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A numerical investigation of the influence of wind on multiple short natural draft dry cooling towers

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Abstract

The deployment of concentrating solar thermal power (CSP) plants in arid areas necessitates the use of dry cooling systems to reject heat from the condenser. As modular CSP plants are expanded, likewise there is a need to add additional cooling capacity, usually by the addition of more cooling towers. One of the challenges in adding additional cooling towers though is how to site these with respect to the original cooling tower.

Previous research has shown that the capacity of short natural draft dry cooling towers (NDDCTs), as a condenser for CSP plants, can be significantly influenced by the wind. In this respect, the aim of this study was to computationally investigate the interaction between multiple NDDCTs. The results show that placement of NDDCTs can lead to significant variations in the cooling capacity under varying wind speeds. Furthermore, this work delivers a generalised relationship describing the effect of wind flow on multiple cooling towers and explores how cooling tower layouts can be better configured for practical applications.

1. Introduction

Cooling towers are the key component of any power plants required to reject the heat from power plant condenser to the ambient. Natural draft dry cooling towers (NDDCT) have the advantage of water conservation which makes them suitable for arid areas and especially for concentrated solar power (CSP) plants. CSP plants with a net generation output of a few megawatts often utilise short NDDCT that are more susceptible to the wind due to weaker natural convective buoyancy effect compared to large-scale towers. In this repspect the impact of the wind and ambient conditions on the performance of single short NDDCTs has previously been investigated both numerically and experimentally (Li et al. 2015; Li et al. 2017; Lu et al. 2015; Lu et al. 2013; Lu et al. 2014).

Of course, as the capacity of CSP power plants is increased, additional cooling is required which necessitates the addition of more NDDCTs. When adding these cooling towers, there is a need to be able to position them correctly so that their performance as a group is maximised. To do this, an understanding of the effect they have on one another is needed, particularly concerning windy conditions. Although much research has been devoted to isolated cooling towers, very few studies have investigated the performance of multiple cooling towers under windy conditions. Each cooling tower in a group may exhibit different characteristics from those of an isolated one. To this end, the performance of two cooling towers under crosswind conditions was experimentally and numerically investigated by Zhai and Fu (Zhai and Fu 2006). This study mainly discussed the realationship between the cooling efficiency recovery and the size of the wind-break walls. Irtaza et al. (Irtaza, Ahmad, and Pandey 2011) used turbulence modelling to explore the effect of wind force on three and five cooling towers without modelling the heat exchanger. In this work, the authors did not study the effect of the wind on thermal performance and only a non-dimensional pressure coefficient was defined to describe the aerodynamic aspect of multiple cooling towers interacting with each other. Wu and Koh (Wu and Koh 1977)developed a mathematical model to predict the behaviour of plumes such as excess plume temperature, humidity and liquid phase moisture (water droplet), plume trajectory, width, and dilution at the merging locations from multiple cooling towers. This study also only detect the properties of plumes from the top side of four cooling towers, and the investigation of cooling towers thermal performance cannot be seen in this work. However, these studies have emphasized on large-scale towers incorporating with vertically finned tube bundles.

The performance of short cooling towers is highly vulnerable to environmental and design condition and the initial design of the cooling tower is usually suitable for stagnant ambient air condition. The differences between a small isolated NDDCT and multi-tower system are not clear, and they merit thorough investigation. Hence, the aim of this study is to investigate the effect of tower spacing on the thermo-flow performance of two short NDDCTs with horizontally arranged air-cooled heat exchanger at different crosswind velocities.

