Experimental Study of the Flue Gas Injection to Improve the Natural Draft Cooling Tower Performance under Crosswind

Mohammad Hassan Kayhani, Ali Abbas Nejad, Mojtaba Khaksar

Abstract—Natural draft dry cooling towers are the common towers that mostly used in waterless areas. Environmental conditions such as crosswind play an important role in the cooling tower performance. In this study, experimental model of a single cooling tower at the base in the KARAJ power station of IRAN is presented as a case study. Pressure coefficient around model at the entrance of the tower has been measured by using wind tunnel. Effects of crosswinds on the thermal performance of natural draft dry cooling towers have been investigated. Finally, the effect of flue gas injection on natural draft cooling tower performance through experimental simulation has been studied. Results indicate that flue gas injection will improve the performance of cooling tower under cross wind condition.

Keywords— Cross wind, Natural Draft Cooling Tower, Pressure distribution, and Wind tunnel.

I. INTRODUCTION

COOLING towers play an important role in the cooling system of power plant, and its cooling capacity can affect the total power generation capacity directly. There are various types of cooling towers, and among of them, natural draft cooling towers are utilized widely in large scale power plants. The performance of dry-cooling towers is highly sensitive to the environment conditions, particularly the crosswind which may cause reduce up to 40% of the total power generation capacity [1]. Therefore, understanding the environmental conditions effect on cooling tower performance is of great importance. The conventional design of cooling towers does not sufficiently consider the impact of wind, which in fact exists most of time in reality. Hence, it is important to study the influence of wind on the performance of cooling towers and suggest suitable improving methods. Several investigations tried to understand the effect of wind on cooling tower performance.

Wei et al. [2] experimentally investigated the mechanism of unfavorable effects of wind on cooling efficiency of dry cooling towers. Du Preez and Kroeger [3] carried out extensive experimental and numerical researches on the performance of wind-break walls. They studied dry cooling towers that have heat exchangers horizontally placed in the inlet cross-section of towers. Bender et al. [4] investigated the utilization of wind-break walls to balance the airflow rate into cooling tower intakes to prevent ice formations due to cold and windy weather. Both of them concluded that suitable arrangement of wind-break walls can lead to significant reduction in the adverse effects of crosswind. With the aim of finding optimal wind-break solutions, this study uses both wind tunnel experiment and CFD simulation approaches to investigate the performance of wind-break methods for cooling towers under windy conditions. The research interest has been consistently focused on the cooling towers with vertical heat exchangers around the bottom of towers, which generally confront the most significant impacts from crosswinds.

As a consequence, an idea to improve the performance of cooling towers is to utilize of flue gas injection to reduce wind effect on cooling tower performance.

Eldredge et al. [5] numerically investigated the Effects of flue gas injection on natural draft cooling tower performance. They considered five independent variables; flue gas flow rate, flue gas temperature, radial injection location, injection orientation, and liquid entrainment in the flue gas. They concluded that flue gas temperature have the most significant effect on tower performance.

Su et al. [6] studied the thermal performance of a dry-cooling tower under crosswind conditions using computational fluid dynamics (CFD) technologies. The tower had vertical heat exchangers placed around the bottom. They showed that the most important factors for the tower efficiency reduction is the wind-caused divergent airflow at external side of heat exchangers.

Fu and Zhai [7] numerically studied the effects of crosswind on two in-line dry cooling towers. The two-tower case demonstrated different heat transfer and airflow patterns from the single tower study, especially when the wind speed is larger than 10 m/s. However, the study verified that the wind induced around flow destroys the radial inflow into the...
cooling towers and thus extensively deteriorates the heat transfer performance at lateral sides.

Cooling tower is normally designed for stagnant ambient air condition, but experimental observation showed that cooling efficiency was changed as a function of crosswind velocity. Experimental and numerical observations identically showed that heat transfer capacity of the cooling tower proportionally increased with wind velocity up to 3 m/s, and then decreased for higher wind velocity, [8].

Al-Waked and Behnia [9] simulated the flow field in the presence of different wind breakers under the wind condition. They evaluated the air mass flux through the radiators. Also, they computed the heat flux from the radiators and concluded that in the presence of wind breakers both the mass and heat fluxes increased under the high wind velocities.

Also, other researchers Parvizi, [10] reported the same beneficial concept of using the wind breakers. Although the wind breakers improve the cooling efficiency, designers have never used them practically.

Al-Waked [11] investigated crosswinds effect on the thermal performance of natural draft wet cooling towers numerically. Goodarzi [12] proposed a stack configuration for dry cooling tower to improve cooling efficiency under crosswind. Numerical simulation of the proposed configuration showed improvement in the cooling efficiency up to 9 percent compared to the present.

II. WIND TUNNEL EXPERIMENTS AND ACCESSORIES

A. Similarity Parameters

The complete coupled equations describing the flow around and through a dry cooling tower and their boundary condition are quite difficult and have numerous similarity parameters in wind tunnel test [2]. In this experiment the two most important similarity parameters are as follows:

(i) Reynolds number

$$\text{Re} = \frac{\rho V D}{\mu}$$  \hspace{1cm} (1)

(ii) Pressure coefficient

$$C_p(h, \theta) = \frac{P(h, \theta) - P_\infty}{\frac{1}{2} \rho V(h)^2}$$  \hspace{1cm} (2)

Where $\rho$ is the ambient air density, $V$ is the mean velocity passing through the tower, $D$ the diameter of tower in base, $\mu$ the dynamic viscosity, $C_p$ the pressure coefficient at a height of $h$ and angle of $\theta$, $P$ local pressure at $(h, \theta)$, $P_\infty$ free stream static pressure, $V(h)$ free stream mean velocity at a height of $h$ and $h$ the height of experiment.

