Mechanics & Industry **18**, 111 (2017)

DOI: 10.1051/meca/2015101
www.mechanics-industry.org

Mechanics & Industry

Use of guide vanes for improvement of flow pattern and enhancement of thermal performance of dry cooling towers

Mohammad Ali Ardekani[1], Mohammad Ali Ranjbar[1,a] and Foad Farhani[1]

Department of Mechanical Engineering, Iranian Research Organization for Science and Technology (IROST), Tehran, Iran

Received 25 April 2015, Accepted 21 October 2015

Abstract – Environmental factors, such as cross winds, adversely affect the performance of a dry cooling tower. In this field study, use of a guide vanes cascade for improvement of thermal performance of a dry cooling tower has been investigated. A four-vane cascade was installed at a delta in a critical sector of the cooling tower and effects on flow pattern through the delta and subsequent enhancement of thermal performance of the radiators in the delta were evaluated. Results show that the use of guide vanes cascade at the delta eliminates the vortex shape flow conditions at the delta inlet, improves flow rate through the deltas by about 35% and reduces the average temperature distribution on the radiators surfaces by about 1.9 °C, which is the equivalent to the amount of reduction in water temperature at the radiators outlet. The results further show that the use of guide vanes cascades in all the affected deltas in the critical sectors would result in a 7% increase in the overall thermal performance of the investigated cooling tower.

Key words: Airflow velocity / dry cooling tower / field measurements / flow visualization / guide vanes

Nomenclature

C	Vane chord
C_p	Specific heat (J.kg^{-1}.K^{-1})
ITD	Initial temperature difference (K)
$\dot{m}$	Flow rate (kg.s^{-1})
Q	Heat transfer in the cooling tower heat exchangers (kW)
R	Radius of the circular vane
U	Overall heat transfer coefficient (W.m^{-2}.K)
W	Heat capacity (J.K^{-1})
Greek Symbols	
ε	Effectiveness coefficient
Θ	Vane angle
Subscripts	
a	Air
w	Water

1 Introduction

The thermal performance of a cooling tower directly affects the production capacity of a power plant. Cooling towers are classified into wet and dry towers, and the choice of the type of cooling tower for a particular power plant depends on many factors, viz. climatic conditions namely relative humidity, ambient temperatures, wind conditions, and availability of a water source such as sea, lake, river, and pond and its distance from the cooling tower. Since the performance of dry cooling towers is more susceptible to the adverse effects of change in climatic conditions, evaluation of the effects of climatic factors, such as cross winds, which can deteriorate the thermal performance of a dry cooling tower, becomes more important for this class of cooling towers.

In recent years, many researchers have investigated both numerically and experimentally, the effects of cross winds on the performance of cooling towers. Based on the results of these studies, various remedies, such as change in cooling tower geometry, have been recommended for performance improvement of cooling towers. Preez and Kroger [1] investigated the effects of cross winds on performance of dry cooling towers. The results of this field study show that, the performance of cooling towers, namely the amount of rejected heat in the radiators, decreases with the increase in wind speed. Similar observations were reported by Amur et al. [2], who investigated the performance of a natural draft cooling tower under cross wind conditions in various directions and at different wind speeds. They also performed a two-dimensional numerical simulation of the cross winds. However, a three-dimensional simulation could have given more realistic

[a] Corresponding author: Ranjbar@irost.ir

Article published by EDP Sciences

results. Kapas [3] used numerical methods to study the effect of the angle of a cooling tower delta (angle between two adjacent radiators) on the flow pattern through the deltas. Results showed that a more uniform flow pattern could be achieved with the increase in the delta angle. Wei et al. [4] carried out a field and experimental investigation to study the effect of cross winds on cooling tower performance. Their results showed that increase in wind speed up to 6 m.s^{-1}, caused a 20% reduction in the speed of flow through the tower, with subsequent reduction in the cooling tower performance.

The aforementioned studies proved the adverse effects of cross winds on the performance of cooling towers. Many solutions have been suggested for alleviating this problem, including the use of wind breakers, change in tower geometry, and injection of gas into cooling tower.