2. Method

To understand the behaviour of NDDCTs under windy conditions, 3D CFD simulations were used to investigate the airflow characteristics around towers and the effect on their performance. The simulations were performed on a tower with a diameter (D) of 12.53m, for three tower spacings 0.125D, 1.6D, and 3.2D and several wind velocites (0-8 m/s). A commercial RANS finite volume code was used to carry out these simulations, where the turbulent field was simulated using the realizable k-ε turbulence model. Realizbale k-ε has been extensively validated for a wide range of flows including rotating shear flows, boundary layer flows and separated flows and had been shown to be well suited to modelling both short and large NDDCTs (Lu et al. 2013; Wu et al. 2014). For this study a cylindrical tower and horizontally arranged air-cooled heat exchanger were examined with the computational domain and boundary conditions shown in

Figure **1**. The dimensions of the computational domain were selected based on a mesh sensitivity showed the boundaries did not affect the domain flow field. The windward tower was placed at the centre of semi-cylinder with a height of 90m and radius of 72 m and the leeward tower was located at rectangular domain with length of 200m as used in the investigation of a multi-tower system by (Zhai and Fu 2006). At no-wind conditon the towers were placed in a cylinderical domain. The details of tower design condition, geometry, and boundary domain dimensions can be found in Table 1

Table 1. Towers design conditions and domain dimensions

Tower Type	Cylinderical natural draft dry cooling tower
Number of towers	2
Tower aspect ratio (ratio of total height to base diameter)	1.66
Ambient air dry bulb temperature (°C)	20.15
Bundle arrangement	Horizontal inside the tower
Tower height (m)	20
Base diameter (D) (m)	12.525
Tower inlet height (m)	5
Tower spacing	0.125D, 1.6D, and 3.2D
Crosswind velocities (m/s)	0-8
Boundary dimensions at windy condition (Cylinder radius* height* rectangle lenght) (m)	90*72*200
Boundary dimensions at no-wind condition (Cylinder radius*height) (m)	140*90

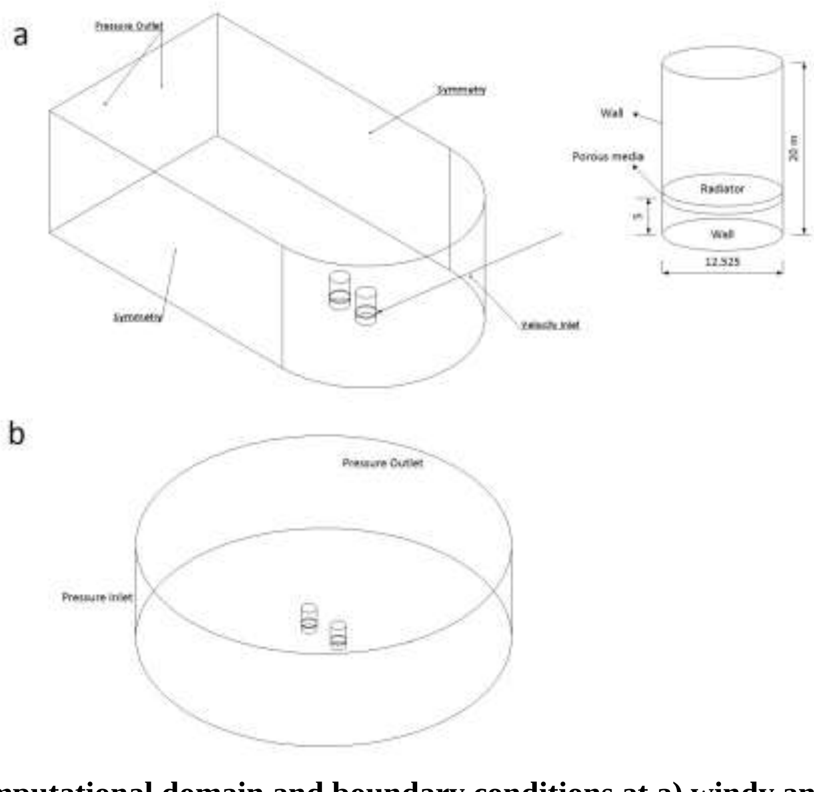

Figure 1. Computational domain and boundary conditions at a) windy and b) no-wind condition

At windy condition, velocity inlet boundary condition is assigned at windward side (surface of half cylinder) of the domain. The velocity profile is applied in this boundary defined by equation 1:

$$v = v_{in} = (\frac{y}{y_{ref}})^{m} v_{ref}$$

Where v_{ref} is a reference velocity at a reference height y_{ref}=10 m and exponent m is defined as the roughness of the ground and the stability of the atmosphere. To determine the rate of heat rejected by each cooling tower, the heat exchangers were modelled as a cylindrical porous media with a radiator on its top face such that the heat rejected to the surrounding air (q) is given by Equation 2.

