

Effect of Wind Loads on Structural Deformation of Cooling Tower

A. D. John, R. Foroughi, A. Gairola

Abstract—This paper presents influence of interfering structures on deformation of cooling tower due to non-axisymmetric horizontal wind loads. First, the pattern of the wind load distribution on cooling tower has been studied in a wind tunnel on 1:150 geometrical scale models with interfering structures, then deformation pattern of the tower have been studied. Wind loads on cooling tower have been obtained under a simulated wind condition for open country and suburban terrain in a Boundary Layer Wind Tunnel at Indian Institute of Technology Roorkee, India. Experimental results show that, in case of interference for an oblique approach wind, there is a significant increase in the magnitude of the net pressure coefficients on windward meridian. Using the experimental wind load values, numerical linear analysis was performed to find the deformation of the tower. The deformations of the tower have evaluated for both mean and fluctuating wind loads. Due to mean wind loads, the maximum deformation occurred at throat level for isolated tower. Also, the fluctuating wind load shows no significant adverse change in the deformation for the interference condition where magnitude of wind loads enhanced significantly as compare to isolated tower.

Keywords—wind loads, interference effect, cooling tower, deformation, fluctuating loads

I. Introduction

According to investigations, strong winds modified due to interference effect may cause severe damage to the shell of cooling tower (Sun et al. 1992). For this, it is essential to understand the effect of wind load on cooling tower due to nearby structures, where amplification in wind loads may occur. The modification of the flow by adjacent structures is known as interference. Experimental investigations on prototypes or wind tunnel models are used for its correct evaluation (Khanduri et al. 1998). Currently, there are no valid theoretical models to evaluate the wind loads on cooling tower due to interference. Armitt (1980) and Blessmann (1991) have shown flexible and rigid model can be used in Boundary Layer Wind Tunnel (BLWT) tests. For flexible model, interference effects on strain are measured with strain gauges placed on the inner and outer surfaces of the model. For rigid model, interference effects on pressure patterns are measured and structural response can be calculated using numerical analysis.

Orlando (2001) has investigated wind induced interference effect on two adjacent cooling towers experimentally and numerically. Author has used experimental pressure values for

numerical linear analysis to calculate the structural response of the isolated and grouped towers. The results obtained agree with those of other researchers and demonstrate the reliability of the procedure adopted to estimate wind induced stresses on rigid structures in close proximity. Niemann and Kopper (1997) studied influence of adjacent buildings on wind effect on cooling towers. Sun et al. (1992) have done full-scale measurement and wind tunnel testing for wind loading on two neighboring cooling towers. Orlando (1998, 2001), Borri et al. (1999), John et al. (2011) have studied interference effect on cooling tower and performed numerical analysis.

In this paper, first part is experimental and describes the pressure patterns measured on the rigid model of cooling tower. Second part describes structural deformations of the tower, particularly at throat level. For this, numerical analysis were performed using experimentally obtained data for isolated and interference condition. The deformations of the tower have evaluated for both mean and fluctuating wind loads. Linear elastic behaviour of the material was taken into consideration in the computations.

II. Experimental Setup

A. Wind-Tunnel and Boundary-Layer Simulation

First, The experiment has been carried out in an open circuit atmospheric Boundary Layer Wind Tunnel at Indian Institute of technology Roorkee. The working section of the tunnel is 15 m long and 2.1 m wide. The height of the working section is approximately 2.0 m. The wind speed of the reference height ($z = 100$ cm) is 11.55 m/s.

In the present study, instantaneous velocity fluctuations have been recorded using hot-wire probe at a sampling frequency of 500 Hz for a duration of approximately 1 second; total 8192 samples were recorded at each point to define flow characteristics.

The mean wind velocity and longitudinal turbulence intensity profile obtained in the wind tunnel is shown in Figure 1. The velocity profile had a power law exponent, $\alpha = 0.14$. The values of mean velocity and longitudinal turbulence intensity at top of model (43.5 cm) from the surface of wind tunnel have found to be 10.1 m/s and 8% respectively.

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The turbulence intensity was about 11% at 320 mm above the floor, which corresponded to the throat level of the model tower.