Using a wind tunnel, Bender et al. [5] investigated the application of wind-break walls for balancing the rate of airflow into the cooling tower intakes with the aim of preventing the formation of ice caused by cold and windy weather. Their results show that for wind velocities exceeding 10 m.s^{-1}, the use of wind-break wall would increase the thermal performance of the cooling tower by 30. Eldredge et al. [6] carried out a numerical study to determine the effect of gas injection on the performance of cooling towers. In this research, five factors namely gas flow rate, gas temperature, gas injection position and angle, and the injected gas type were studied. Their results show that gas temperature, which greatly influences the buoyancy phenomenon in the cooling tower, has the maximum effect on the performance improvement of the tower. Wang et al. [7] studied experimentally the effect of guide channels on the thermal performance of wet cooling towers under the cross wind conditions. They constructed a model of the wet tower, placed some flat plates at various angles around the model, to study the thermal performance of the tower. Their results showed a considerable increase in mass flow into the radiators, resulting in improved thermal performance of the cooling tower. Ardekani and Ranjbar [8] carried out a field study to investigate the effect of cross winds on the flow pattern through the radiators of a dry cooling tower. Their results show that under cross wind conditions, sectors facing the wind and those at the back of the tower have acceptable performance, while the performance of sectors at the tower periphery is severely affected by the cross winds. This is because of the acceleration of wind at the tower periphery and inadequate flow pattern through the peripheral sectors due to the semi vortex flow conditions at these sectors, which reduces the airflow rate through the sectors. Ardekani et al. [9] carried out a field investigation to study the effects of cross winds on the thermal performance of a dry cooling tower. Their observation shows that the rate of heat transfer in the deltas in sectors facing the wind is about 20% higher than the deltas in peripheral sectors.

Considering the dry climatic conditions and the wide use of dry cooling towers throughout the most country, study of such cooling towers becomes very important.

(a) (b) (c)

Fig. 1. The three types of vane configuration: (a) bent sheet vane, (b) bent sheet with trailing edge extension, (c) airfoil vane.

Although guide vanes have been widely used in wind tunnels, no work has been reported on the use of guide vanes as a feasible solution for performance improvement of dry cooling towers. In the present field study, guide vanes were constructed and installed at the most critical sector in a Heller dry cooling tower, and improvement in flow pattern and enhancement of thermal performance of radiators in deltas of the critical sector in the cooling tower were investigated.

2 Design of the guide vanes cascade

In many cases it is necessary to turn the flow direction in particular direction. One such method is to use guide vanes [10]. Klein et al. [11] carried out experimental study on the design of different vane types for use at 90° corners for flow turning. They experimented on two thin metallic sheet vanes and two metallic vanes of thick cross section. Their results show that uniform velocity distribution can be achieved using either vane types. Configuration of the vanes can vary from a bent sheet to an airfoil. The following criteria should be considered in the vane design:

- Loss coefficient.
- Fabrication cost.
- The extent of change in flow direction.

The loss coefficient (ratio of the total pressure drop to the dynamic pressure) consists of frictional losses and those due to the change in the flow direction. Figure 1 presents three types of vane configuration [12]: (a) bent sheet vane (with loss coefficient of 0.2), (b) bent sheet with trailing edge extension (with loss coefficient of 0.13), and (c) airfoil vane (with loss coefficient of 0.11).

Although the airfoil vanes have the lowest loss coefficients, these vanes may act as diffusers in the flow path. In such cases, the vanes can result in flow separation at the boundary layer, which increases the loss coefficient. Moreover, due to their sensitivity to changes in flow direction, the airfoil vanes must be installed in locations with well-defined flow direction.

Considering the above mentioned design parameters and fabrication cost of the various vane types, a guide vane assembly consisting of a four-vane cascade of bent sheet with trailing edge extensions was fabricated and used for the present study. The cascade consists of metal

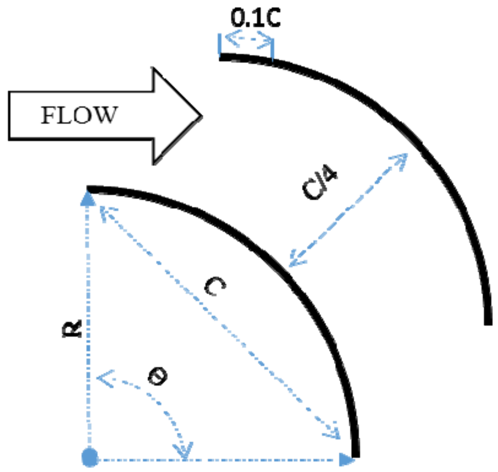


Fig. 2. Geometrical specifications of the designed guide vanes.