In general, the Reynolds number similarity cannot be achieved in wind tunnel testing; the Reynolds number of full-scale tower order is $10^7, 10^8$ and in wind tunnel order is $10^5$ [13]. However outer pressure coefficient of model and prototype must be equal.

$$C_p(\theta, h)_{\text{model}} = C_p(\theta, h)_{\text{prototype}}$$  \hspace{1cm} (3)

B. Wind Tunnel Specification

All experiments hold in wind tunnel of Shahrood University of Technology. This tunnel is open-circuit with at length of about 18m and 80cm $\times$ 80cm $\times$ 200 cm test section. The wind tunnel is equipped with a centrifugal fan and three phases motor. Schematic of wind tunnels and test section shows in Fig. 1. Maximum velocity of this is approximate 35m/s and turbulence intensity in maximum velocity is about 0.05% and 0.2% in minimum velocity as shows in Fig. 2.

C. Model

Hyperbolic model made of ceramic material is used to scale the 1/400 of the prototype. The prototype was the KARAJ cooling tower which has the following dimensions: 92m height, 72m diameter of the base, 49m diameter of the tip, 48m diameter of throat and 15m height of the heat exchanger.
24 holes with 2mm diameter and 15 degree circumferential spacing are located around the model inlet to measure the pressure distribution. The holes placed at a height of $a/b = 0.5$, where $a$ is the height of holes and $b$ is radiator height. The test tubes connect the holes and the pressure transmitter. All measurements were stored in computer data storage system. The rate of pressure signals were $200 \text{Sample/s}$.

The model position in wind tunnel was at a height of 0.2m from test section floor and 1m from its beginning. Figs. 3 and 4 show the model and schematic of the used equipments, respectively.

III. RESULTS AND DISCUSSION

In order to determine the pressure distribution, the dimensionless pressure coefficient was used, as in (2). Pressure distribution curves for different Reynolds numbers based on the angle at the outer surface and inner surface are plotted in Fig. 5, and Fig. 6.

As is shown in Fig. 5, with increasing Reynolds number the external pressure distribution becomes more negative, in the side part of tower (outside the radiator), that means the flux of the air entering into the tower is reduced in that part of tower and so the cooling efficiency decrease because the air tangential velocity is lower similar to flow over a cylinder.

According to Fig. 5, the flux of air entering the radiators increases in the front part of tower (facing the wind).

From Fig. 6, it is clear that the internal pressure distribution increases and became worse with increasing Reynolds number. As a result the cooling efficiency decreases with increasing wind velocity.

The change in internal and external mean pressure coefficient based on the Reynolds number is depicted in Fig. 7.

(a)

(b)
It is obvious that increasing the wind speed can cause the reduction of air entering into the tower and cooling tower efficiency.

To reduce the adverse effects of wind on the performance of cooling towers, various proposals have been presented. One way was to use the flue gas injection into natural draft cooling tower. Although natural draft towers are not usually as tall as the stacks, benefit is taken of the upward momentum in the towers, along with the buoyant plume, to achieve the necessary atmospheric rise for the flue gas. Another advantage of gas injection into a cooling tower is that the discharged flue gas gets diluted by as much as a factor of ten before disposal to the atmosphere. As shown in Table I the pressure distribution becomes more negative due to the injection, and thus the tower performance can be improved. In Fig. 8 the influence of external pressure distribution is plotted for the flue gas injection. Notice that as a result the external pressure distribution does not change. So this method cannot be used to improve the distribution of external pressure.

<table>
<thead>
<tr>
<th>Re $\times 10^5$</th>
<th>Mean Pressure Coefficient</th>
<th>Mean Pressure Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Flue Gas Injection</td>
</tr>
<tr>
<td>0.66</td>
<td>-0.65</td>
<td>-0.85</td>
</tr>
<tr>
<td>0.76</td>
<td>-0.58</td>
<td>-0.73</td>
</tr>
<tr>
<td>1</td>
<td>-0.48</td>
<td>-0.56</td>
</tr>
<tr>
<td>1.2</td>
<td>-0.46</td>
<td>-0.50</td>
</tr>
<tr>
<td>1.9</td>
<td>-0.45</td>
<td>-0.48</td>
</tr>
<tr>
<td>2.8</td>
<td>-0.44</td>
<td>-0.47</td>
</tr>
<tr>
<td>3.2</td>
<td>-0.43</td>
<td>-0.46</td>
</tr>
</tbody>
</table>

Fig. 9 the outer pressure distribution

IV. CONCLUSION

In this study, effects of crosswinds on the thermal performance of natural draft dry cooling towers have been investigated. It was observed that with increasing the wind speed the circumferential pressure distribution becomes more unfavorable and the cooling efficiency decreases. To reduce the unfavorable effects of wind on the performance of cooling towers, effect of flue gas injection on natural draft cooling tower performance through experimental simulation has been studied. Using flue gas injection into the cooling tower the internal pressure distribution becomes more negative, which improves the performance of the cooling tower. It was observed that changes in external pressure distribution are not significantly influenced by gas injection either.

As a conclusion, flue gas injection into natural draft dry cooling towers will improve their performance under cross wind condition.

REFERENCES