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Analysist of Unfavorable Effects of Wind on a Heller Dry Cooling Tower and Optimization of its Performance

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Abstract

The thermal and combined-cycle power plants generally consist of several steam-electric power stations which are made and installed next to each other. Each steam-electric power station has a separate cooling tower that is responsible for heat loss of steam output from the same station. The cooling towers are built sides by sides that will be under the effect of each other during the wind blowing of the surrounding environment. Some studies works have shown the unfavorable effects of wind arises two factors of the vortex flow around the radiators and tilting the exhaust plume of their flues. They purposed in order to reduce these effects use windbreak wall next to the radiators or tilting the exhaust plume. This study use both purposes simultaneously, considering a tilting the exhaust plume with elliptical cross section, a dry cooling tower is simulated. The results are compared with the obtained results whit a simple cooling tower with circular section in two cases; no wind conditions and a wind of 3 m/s speed. This comparison shows that the cooling tower with elliptical cross exposing front of wind has better performance. A more examination of the results it reveals that the cooling tower with elliptical cross section with a diameter ratio of 2:1 is determined a optimum cross section which in compared of circular cross section has 12% higher efficiency.

***Keywords*:** Heler cooling tower, wind effect, plume, wind break wall and elliptical cross section

1. Introduction

One of the critical components of a steam power plant is the cooling tower. In regions where water access is limited, dry cooling towers are employed. This type of tower consists of two distinct sections. The lower section is a cylindrical structure with a low height and large diameter, housing radiators through which the hot water exiting the condenser flows. The upper section is a tall cylindrical chimney with a small diameter. A conical-shaped segment connects these two sections. The tower's design is generally based on ambient air stagnation conditions around the tower. Empirical observations and numerical simulations have demonstrated that wind adversely affects the tower's thermal performance. Specifically, when wind speeds exceed 3 m/s, air entering the tower and passing over the radiators decreases. As a result, the heat transfer across the radiators is reduced [1]. The first numerical study to investigate the causes of this phenomenon was conducted by Preez and Kroger [2]. An experimental study was later carried out by Wei and colleagues [3]. The results of these studies revealed that two primary factors contribute to the reduction in tower efficiency during wind conditions:

1. The first factor is the presence of accelerated flow around the lower section (i.e., the radiator region). This leads to a localized reduction in air pressure in this area and causes flow separation behind the tower. The resulting pressure drop across a wide area of the radiator region reduces the pressure difference across the radiators. Consequently, the mass flow rate of air passing over the radiators stagnates.
2. The second factor is the phenomenon of wind-induced choking at the tower's outlet. This occurs due to the difference in momentum between the exhaust airflow from the chimney and the incoming wind. Wind causes the plume exiting the tower to tilt, reducing the effective cross-sectional area of the exhaust flow. As a result, choking occurs at the chimney outlet, reducing the exhaust flow and increasing the internal pressure of the tower compared to the design conditions. Figure (1) illustrates these two factors using velocity vector contours.

Given the dependence of heat transfer efficiency on the flow pattern near the radiators, many researchers have proposed solutions to mitigate the adverse effects of the low-pressure, high-speed flow around the sides of the tower (the first factor). Among these, the work of Al-Waked and Behnia [4] is noteworthy. Through numerical simulations of the flow around the tower, they proposed the utilization of windbreak walls as a solution to reduce the impact of the low-pressure zone around the radiators. These windbreaks extend radially perpendicular to the wind direction from the sides of the radiators. In another study, Parvizi [5] suggested the application of windbreaks for this purpose through numerical analysis.

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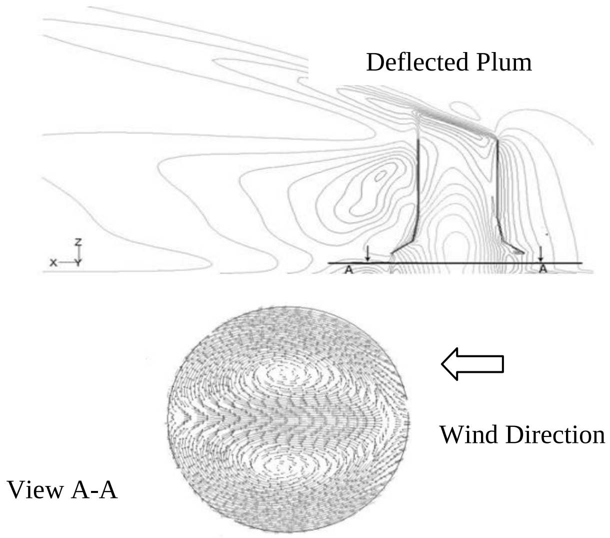