Fig. 3. The guide vanes cascade installed in the cooling tower at Montazer Ghaem Power Plant.

sheets; bend circularly over 90° with both straight leading and trailing edge extensions of 0.1 times chord length. Geometrical specifications of the designed guide vanes are shown in Figure 2. In this figure, C is the vane chord and R is the radius of the circular vane.

As shown, vane angle is 86°, the vane leading edge angle is 4°, trailing edge angle is 0° and distance between the vanes is about 1/4 the vane chord ($C/4$). Normally, the ratio of the distance between the vanes to the length of the chord for vanes made of sheet metal is in the range of 0.2 to 0.35. The four-vane cascade designed and constructed is of 3 m height, 1 m radius with 0.5 m distance between the vanes was, as shown in Figure 3. The vane cascade was installed at the center of Sector 2 (one of the periphery sectors shown in Fig. 4.).

3 Experiment procedure

This field study was carried out at Montazar Ghaem Power Plant (Karaj, Iran), which uses three Heller dry cooling towers, arranged along the North to South direction. The total number of deltas, arranged peripherally around the tower, is 96, and every 16 deltas constitute a sector as shown in Figure 4. The reported results in reference [8] show that sectors facing wind have the best thermal performance while those on the periphery of the tower, where wind is tangential to the sectors, exhibit the worse performance. Additionally, on the basis of the past decade metrological data for Karaj region, published by the regional metrological organization [13], the prominent wind direction during the hot months, beginning June to September end, is 290° with respect to North. That means Sector 3 (SEC3) in Figure 4 directly faces the wind. Hence, the most appropriate location for installation of the four-vane cascade structure, consisting of the guide vanes, would be the periphery Sectors 2 or 4, at which the wind blows tangentially. In the present study, Sector 2 has been selected for this purpose.

Increasing the number of measurement data was considered to be a practical way to alleviate this difficulty and enhance measurements accuracy. Consequently, Gauss distribution function was used to normalize and analyze the possible measurement errors due to the uncontrollable wind conditions. For each set of data, average, mean, variance, standard deviation and skewness were calculated. Based on the skewness data, the erroneous data was omitted to obtain a confidence interval of 95%.

3.1 Visualization of flow in the cooling tower Deltas

Considering the large area of the studied site and the functioning condition of the power plant, visualization of the flow pattern through the deltas was a major task. On the other hand, as it was difficult to implement accurate visualization methods, such as Particle Image Velocimetry (PIV), tufts were used for this purpose (see Fig. 6). Hence, a set of tufts were used to visualize flow patterns in Delta70, where the guide vanes cascade is installed, and Delta67, which is not influenced by the presence of guide vanes. The tufts were placed at three sides of a delta and an image was taken for visual representation of the flow pattern. In order to cover the vertical direction, a mesh plate, with tufts positioned in various locations, was used. Figure 5 shows a horizontal cross section of the delta and the positions of the tufts.

A particular delta consists of two radiators, positioned on the adjacent sides of the delta, and a louver positioned on the base of the delta, as shown in Figure 5. In the present study, the length of each radiator is 2280 cm. The point of intersection of the radiators (delta's vertex) is considered as the origin (0) for making the measurements. Subsequently, the distances on the right hand side radiator have been shown by positive numbers, while distances on the left hand side radiator have been indicated by negative numbers (see Fig. 5).

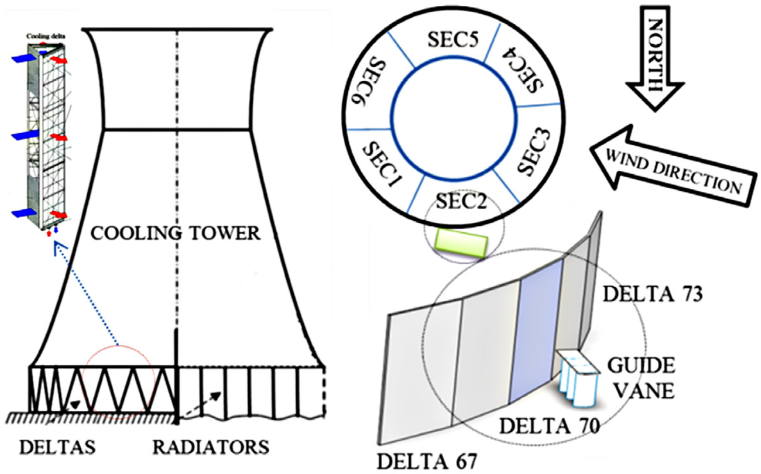


Fig. 4. Schematic of the cooling tower sectors and the position of the installed guide vanes cascade.

