administration of Engineering College Ajmer for providing the opportunity to undertake doctoral research at Centre for Energy Studies, Indian Institute of Technology Delhi.

Authors' contributions Tarun Kumar Aseri: Conceptualization, problem formulation, methodology, data curation, formal Analysis, visualization, writing – original draft. Chandan Sharma: Conceptualization, problem formulation, methodology, investigation, writing – review & editing. Tara C. Kandpal: Conceptualization, problem formulation, methodology, supervision.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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