Fig 1. The two main factors of the unfavorable performance of cooling towers

To address the effect of wind on plume tilting and prevent choking at the chimney outlet, Goudarzi and Raoufi [9] proposed a design that improves the thermal performance of the tower. Their research demonstrates that in regions where the wind direction is predominantly from one side, chimneys with an inclined exhaust cross-section (angled away from the wind direction) can be used. However, the inclination angle of the exhaust outlet has an optimal value, which was determined through simulations and measurements to be approximately 27 degrees, minimizing the reduction in heat transfer. It is important to note that this research focused on hyperbolic cooling towers. In this paper, Heller-type cooling towers are investigated, and the impact of both adverse factors on the thermal efficiency of the cooling tower is studied. To this end, a combined approach using windbreaks and an inclined chimney outlet in Heller towers is proposed.

2. Governing Equations and Numerical Model

To perform a numerical simulation of the flow around and inside the cooling tower, it is essential to define the governing equations of the flow and the corresponding boundary conditions. The flow within the tower, particularly in the absence of wind, is driven by buoyancy forces resulting from the temperature difference between the air inside and outside the tower. Cold external air passes through the radiators, absorbs heat from the hot water exiting the condenser, and warms up, thereby reducing its density. However, the change in density is so minimal that the flow can be accurately approximated as incompressible. To account for the buoyancy force arising from the slight density variation, the Boussinesq approximation [6] is applied to the momentum equation in the direction opposite to gravity. Moreover, the flow inside the tower is turbulent due to the high Grashof number. Consequently, the governing equations for steady, incompressible, turbulent flow with the Boussinesq approximation and heat transfer include the continuity, momentum, energy, and turbulence model equations. For brevity, only the continuity and momentum equations are presented here to illustrate the Boussinesq approximation:

Mass conservation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

Momentum conservation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu_{\text{eff}}\left(\frac{\partial_u^2}{\partial x^2}+\frac{\partial_u^2}{\partial y^2}+\frac{\partial_u^2}{\partial z^2}\right) \quad (2)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu_{\text{eff}}\left(\frac{\partial_u^2}{\partial x^2}+\frac{\partial_u^2}{\partial y^2}+\frac{\partial_u^2}{\partial z^2}\right) \quad (3)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu_{\text{eff}}\left(\frac{\partial_v^2}{\partial x^2}+\frac{\partial_v^2}{\partial y^2}+\frac{\partial_v^2}{\partial z^2}\right) \quad (3)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+g\beta(T-T_\infty)+\nu_{\text{eff}}\left(\frac{\partial_w^2}{\partial x^2}+\frac{\partial_w^2}{\partial y^2}+\frac{\partial_w^2}{\partial z^2}\right) \quad (4)$$

In these equations u,v,w represent the velocity components in Cartesian coordinates; p denotes the static pressure; ρ is the air density; ν_{eff} is the effective dynamic viscosity; T and T_∞ are the air temperature and reference temperature, respectively; β is the thermal expansion coefficient of air; and g is the gravitational acceleration. The turbulence model employed in this study is the standard k-ε model [7]. For the numerical solution of the flow field, a semi-cylindrical domain is utilized in all cases. Due to symmetry in the wind direction plane, only half of the domain is simulated. Figure (2) illustrates the flow domain, where the lower base of the semi-cylinder represents the ground, and the upper base represents the outflow boundary. The tower walls, windbreaks, and ground surface are modeled using adiabatic wall boundary conditions. A symmetry boundary condition is applied to the symmetry plane. The radiators are part of the defined boundaries in the flow domain and are modeled as permeable flat surfaces, where the flow experiences both heat transfer and a pressure drop. The heat transfer and pressure drop across the radiators are calculated based on the Forgo heat exchanger data [8], using empirical relationships that depend on the velocity component normal to the radiators [5]. The boundary conditions on the lateral surface of the domain differ for cases with and without wind. In the absence of wind, a far-field fluid boundary condition is applied. While this condition may introduce errors in the far-field flow, these can be minimized by extending the computational domain to reduce their impact near the tower. Since the primary objective is to compare the performance of two tower designs, applying identical boundary conditions is sufficient for the intended purpose. In the presence of wind, the lateral surface of the semi-cylindrical domain is treated as a velocity (flow) inlet boundary. All other surfaces are modeled using symmetry boundary conditions.