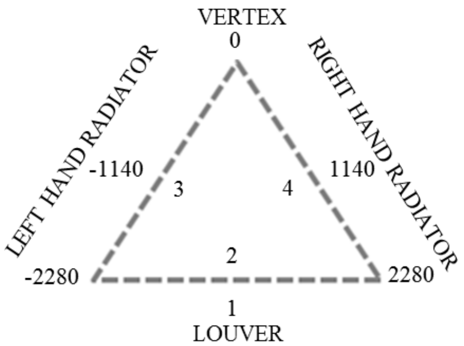


Fig. 5. Schematic of the horizontal cross section of a delta and the tufts positions.

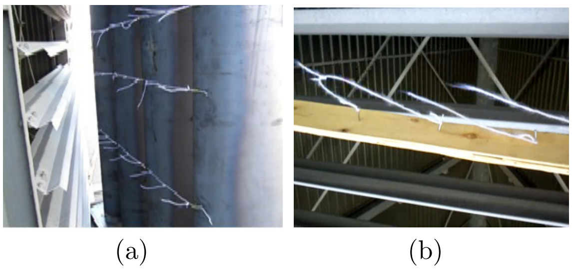


Fig. 6. Flow pattern at location 1: (a) Delta70, (b) Delta67.

3.2 Speed measurement

To study the effect of guide vanes on the performance of the cooling tower, speed of flow, perpendicular to radiators in Delta70, the radiators in Delta73 (positioned upstream) and radiators in Delta67 (positioned downstream) was measured (see Fig. 4). Simultaneously, wind speed at the reference point, at a distance of 200 m from the cooling tower, was also measured. Different anemometers, namely digital anemometer (TERMINATOR TAM 618, Impact Technology, China) and cup type anemometer (LUTRON AM-4420, Lutron Electronic Enterprise Co.), having maximum measurement error of 2% in the velocity range 0.3 to 35 m.s^{-1}, were used for these measurements.

3.3 Temperature measurement and thermal imaging

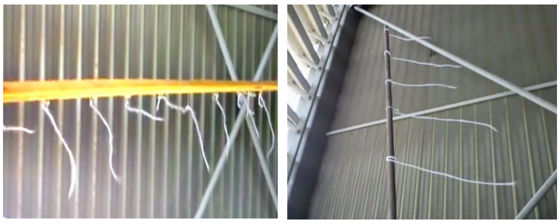
Effect of flow pattern on the thermal performance of radiators is studied by measuring the temperature distribution in the radiators. Due to high thermal conductivity of aluminum radiators, surface temperature of the radiator may be considered same as the temperature of water flowing through the radiators. As a result, surface temperatures of radiators have been measured and used to compare the effect of guide vanes on the thermal performance of radiators with and without guide vanes. It is evident that improved heat transfer and airflow through the radiators would result in reduction in the surface temperature of the radiator. Hence, it may be concluded that higher temperatures at any location on the radiator would be indicative of an improper transfer of heat, which is due to an inadequate airflow through the radiators. Temperature distribution in radiators of Deltas67 and 70 were further studied (Fig. 13) using a thermal imaging camera (TESTO 882, UK). The camera provides a thermal accuracy of 0.05 °C.

4 Results

4.1 Flow visualization

Figures 6a and 6b show the airflow pattern at location 1 (see Fig. 5), in Deltas70 and 67, respectively. In Figure 6b, the direction of tufts indicates the flow direction parallel to the louver (at delta entrance), while in Figure 6a, due to the installed guide vane-cascade; the flow direction is perpendicular to the louver.

For Deltas67 and 70, Figures 7 and 8 show the left and right hand side radiators (at locations 3 and 4 in Fig. 5), respectively. The tufts indicate that in Delta70 (Figs. 7a



(a) (b)

Fig. 7. Flow patterns at location 3: (a) Delta70, (b) Delta67.