$$q = h\left(T_{air,d} - T_{ext}\right) \quad (2)$$

Where $T_{air,d}$ is the temperature downstream of the heat exchanger (radiator), T_{ext} is the reference temperature for the liquid. The combination of a porous media zone and radiator boundary condition was used for heat exchanger modelling in short NDDCTs previously (Lu et al. 2013; Lu et al. 2014). The radiator model is taken to characterize the heat transfer of the heat exchangers while the porous media is made to represent the pressure loss within heat exchanger by adding a momentum sink in the governing momentum equations where the heat exchanger parameters were taken from (Li et al. 2015).

2.1. Validation

There are no available research data on multiple small-size NDDCTs, so to validate the computational model, numerical results of a single NDDCT were compared to those of (Li et al. 2015) as shown in Table 3.

Table 1. Design conditions of modelled NDDCTs in current study and (Li et al. 2015).

Ref	Height (m)	Diameter (m)	Inlet Height (m)	Tower shape	Heat exchanger area (m^2)
(Li et al. 2015))	20	12.525	5	Hyperbolic	86.21
Current study	20	12.525	5	Cylindrical	123.16

Following on from this simulations of single NDDCTs were performed at various wind velocities (0-8 m/s) and the results were compared with the available literature. Figure 2 shows the comparison between the Q/Q_{nowind} for windy conditions of one individual cooling tower with that reported by (Li et al. 2015). The comparsions indicates that both towers follow a same trend. The hevaiour of this trend was discussed by (Lu et al. 2013). The deviation between the simulation data and the literature data at different crosswind velocities varies between 2.4% -5.4%. The results shows that the modeling results has agood agreement with litearture data. The deviation may be due to different tower geometry and heat excahgner nuldes arranegment in the tower.