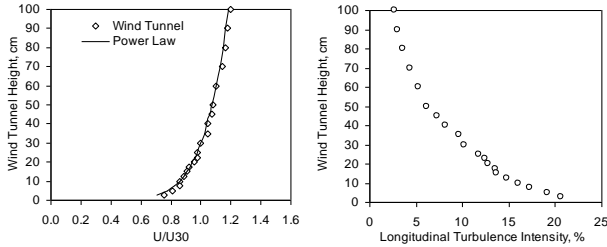


Figure 1. Mean wind velocity and turbulence intensity profile

B. Cooling Tower and Interfering Structures

The rigid model of cooling tower was fabricated to the scale of 1:300. The model was made out of a solid teak wood that was machined properly to obtain the desired shape accurately. The machining was done on both external and internal surfaces. The thickness of the model wall was about 23 mm. The model had 75 percent opening at the base. The model was provided with two sets of external pressure points along two meridians separated by 120°. Besides, one set of internal pressure points was used for measuring internal pressures. The pressure distribution on azimuth was obtained by rotating the model, which was mounted on a turntable in the test section of the wind tunnel. The outer surface of cooling tower model is suitably roughened by sand particles of size about 1 mm so that the boundary layer tends to become turbulent at Reynolds number prevalent in the wind tunnel and flow conditions are similar to that for the prototype.

Model tower consist of the pressure points at ten different levels. The sets of pressure points for internal as well as external pressure were so made that the connecting plastic tubes remained inside the tower model and did not affect the external flow. Equations 1 and 2 give the mathematical expressions (IS:11504, 1985) for the profiles of cooling tower above and below the throat respectively.

$$\left(\frac{R}{31.025}\right)^2 - \left(\frac{Z}{126.985}\right)^2 = 1 \quad (1)$$

$$\left(\frac{R - 14.410}{16.615}\right)^2 - \left(\frac{Z}{45.774}\right)^2 = 1 \quad (2)$$

where, R is the centreline radius of the tower shell and Z is the height from the throat.

The model of test cooling tower was once tested in the isolated condition; it was then placed along with the simulated terrain in the wind tunnel to measure pressures corresponding to different angles of wind incidence as shown in Figure 2. For

surface pressure measurements, the choice of tubing system for pressure measurements is based on the study of Holmes and Lewis (1986, 1987, 1989). Small diameter of 1.2 mm plastic tubes has been used to transmit the pressure from the pressure tap to the pressure transducer.

C. The Prototype

The prototype cooling tower for which the wind tunnel test was conducted is a natural draught type tower with base diameter 107 m, 62.05 m at the throat, and 64.05 m at the top. Shell thickness of the tower varies from 500 mm at the top to 700 mm at the bottom with a minimum shell thickness of 250 mm at the throat level. The height of the air opening is 6.0 m above, having 88 diagonal columns and height of the hyperbolic shell is 124 m. Layout of tall structures (whose heights are greater than 25 m) in the vicinity of cooling tower to be studied is as shown in Figure 2.

The hourly mean wind speed (V_z) and design wind pressure (P_z) at the top of cooling tower can be obtained from the Equations 3 and 4 respectively.

$$V_z = k_1 \times k_2 \times k_3 \times V_{3\text{-sec}} \quad (3)$$

$$P_z = \frac{1}{2} \rho V_z^2 \quad (4)$$

where, $V_{3\text{-sec}}$ is the basic wind speed at site (3-sec gust velocity) at a height of 10 m above the ground surface as specified in the Indian Standard Code, IS: 875 Part 3 (1987), k_1 is return period, k_2 is terrain-height factor and k_3 is topographic factor. The aim of this study is to calculate relative deformation of shell of cooling tower for different wind conditions, unit load per square meter area is considered.

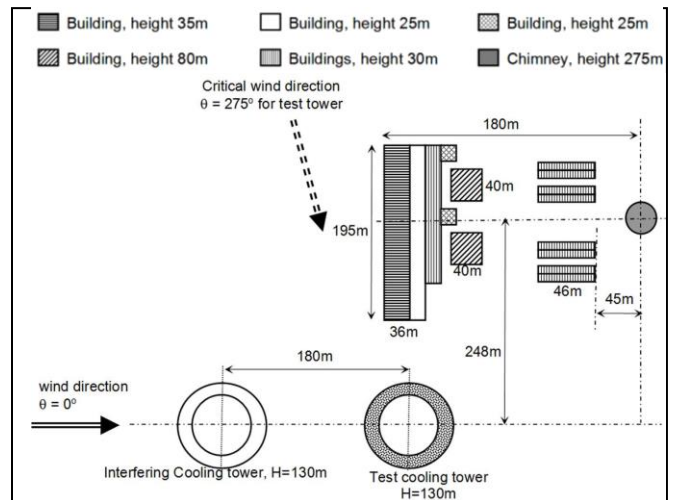


Figure 2. Full-scale schematic diagram of cooling tower and other structures

D. Data Acquisition System

Pressure taps (10 mm long, 1.3 mm external diameter and 1 mm internal diameter) of stainless steel tube were fixed through the holes drilled into the wood. One end of the tap was flushed with the surface of cooling tower. Tubing for measuring surface pressure consisted of 300 mm vinyl tube with a 20 mm long restrictor placed at 200 mm from the pressure point. Pressure measurements were carried out by using a Scanivalve ZOC23B, a 32-port pressure scanner, having a linear response up to 200 Hz. The sampling rate was kept at 500 samples per second per channel. The duration of each run was 16 seconds. Wind pressures measured on the model of cooling tower are expressed in a non-dimensional pressure

E. Mean Pressures on the Isolated Tower

The mean pressure on the isolated tower varies with height and longitude. To enable the mean data obtained from wind tunnel tests to be applied to prototypes, non-dimensional pressure coefficients (C_p) is defined in equation 5.

$$C_p = \frac{P_i - P_0}{1/2\rho U^2} \quad (5)$$

where, P_0 = static (ambient, atmospheric) reference pressure, P_i = instantaneous surface pressure, ρ = air density, U = mean velocity measured at eaves height of the model.