(a) (b)

Fig. 8. Flow pattern at location 4: (a) Delta70, (b) Delta67.

and 8a, locations 3 and 4, the guide vane-cascade causes an inward flow perpendicular to the radiators, resulting in an improved thermal performance of the radiators in Delta70. On the other hand, for the left hand side radiator in Delta67 (Fig. 7b), the major part of the flow is parallel to the radiator surface, and only a fraction flows through the radiator. As a result, at distances between −2280 and −1140 cm on the radiators surface (see Fig. 5), the airflow through the radiator is adequate, resulting in acceptable thermal performance of the radiator. However, on moving towards the delta vertex (at distances between −1140 cm and 0), the airflow through the radiator is severely reduced, with the resulting degradation of the thermal performance of the radiator. At the vertex, the flow turns and moves along the right hand side radiator.

Subsequently, at location 4 in Delta 67 (Fig. 8b), the major part of the flow is parallel to the radiator surface, moving towards the louver. At distance between the delta vertex (0) and 1140 cm), a minimal flow passes through the radiator. At distance between 1140 and 2280 cm, no flow passes through the radiator, and hence, this part of the radiator has the most critical thermal performance. At the distance 2280 cm, the flow turns and moves along the louver.

Considering the images of the tufts on three sides of the delta, the flow pattern in Deltas67 and 70 can be presented schematically as shown in Figure 9. Figure 9 shows the top view of the cooling tower and the arrangement of Deltas67 and 70 and the corresponding flow patterns in the deltas. As shown, at the inlet to Delta67, the air flows at an angle to the louver, which results in a vortex flow, thereby, reducing the flow of air through the radiators and affecting adversely the performance of the radiators. However, due to the installation of guide vanes-cascade at the inlet of Delta70, the vortex flow is eliminated, which improves the flow pattern through the radiators and enhances their thermal performance, as expected for the radiators of a wind facing sector [8].

4.2 Study of wind speed

Figure 10 shows the variations in flow speed through Deltas67, 70 and 73 versus the variations in wind speed at the reference point. As shown, with the increase in wind speed at the reference point, the increase in tangential flow in Sector 2 and the vortex flow pattern in Deltas67 and 73, the flow speed through these deltas decreases by about 40 compared to the no wind condition (In this investigation, velocities equal or lower than 0.1 m.s^{-1} have been considered to represent still-air conditions, which results in symmetrical airflow around the cooling tower.). However, in Delta70, the flow turning perpendicular to the delta, due to the installation of the guide vanes-cascade, increases the flow speed through this delta by about 35%. The increase in flow speed would result in increased airflow rate through the delta, which improves the thermal performance of the radiators in Delta70.

Figure 11 shows the speed of wind exiting from the back of the radiators in deltas located in Sector 2. As shown, with increase in wind speed at the reference point, radial speed of airflow through Deltas67 and 73 is reduced, resulting in degradation of performance of these radiators. However, speed of airflow through Delta70 increases and thermal performance improves due to the installed guide vanes in this delta.

4.3 Thermal study

The amount of transferred heat in the heat exchangers of a cooling tower is obtained as [14]:

$$Q = W_a\,(ITD)\,\varepsilon \tag{1}$$

where $W_a = \dot{m} \times C_p$ is the heat capacity of air, $\dot{m}$ is the airflow rate, and C_p is the specific heat of air, ITD is the initial temperature difference, which is the difference between the inlet temperature of the hot water and the cooling air temperature, and ε is the effectiveness coefficient. The effectiveness coefficient, ε, is function of the overall heat transfer coefficient, U, heat transfer area, A, and water pipes configuration and arrangement:

$$\varepsilon = f(W_a/W_w, UA/W_a) \tag{2}$$

where W_a/W_w is the ratio of the heat capacities of air and water.

The effectiveness coefficient for cross flow non-mixing heat exchangers, which are identical to the arrangement of heat exchangers in the Heller dry cooling tower, is given by [14]:

$$W_a = W_w \rightarrow \varepsilon = 1/(1 + (W_a/UA) \tag{3}$$

$$W_a \neq W_w \rightarrow \varepsilon = \frac{1 - \exp\left[((W_a/W_w) - 1)(UA/W_a)\right]}{1 - (W_a/W_w)\exp\left[((W_a/W_w) - 1)(UA/W_a)\right]} \tag{4}$$