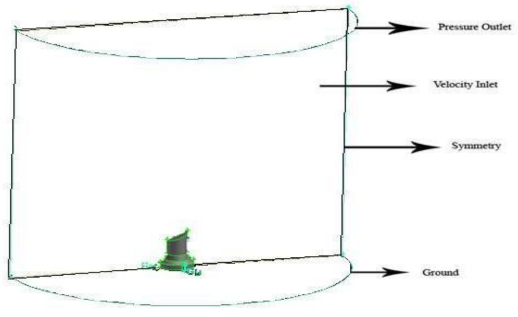


Fig 2 The simulated flow field

4. Review of numerical results

The proposed idea is fundamentally simple. To reduce the choking effect at the tower's outlet, the cross-sectional area of the tower must be increased without reducing its diameter. This can be achieved by designing the outlet cross-section as an ellipse formed by the intersection of a plane inclined relative to the tower's axis. Additionally, the taller side of the chimney should face the wind direction; otherwise, choking at the outlet will be exacerbated. The average height of the chimney remains the same as in the conventional design. In the radiator region, to reduce vortex formation and flow separation behind the tower, and to increase the mass flow rate of air entering the radiators, two windbreaks are installed at 90° and 270°, perpendicular to the wind direction. Figure (3) illustrates the proposed design under wind conditions. As shown, the plume still tilts under wind; however, due to the larger cross-sectional area of the inclined outlet, choking is reduced, and the flow area is larger than in the conventional design. To compare the proposed design with the conventional one, their performance was numerically simulated under two conditions: no wind and wind at 10 m/s. Table (1) presents the mass flow rate of air entering the radiators and the heat transfer rate for the conventional design and the proposed design (with windbreaks and a 27° inclined outlet) under no-wind conditions. The results show that the utilization of windbreaks and an inclined outlet slightly reduces the mass flow rate and heat transfer in still air. This reduction is attributed to increased frictional effects from the chimney walls and a relative decrease in buoyancy compared to the conventional design. However, since the goal is to improve performance under wind conditions, this minor reduction in still air is negligible. Table (2) shows the percentage increase in heat transfer relative to the no-wind condition when wind blows at 10 m/s. The results indicate that the implementation of windbreaks and an inclined outlet significantly improves the performance of the Heller dry cooling tower under wind conditions. This improvement is far greater than when using either windbreaks or an inclined outlet alone.

Table 1

Heat transfer rate of the cooling tower in normal conditions and the proposed design

Kind of cooling tower	The mass flow rate of incoming air into the cooling tower in kilograms per second	Heat transfer in radiators in megawatts	The percentage of heat transfer reduction due to the proposed design
Conventional cooling tower	20458	323.94	-
Cooling tower with wind breaker and outlet section of 27 degrees	20306	321.854	65%

Table 2

The percentage of cooling tower heat transfer in normal conditions, with wind breaker, with inclined section and the proposed design

Kind of cooling tower	**Typical design of a cooling tower**	**Cooling tower with wind breaker Reference [5]**	**Cooling tower with outlet cross-section of 27 degrees reference [9]**	**Cooling tower with wind breaker and outlet section of 27 degrees**
The percentage of heat transfer compared to the situation without wind	%60.5	%87	%82	%98.5
The percentage of improvement due to the proposed plan	-	%16	%9	%64.5

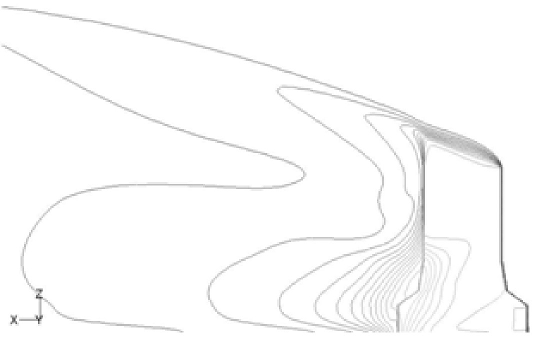


Fig 4. Isothermal contours on the plane of symmetry of a tower with a conventional outlet