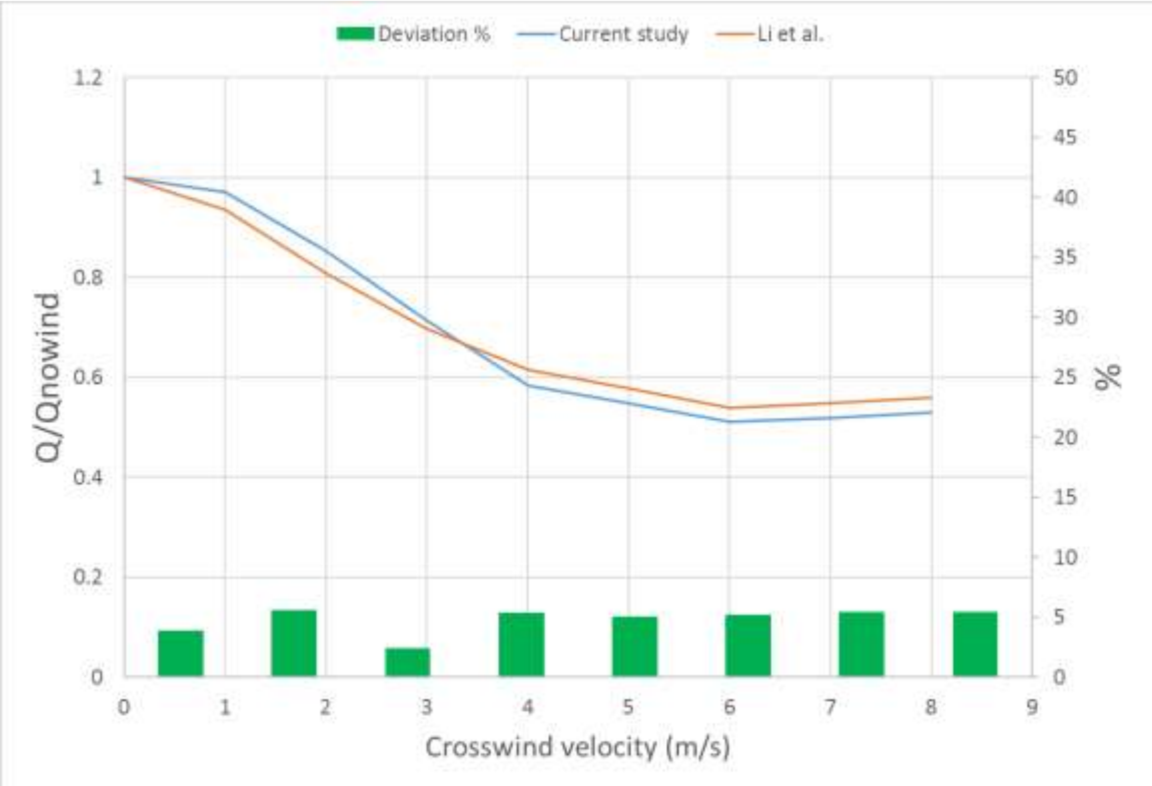

Figure 2. Heat dissipation rate of NDDCTs in current study and (Li et al. 2015)

3. Results and Discussion

Having shown that the model was capable of predicting the performance of a single tower it was applied to a multi-tower configuration. As it had been that a crosswind reduces the cooling efficiency of a NDDCT it was decided to explore the reasons for this. Figure 3 shows the crosswind causes two recirculations within the tower which impair the buoyancy, the negative pressure beneath the heat exchanger draws down the hot air inside the tower and results in the deflection of the plume at the exit plane of the tower. The recirculation of hot air at the bottom of cooling tower causes a reduction in velocity (and hence heat transfer) which results in higher radiator temperatures at windward section (Figure 4).

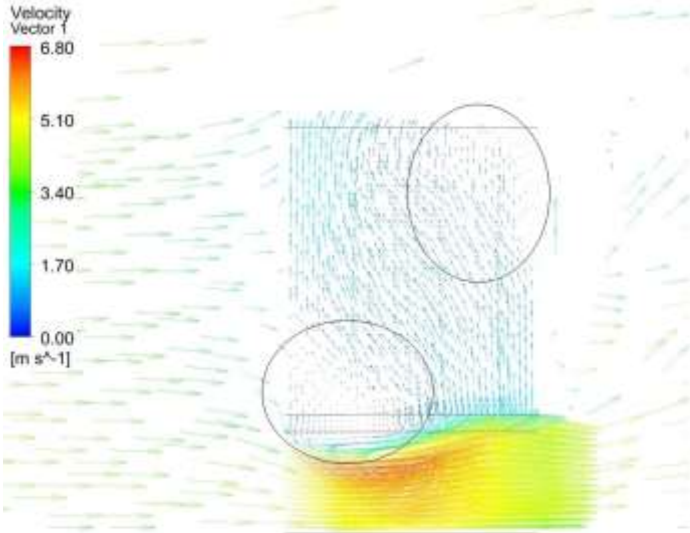

Figure 3. Velocity vectors for a vertical central cross section

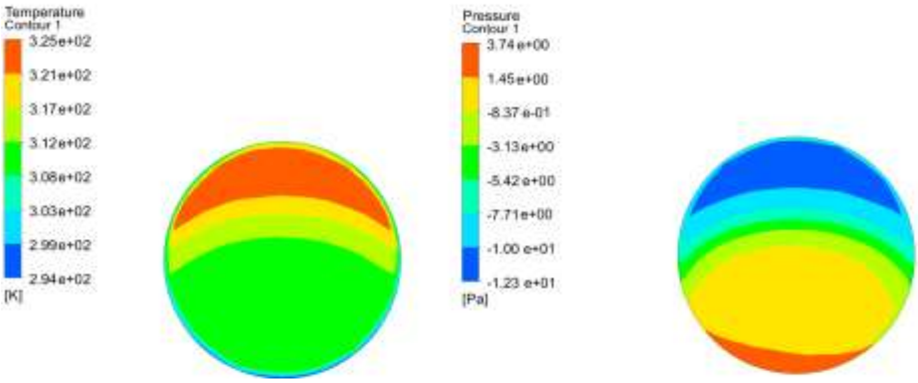

Figure 4. Temperature contours at radiator and pressure contours at heat exchanger inlet face