The mean pressure coefficient diagram on the isolated tower was symmetrical compared with the flow direction. The pressure on the windward meridian at outer surface was positive ($C_p = 1.0$ at the throat), the maximum negative pressure (suction) was located on both sides ($C_p = -0.80$ at the throat), and the wake pressure was constant ($C_p = -0.45$ at the throat). The minimum value of the pressure coefficients at the throat occurred at 60° of longitude (Figure 3).

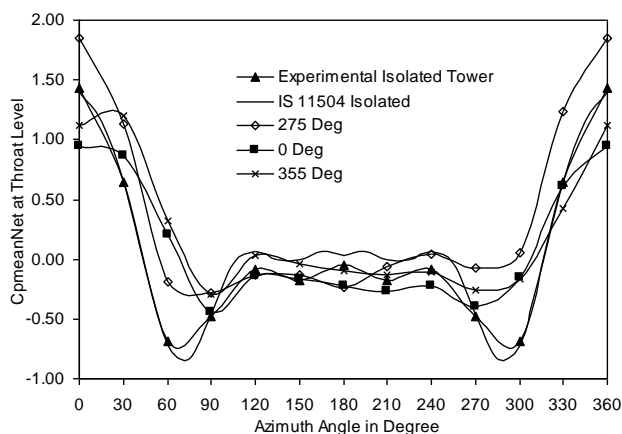


Figure 3. Variation of net mean pressure coefficients at throat levels of cooling tower

F. Maximum Pressures

Design pressure coefficients, C_{pq} were calculated using the equation 6.

$$C_{pq} = C_{pmean} + C_{psd} \times g_p \quad (6)$$

where, g_p is peak factor. All peak factors equal to about 3.2 at all levels and longitudes, in both the upwind and downwind regions were examined. Other researcher, Orlando (2000) mentioned the values of about 3.14 and Niemann and Ruhwedel (1980) stated the peak factor value of about 3.6.

III. Results and Discussion

A. Pressure Coefficients on the Isolated Tower

The isolated situation is a non-existent case and is used only for appreciating the enhancement in the values of pressure coefficients due to interference, and for the validation by making comparison with the theoretical variation of the pressure coefficient.

The net-mean pressure coefficient ($C_{pmeanNet}$) on the isolated tower varies with height and longitude. The $C_{pmeanNet}$ on the isolated tower have found to be symmetrical compared with the flow direction and there is a good match between the experimental results with values given in Indian code, IS:11504 (1985). Figure 3 also shows the variation of the $C_{pmeanNet}$ on the cooling tower for interference condition at 0° , 300° and 275° (critical) angle of wind incidences.

The net C_{pmean} on the windward meridian was positive and it is found to be +1.43 at the throat level. The maximum negative pressure (suction) of -0.69 was located at -60° (or 300°) angle in azimuth at the throat, thus indicating a change of 2.12 within 60° angle in azimuth. Wake pressure of approximately -0.15 was observed and it was constant at the throat level.

B. Pressure Coefficients for Interference Condition

The wake produced by the interfering effect of nearby structures changes the flow separation points on the test-cooling tower. This leads to the change in pressure distribution on the surface of the cooling tower. The wind tunnel test results for the $C_{pmeanNet}$ on tower due to interference at different angle of wind incidence are given in Figures 3. The values corresponding to the most critical wind direction i.e. $\theta = 275^\circ$. The maximum positive value of the net pressure coefficient is obtained as +1.89 at throat level at 0° angle of wind incidence. This value is found to be 30% more as compare to that of isolated tower. Maximum negative pressure was found to be -0.3 at 90° angle in azimuth.