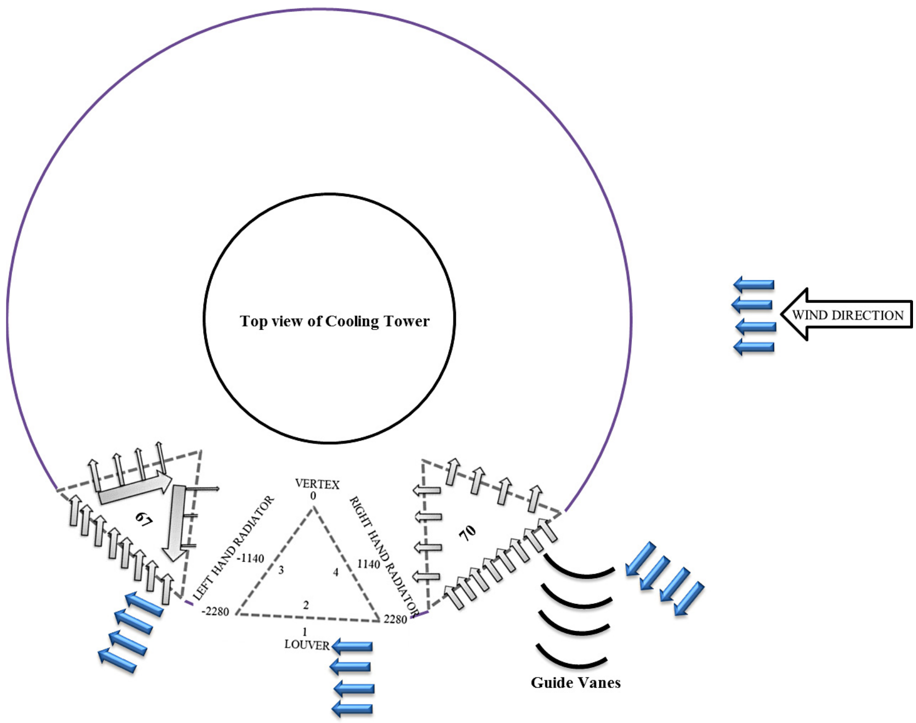


Fig. 9. Cooling tower top view, showing flow pattern in Delta67 (without guide vanes-cascade) and Delta70 (with the cascade).

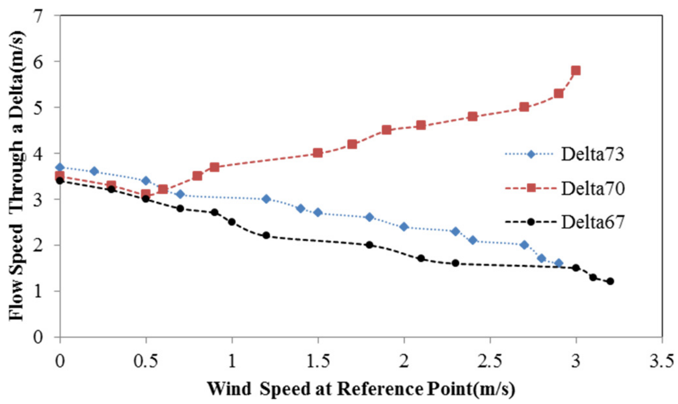


Fig. 10. Flow speed through a delta versus wind speed at the reference point.

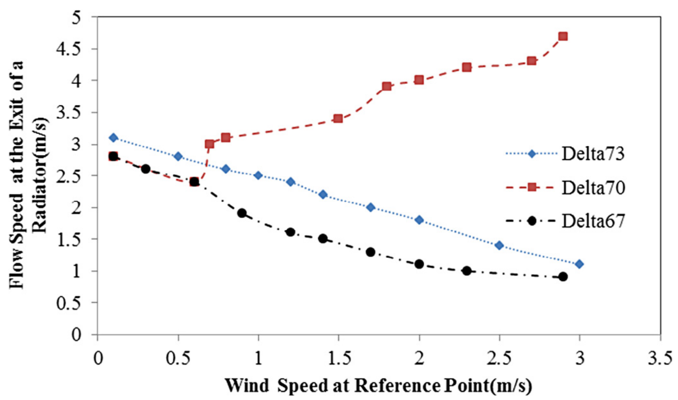


Fig. 11. Flow speed at the exit of a radiator versus wind speed at the reference point.