In multi-tower systems the windward tower can act as a windbreak for the next tower. In these simulations, the heat transfer for both the windward and leeward towers was evaluated over a range of wind velocities and tower spacings. Figure 5, shows the heat transfer rate from both towers at tower spacing of 0.125D, 1.6D, and 3.2D, respectively. It is apparent that the heat rejected by the windward tower is significantly reduced while the leeward tower shows an increase in heat transfer rate that can be attributed to it being located in the wake of the first tower. Again referring to Figure 5, it is apparent that the heat transfer rate of the leeward tower increases as the towers are placed closer together. The exception to this is when the towers are at 0.125D and there is no-wind, hence both towers are attempting to draw air under natural convection and their proximity means they "fight" to get sufficient air flow, thus leading to a reduction in their combined cooling capacity.

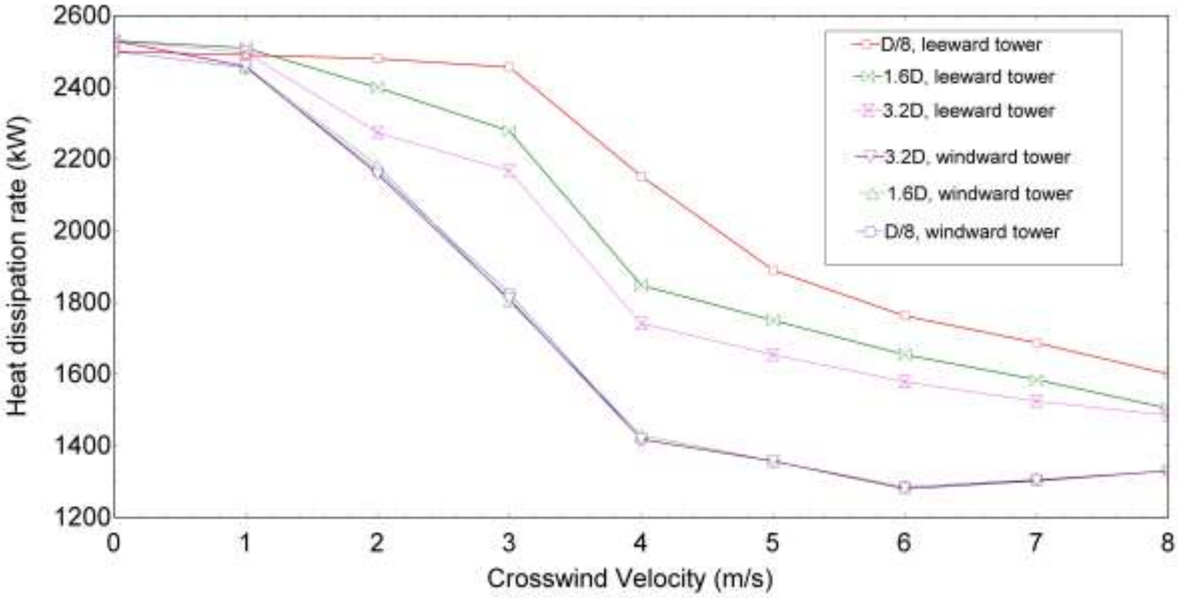

Figure 5. Heat dissipation rate from both towers with variation of wind velocity at different tower spacing

To illustrate the effect that wind has on multiple cooling towers, Figure 6 shows the velocity streamlines for different tower spacing at V=3 m/s. This clearly shows that the windward tower affects the crosswind acting on the leeward tower and that this varies significantly with tower spacing. In particular, it shows that the flow recirculation, which was also observed in a single tower, becomes smaller as the tower spacing decreases.