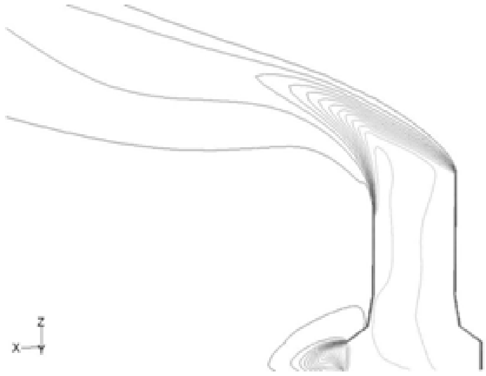


Fig 5. Isothermal contours in the plane of symmetry of the tower with the inclined outlet

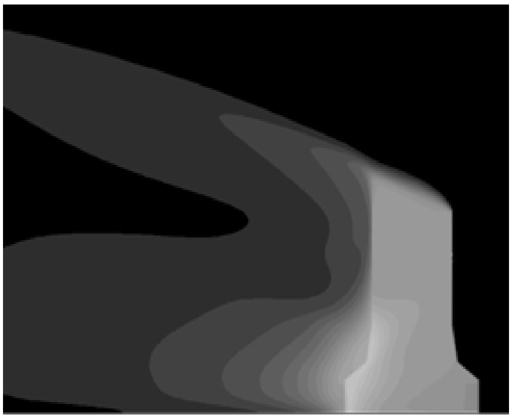


Fig 6. Temperature spectrum on the symmetry surface of the tower with a normal outlet

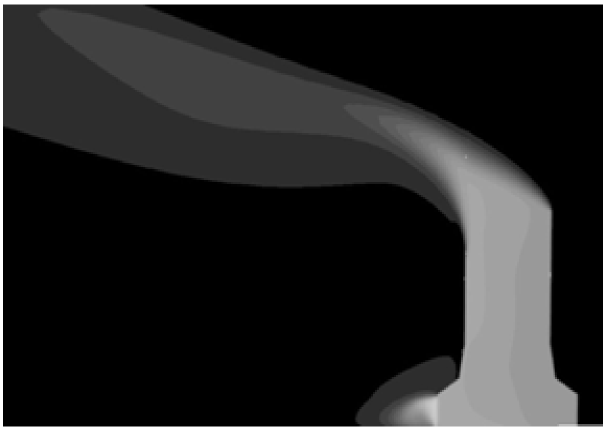


Fig 7. Temperature spectrum on the symmetry surface of the tower with the inclined outlet

Figure (4) shows the isotherms on the symmetry plane, illustrating the plume's extent. The proposed design exhibits a wider plume, indicating reduced choking compared to the conventional design. Figure (5) further confirms this by showing the temperature spectrum, which highlights the improved flow distribution in the proposed design. Figure (6) depicts the velocity field in the mid-section of the lower part of the tower (radiator region). The proposed design shows a reduction in vortex size and intensity, leading to an increased mass flow rate of air entering the tower.

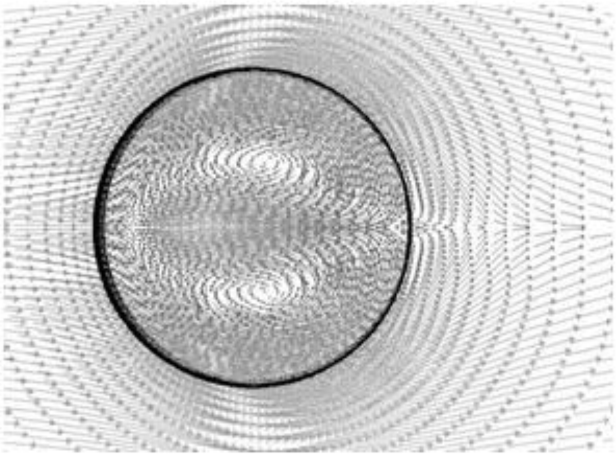


Fig 8. Velocity vectors in the middle layer of the radiators of the tower to the normal outlet opening