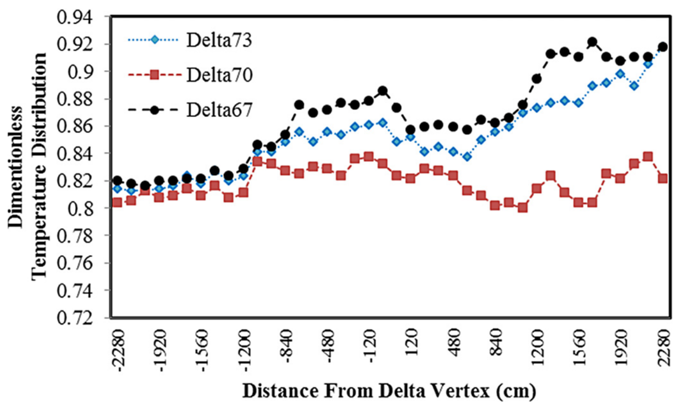
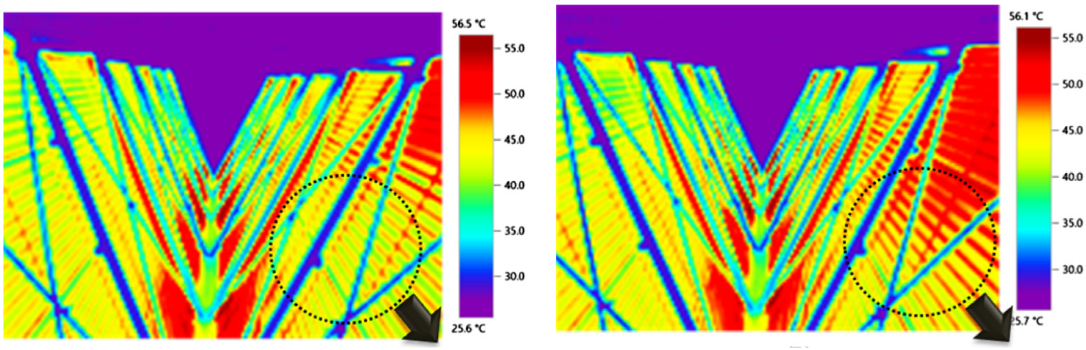


Fig. 12. Dimensionless temperature distribution in various deltas under wind speed of 3 m.s^{-1}.

These equations show that the rate of heat transfer in the cooling tower heat exchangers depends on the ambient and water temperatures and flow rates of the cooling air and the inlet water to the cooling tower. However, as temperature and flow rate of the cooling tower inlet water are almost constant, the main parameters that affect the rate of heat transfer shall be the ambient air temperature and the flow rate of the air entering the cooling tower.

In order to present the temperature data pertaining to radiators in each delta, a dimensionless temperature distribution is defined as the ratio of radiator outlet water temperature to inlet water temperature. Figure 12 depicts the dimensionless temperature distribution in Deltas67, 70 and 73, under wind speed of 3 m.s^{-1}. As shown, for radiators in Deltas67 and 73 (at distances −2280 to 2280 cm



(a) Zone average temperature = 45°

(b) Zone average temperature = 46.9°

Fig. 13. Thermal image (bottom view) of the investigated cooling tower deltas: (a) Delta70, (b) Delta67.

from a delta vertex), the temperature distribution shows an increasing trend, which is due to the vortex flow pattern in these deltas. On the other hand, the radiators in Delta70 have identical temperature distributions on both sides of the delta vertex. Moreover, the temperature distribution for radiators in Delta70 shows an average of 3.3% decrease in comparison with the radiators in other deltas, which is equivalent to about 1.9 °C reduction in the outlet water temperature of the radiator in delta with guide vanes-cascade. Therefore, it can be concluded that the airflow through the radiators and thermal performance of Delta70 has been improved by the cascade installation. In addition, a comparison of the heat transfer in the deltas, with and without the guide vanes cascade, shows a 23% improvement in the performance of the delta with cascade. Moreover, as 32 out of 96 deltas of the investigated cooling tower are critical, the use of guide vanes cascade would improve the overall thermal performance of the cooling tower by about 7%.

4.4 Thermal visualization

Figures 13a and 13b show the thermal images of Deltas70 and 67, respectively. The different temperature distributions on the left and right hand side radiators in Delta67 are depicted in Figure 13b. Moreover, the worse temperature distribution in radiators in Delta67 pertains to the right hand side radiator due to inadequate flow pattern in the delta (see Fig. 9). In addition, Figure 13a shows a decrease in the temperature difference between the right and left hand side radiators in Delta70, which is due to the installation of guide vanes-cascade in this delta. Comparison of temperatures in the right hand side radiators of Deltas67 and 70, the marked regions in Figures 13a and 13b, shows a 3% decrease in radiator temperature in the delta with guide vanes-cascade.