To further illustrate this point Figure 7 shows the velocity profiles at the top and bottom of a single leeward tower with various tower spacings and constant wind velocity. It is clear that the velocity profiles of leeward tower are quite different from that of an isolated tower. As would be expected, the influence of the windward tower becomes less significant as the tower spacing increases. Thus, the velocity disturbance at the front face of leeward tower is decreasing with increased tower spacing. As such, with the tower spacing of 3.2D , the crosswind velocity effect at the top of the leeward tower is higher and it can be seen that the velocity profile is similar to an individual NDDCT.

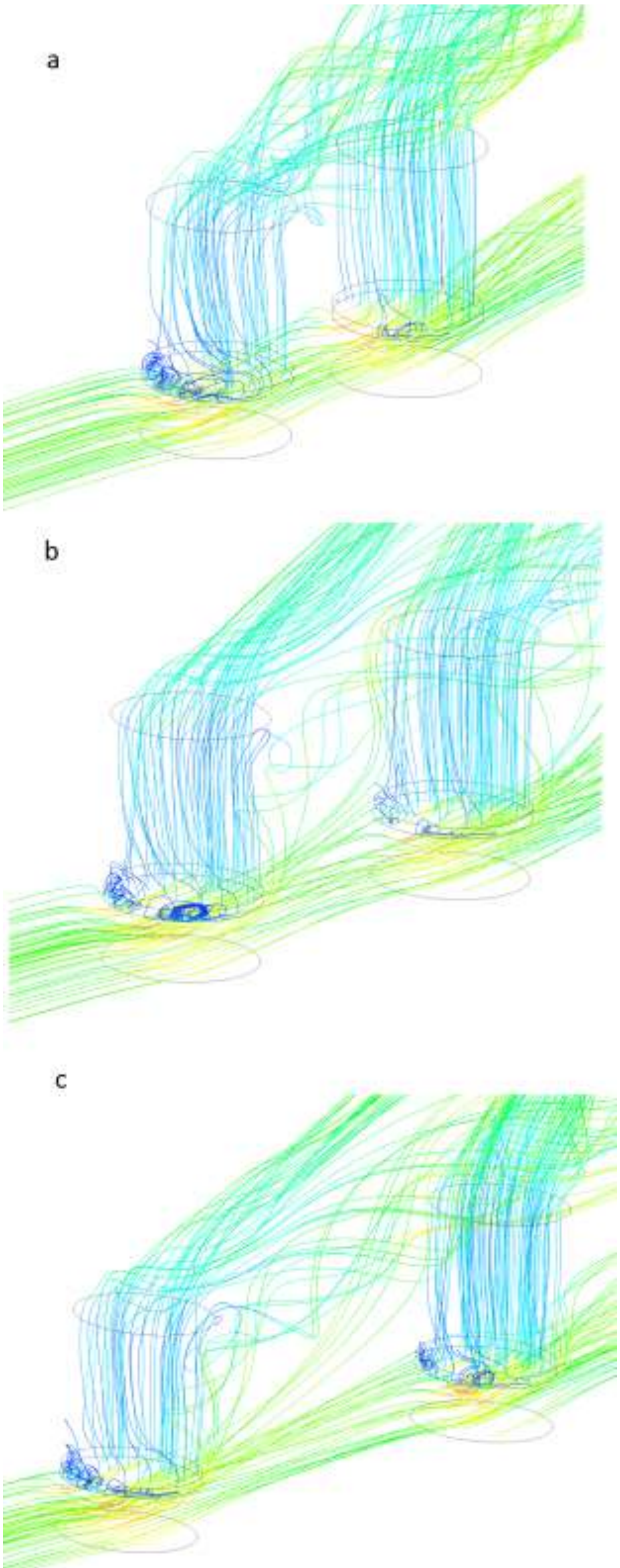

Figure 6. 3-D streamlines of the cooling towers with the tower spacing of a) 0.125D, b) 1.6D, and c) 3.2D at V=3 m/s