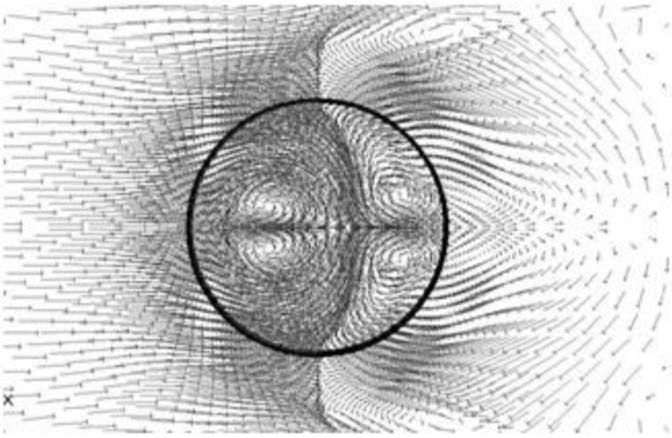


Fig 9. Velocity vectors in the middle layer of tower radiators with inclined outlet opening

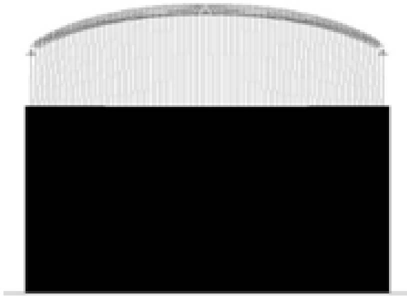


Figure 10: Velocity profile at the outlet opening of the tower with normal outlet opening under wind speed of m/s

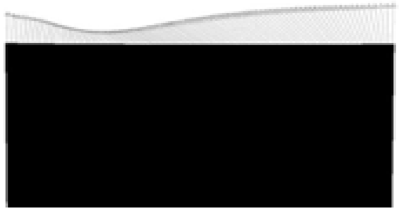


Fig 11. Velocity profile at the exit opening of the tower with normal exit under wind speed of 10 m/s.

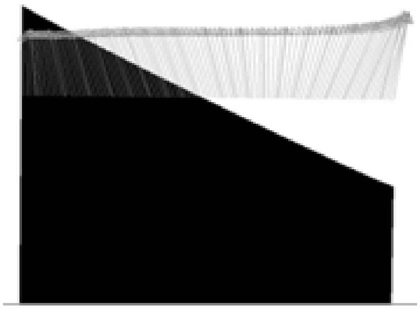


Fig 12. Velocity profile at the exit opening of the tower with inclined exit opening under wind speed of 10 m/s.

Figure (7) presents velocity profiles under different conditions. In the conventional design, the velocity profile at the outlet is symmetrical and regular in still air but becomes irregular and tilted under wind due to choking. In the proposed design, the velocity profile is more uniform due to the reduced choking effect. Figure (8) shows the local velocity distribution along the centerline of the outlet under different conditions. These plots confirm the findings from Figure (7) and demonstrate that the average outlet velocity in the proposed design is higher than in the conventional design under wind conditions. This is due to the increased mass flow rate resulting from the windbreaks. In summary, the proposed design mitigates choking at the outlet, increases the mass flow rate of air through the radiators, reduces turbulence and flow separation inside the tower, and creates a more uniform temperature distribution in the plume. The average outlet velocity in the proposed design approaches that of the conventional design in still air, indicating improved efficiency under wind conditions. In the examination of the numerical results in the elliptical geometric design, the wind causes disorder in the orderly distribution of the outlet velocity at the tower opening. According to Figure 14, it can be seen that the radiators are attacked by the wind on one side and are located in the flow separation area on the other side. Also, the radiators parallel to the wind, which is the most critical area of the radiators. The size of the tangential speed has increased greatly, and this increase in speed causes a decrease in pressure, so that little air enters the tower from these parts. Therefore, the suction of the tower will drop sharply in these areas and will reduce the tower efficiency. Contrary to the article mentioned, the radiators facing the wind, It has an increase in total pressure in its inlet section, which causes a greater flow rate of air to enter the tower from this area. On the other hand, the radiators that are placed behind the tower are located in the flow separation area, which does not naturally change the suction of the tower. The difference in the amount of movement between the incoming flows from the radiators located behind the tower and the radiators facing the wind, inside the tower, is inclined to the side parts. and form a pair of vortices along the centerline of the tower, the presence of which destroys the uniform distribution of hot air flow inside the tower and creates a pressure drop in the path of the air flow, reducing the flow rate through the tower. As a result, it reduces the cooling efficiency of the tower. With a glance at the obtained results, it can be seen that in the case of blowing wind, there are more or less the mentioned events for all the states investigated in this research. But the elliptical cooling tower with a diameter ratio of a=0.5b has better efficiency than other towers with different diameter ratios, including the circular one. The reason for this is that the number of radiators exposed to the wind and located in the back to the wind is greater. Therefore, the geometric shape a=0.5b is introduced as the optimal and recommended shape instead of the circular tower (relative to the diameter a=b), which is about 12% more efficient in comparison.