5 Conclusions

On the basis of the field study and the results obtained for the dry cooling tower under investigation, the following conclusions can be derived:

(1) Use of guide vanes cascade at peripheral sectors (critical deltas) of the cooling tower turns the flow perpendicular to the corresponding critical delta, which improves the flow pattern and eliminates vortex shape flow. In this case, with increase in wind speed at the reference point, flow speed through the critical delta increases. For example, for the reference point wind speed of 3 $m.s^{-1}$, flow speed through the critical delta increases by 35%.

(2) When using guide vanes cascade, temperature distribution on the radiators surface in the critical delta is uniform and its average value decreases. For example, the average temperature distribution reduces by 1.9 °C for the reference point wind speed of 3 $m.s^{-1}$.

(3) In general, use of a guide vanes cascade results in considerable improvement in the performance of a delta in a critical sector of the cooling tower, approaching the performance of the wind facing sectors. Moreover, as 32 out of 96 deltas of a cooling tower are critical under cross wind conditions, it is recommended to use guide vanes cascade for all the affected deltas. For example, based on the results of the present study, use of guide vanes cascade for each critical delta would result in 7% improvement in the overall thermal performance of the investigated cooling tower.

References

[1] A.F. Preez, D.G. Kröger, The effect of the heat exchanger arrangement and wind-break walls on the performance of natural draft dry-cooling towers subjected to cross-winds, J. Wind Eng. Ind. Aerodyn. 58 (1995) 293–303

[2] G. Amur, B. Milton, J. Reizes, J. Madadnia, S. Beecham, P. Brady, H. Koosha, Role of Plant Building in a Power Plant Acting as Barrier to the Wind Affecting the Natural Draft Cooling Tower Performance, Proc. 15th Australasian Fluid Mech. Conf., 2004, 470–475

[3] N. Kapas, Investigation of Flow Characteristic of Heller Type Cooling Towers with Different Cooling Delta Angle, Period. Polytech. Ser. Mech. Eng. 47 (2003) 143–150

[4] Q. Wei, B. Zhang, K. Liu, X. Du, X. Meng, A Study of the Unfavorable Effects of Wind on the Cooling Efficiency of Dry Cooling Towers J. Wind Eng. Ind. Aerodyn. 54-55 (1995) 633–643

[5] T.J. Bender, D.J. Bergstrom, K.S. Rezkallah, Study on the Effects of Wind on the Air Intake Flow Rate of a Cooling Tower: Part 2. Wind Wall Study I, J. Wind Eng. Ind. Aerodyn. 64 (1996) 61–72

[6] T.V. Eldredge, D.J. Benton, J.W. Hodgson, An Investigation of The Effects of Flue Gas Injection on Natural Draft Cooling Tower Performance, J. Eng. Gas Turbine Power 119 (1997) 478–484

[7] K. Wang, S. Feng-zhong, Z. Yuan-bin, G. Ming, R. Lei, Experimental research of the guiding channels effect on the thermal performance of wet cooling towers subjected to crosswinds, Appl. Thermal Eng. 30 (2010) 533–538

[8] M.A. Ardekani, M.A. Ranjbar, Field study on airflow pattern through radiator of Heller dry cooling tower, Modares Mech. Eng. 13 (2013) 30–40 (In Persian)

[9] M.A. Ardekani, F. Farhani, M. Mazidi, Effects of Cross Wind Conditions on Efficiency of Heller Dry Cooling Tower, Exp. Heat Transfer J. 28 (2015) 344–353

[10] M.A. Ardekani, Design and Application of Low Speed Wind Tunnel, Tehran, Khaje Nasir Toosi University Publication, 2009, pp. 142–170

[11] G.J. Klein, K.F. Tupper, J.J. Green, The Design of Corners in Fluid Channels, Canadian J. Res. 3 (1930)

[12] J.B. Barlow, W.H. Rae, A. Pop, Low Speed Wind Tunnel Testing, A Wiley-Intercience Publication. John Wiley and Sons, Inc. (1999)

[13] Metrological report, Karaj Agricultural Synoptic Weather Station, 2001–2012

[14] The Heller Systems, Ref. No. 8325-LK, EGI, Budapest, Hungry, 1984