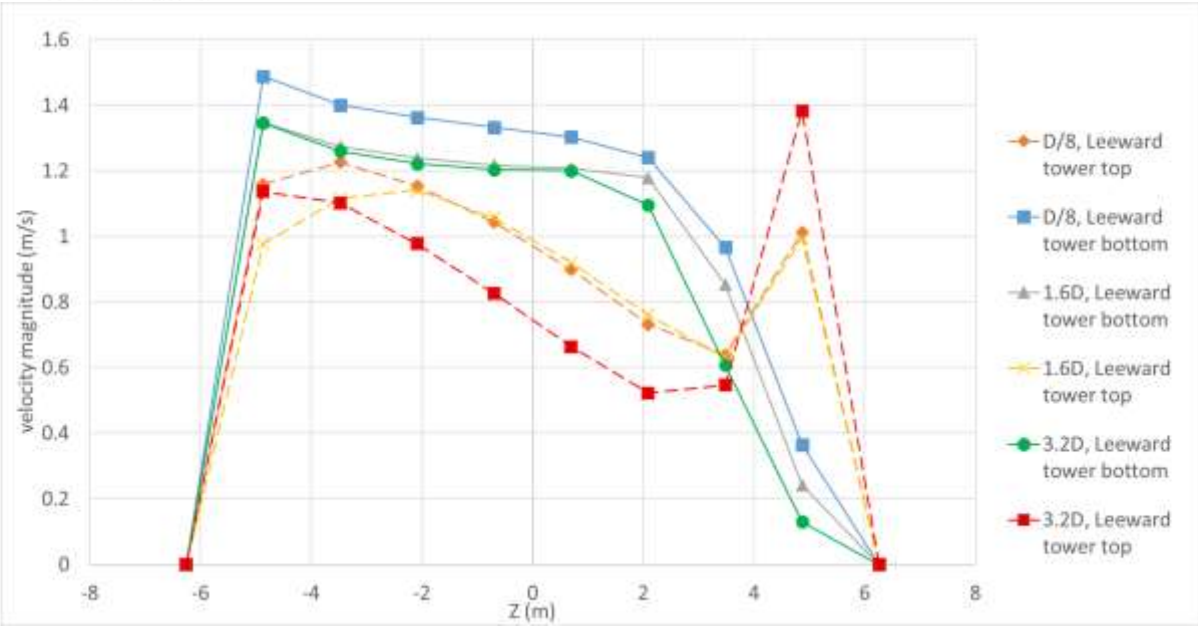

Figure 7. Velocity distribution at top and bottom level of the leeward tower, at various tower spacing and constant wind velocity of V=3 m/s

Following on from this, the temperature contours shown in Figure 8 further demonstrate the influence of the windward tower on the leeward tower. As shown in Figure 6, the bottom recirculation becomes larger at greater tower spacings. This recirculation causes the crosswind to draw air downward such that a pocket of hot air forms on the windward (internal) face of the tower. At small tower spacings, the temperature contours of the leeward tower are more uniform and the temperature at windward face is lower.

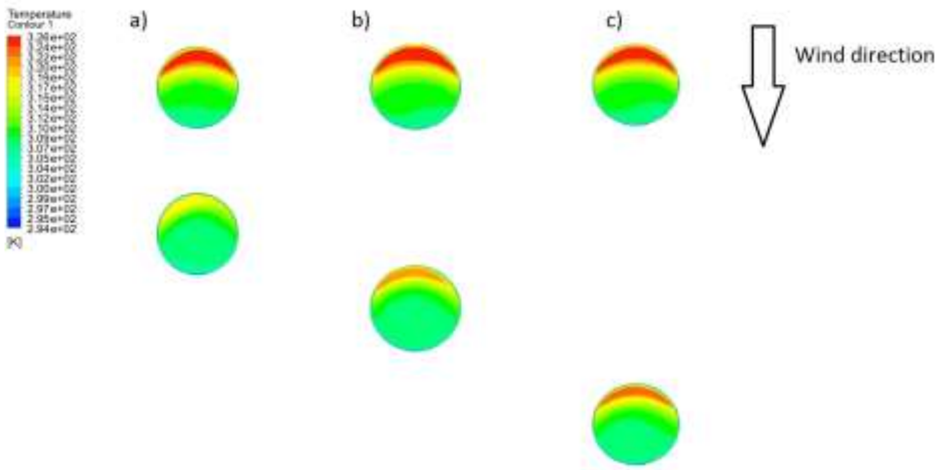

Figure 8. Temperature contours with the tower spacing of a) 0.125D, b) 1.6D, and c) 3.2D at V=3 m/s

From the temperature and velocity distributions, it is clear that at small tower spacings, that there is a performance improvement of the leeward tower, this is clearly borne out in Figure 9.