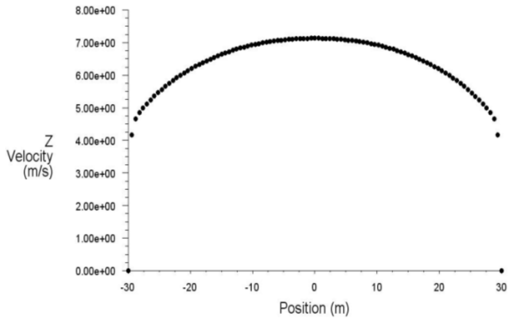
4. Conclusion

This study investigated the adverse effects of wind on the performance of a cooling tower through numerical simulations under various structural configurations. The results demonstrate that:

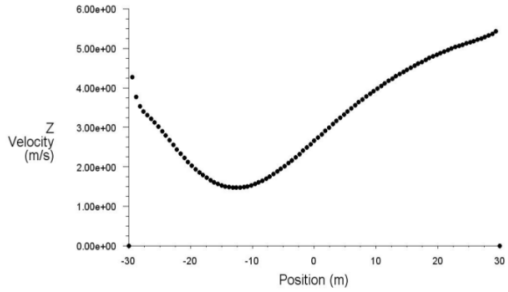
1. In regions with a predominant wind direction, chimneys with an inclined outlet cross-section (angled away from the wind) can reduce choking in the exhaust plume.
2. The application of windbreaks in the radiator region increases the mass flow rate of air entering the radiators and delays flow separation on the leeward side.
3. The implementation of windbreaks and an inclined outlet significantly improves the performance of the Heller dry cooling tower under wind conditions, bringing its efficiency closer to the design condition (no wind).
4. Changing the tower's shape from circular to elliptical, with the major axis facing the wind, can further mitigate the adverse effects of wind and improve heat transfer by exposing more radiators to the wind. The optimal elliptical shape with a 2:1 aspect ratio provides approximately 12% higher efficiency than the conventional circular design.

In conclusion, the proposed design effectively reduces the adverse effects of wind, bringing the tower's performance under wind conditions closer to its design performance in still air.

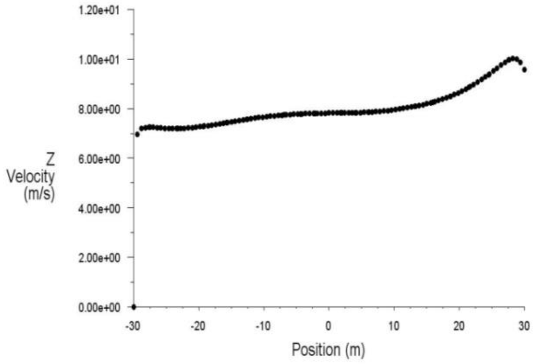
In areas where the wind direction is from one side, you can use chimneys that have an exit cross section with an angle of inclination towards the wind direction. This work reduces the severity of choking in the exhaust plume. The use of wind breakers in the radiators also increases the mass flow rate of the air entering the radiators and delays the separation of the flow in the back to the wind. The desired effect of the proposed design is much greater than the proposed windbreak design or the proposed inclined outlet section design. The application of this plan brings the efficiency of the Heller dry cooling tower under wind very close to the design condition (tower in still air). And in fact, it can be said that it eliminates the adverse effects of wind blowing to an acceptable extent. Also, by changing the shape of the tower structure, from circular to oval, it is possible to reduce the adverse effects of wind. and increased the heat transfer rate of the radiators by exposing them more to the wind. To achieve this purpose, the structure of the elliptical tower should be exposed to the wind in such a way that the large diameter of the ellipse is against the wind, so that more radiators are exposed to the wind. It should be noted that if the large diameter of the ellipse is placed against the wind, the result will be the opposite. Therefore, in places where the wind always blows in the same direction most of the year, Elliptical towers, whose large diameter is against the wind They can have better efficiency And the geometric shape a=0.5b is introduced as the optimal and suggested shape instead of the circular tower which is about 12% more efficient compared to that. In the other case, in any part of the radiators that is exposed to wind, By closing its louvres to the required amount and distributing the water asymmetric in the radiators, The mass flow rate of water in the radiators facing the wind has increased to reduce the same amount of other radiators that have less cooling capacity. Applying this method brings the efficiency of the dry cooling tower under the wind very close to the design state (still air tower). In fact, it can be said that it reduces the adverse effects of the wind to a significant extent.