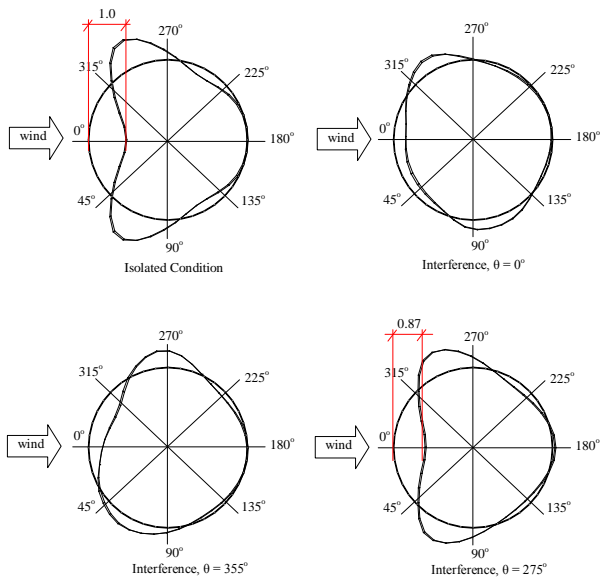


Figure 4. Deformed shape of cooling tower at throat level under mean loads

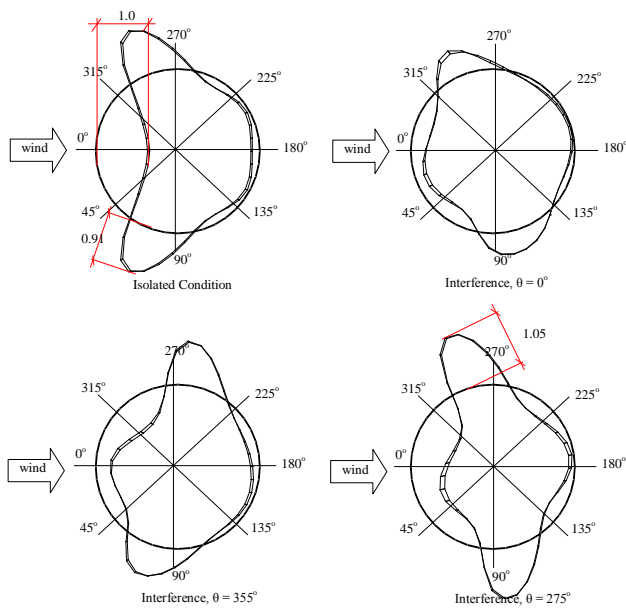


Figure 5. Deformed shape of cooling tower at throat level under fluctuating loads

C. Deformation in Cooling Tower

To understand the deformed shape of cooling tower for different wind conditions, static analysis of the tower was performed using the Finite Element (FE) models. The structural deformations were calculated by numerical analysis for different conditions of wind. Experimental values of pressure coefficients, $C_{pmeanNet}$ and C_{pq} are used for the numerical analysis. The deformations due to the applied pressures in the tower were calculated with the FE model. The model shell was discretised into isoperimetric plane elements with four nodes. The calculated pressure values were

perpendicularly applied on the model plates. For deformation analysis of tower, self-weight and wind loads was considered. The aim of this study is to analyse the relative deformation in the tower for different wind conditions. Therefore, deformation values have been normalised by the nodal displacement at throat level at windward meridian for both mean and fluctuating wind loads.

Deformed shapes of cooling tower and its magnitude (normalized resultant) at throat and top level for mean and fluctuating wind loads are given in Figure 4 and 5. Although, Interference effect has shown increase in the values of positive mean pressures of about 30%, resultant displacement in the interference condition is found to be less as compared to the isolated tower. Due to $C_{pmeanNet}$ maximum deformation was observed at throat level on the windward meridian for isolated tower. Whereas, for critical wind direction at interfering i.e. $\theta = 275^\circ$, the maximum nodal displacement is found to be 13% less at throat level on the windward meridian. For interference condition, nodal displacement in tower has found to be less in all azimuth compare to the isolated one.

Similar situation has found under fluctuating wind loads. Maximum amplification for C_{pq} was about 30% and was found for interfering positions at $\theta = 275^\circ$ as compare to isolated tower. However, interference shows no significant change in the magnitude of deformation. This is due to the combined effect of C_{pq} for both positive and negative pressures on all azimuth of the tower.

Conclusions

This paper has investigated wind-induced interference effects on cooling towers due to nearby structures experimentally and numerically. First, wind tunnel tests were performed to characterise the pressure patterns on the rigid model of the cooling towers at different angle of wind incidences. Then experimental data were used to evaluate the deformation of the tower. The most significant interference effects were found at $\theta = 275^\circ$ where $C_{pmeanNet}$ and C_{pq} increase by 30% and 70% respectively at the throat level as compared to that of isolated tower.

The experimental values of pressures were used for numerical linear analysis to find the deformation of cooling tower. The deformation results in this study are based on mean as well as fluctuating wind load. It is found that the maximum nodal displacement in the tower due to mean wind loads occurred at throat level for isolated tower. Also, there is no significant adverse change in the deformation of the tower due to the increase in the values of fluctuating wind loads obtained experimentally at interference condition. This is due to the combined effect of pressure values developed on the azimuth of the cooling tower.

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