Q_{sum} is the summation of both cooling towers heat rejection and Q_{nowind} is summation of two individual towers heat rejection. of However, as discussed previously, the reduction of the scavenging area at low tower spacings limits the air supply for both towers which results in a lower heat dissipation rate ($Q_{sum}/Q_{no\text{-}wind}<1$) under purely natural convection conditions. The consequence of this is that there may be an opportunity to orient multiple cooling towers with respect to prevailing winds in order to achieve an improved cooling capacity. At different cases, more tower spacings were examined to observe if any opposite effect occurs at a certain distance. The results showed the similar trend, hence D/8, 1.6D, and 3.2D were selected as tower spacing for this study.

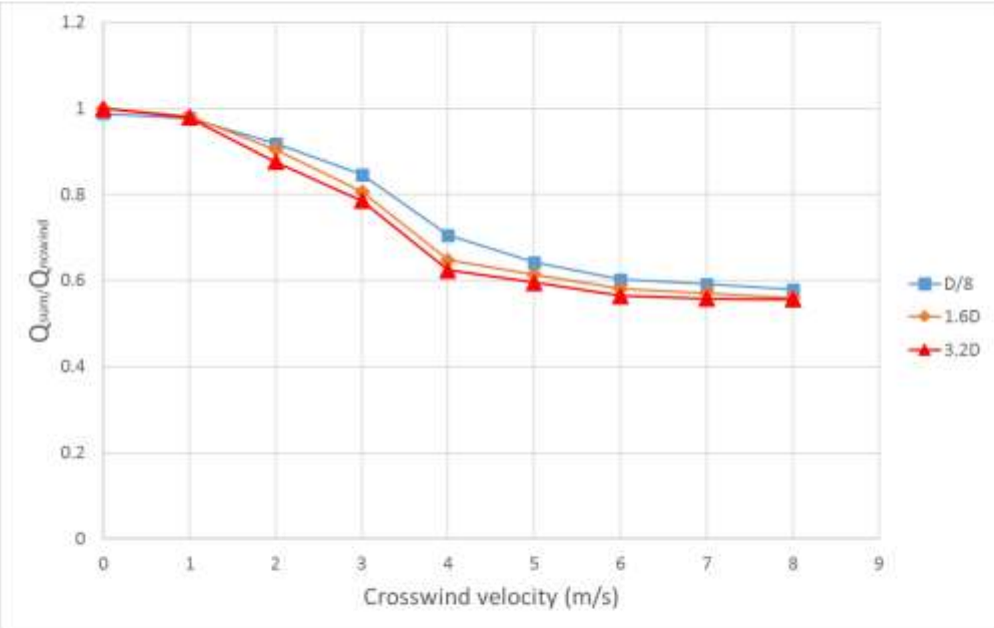

Figure 9. Performance improvement of leeward tower at different tower spacings and crosswind velocities

Conclusion

This study examined the effect of tower spacing (0.125D, 1.6D, and 3.2D)and crosswind velocity (0-8 m/s) on the performance of two NDDCTs. The results showed that the windward tower in such a configuration shelters the leeward tower. In this respect the wake leads to a more uniform velocity and temperature distribution within the leeward tower. Except no wind condition, the combined heat rejection from both towers can be impreoved by 4%-13% with decreasing the tower spacing from 3.2D to 0.125D. This improvement is more significant when wind is blowing between 2-6 m/s. The overall result of this is that the cooling capacity of the towers can be increased for moderately windy conditions by reducing the spacing between the towers

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