Tower with normal outlet in still air



Tower with a normal outlet opening under a wind speed of 10 m/s



Tower with windbreak and inclined outlet under wind speed of 10 m/s

A tower with a wind breaker and an inclined exit opening under a wind speed of 10 m/s

Figu 13. Velocity distribution drawing in the center line of the tower outlet

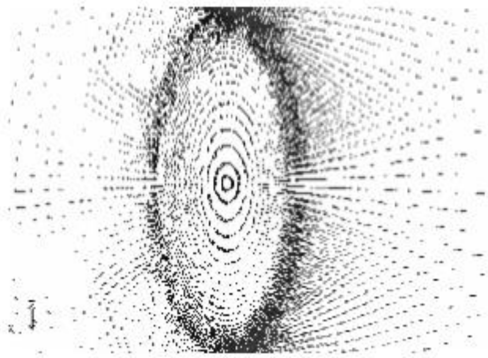


Fig. 14. Distribution of velocity vectors in the vicinity of the 10-meter height for figure a = 0.5b

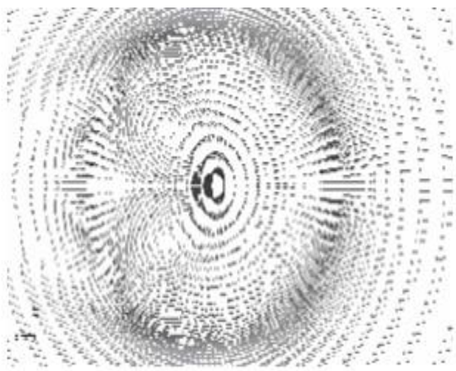


Fig 15. Distribution of velocity vectors in the vicinity of 10 meters height for figure a=0.5b

References

[1] Kapas, “Behavior of Natural Draught Cooling Towers in Wind”, CMFF, 30, Budapest, Hungary, 2003.

[2] A.F.DuPreez, and D.G. Kroger, “Effect of Wind on Performance of a Dry- Cooling Tower”, Heat Recovery Systems and CHD, VOL. 13, pp. 139-146, 1993.

[3] Wei Q., Zhang B., Liu K., Du X., and Meng X., “A Study of The Unfavorable Effects of Wind on the Cooling Efficiency of Dry Cooling Towers”, Journal of Wind Engineering and Industrial Aerodynamics, Vols. 54 and 55, pp. 633–643, 1995.

[4] Al-Waked R., Behnia M., “The Performance of Natural Draft Dry Cooling Towers under Cross Wind: CFD Study”, International journal of energy research, Vol. 28, pp. 147-161, 2004.

[5] Parvizi. Bahram, "Analysis and investigation of the negative impact of wind on the performance of dry cooling towers in power plants and providing a solution," Master's thesis, Mechanical Engineering, Energy Conversion, Tarbiat Modares University, 2007.

[6] B. Gebhart, “Buoyancy-Induced Flows and Transport”, Textbook Edition, Hemisphere Publishing Corporation, 1988.

[7] B. E. Launder, and D. B. Spalding, “The Numerical Computation of Turbulent Flow”, Comput. Metods Appl. Mech. Eng, Vol. 3, pp. 269-289, 1974.

[8] “The Heller System”, EGI, Budapest, 1984.

[9] Dr. Goodarzi. Mohsen, Raofi. Mina, "A design proposal for the shape of the dry cooling tower chimney in order to reduce the adverse effects of wind," Proceedings of the First National Conference on Power Plants, pp. 206-213, Qazvin, Imam Khomeini International University, March 2008.