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Fluctuating wind pressure distribution around full-scale cooling towers

Lin Zhao[a,*], Yaojun Ge[a], Ahsan Kareem[b]

[a] State Key Lab for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[b] NatHaz Modeling Laboratory, University of Notre Dame, 156 Fitzpatrick Hall, Notre Dame, IN 46556, USA

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ABSTRACT

At present, external wind pressure description around cooling towers in various loading Codes is based on full-scale measurement data. The data has been collected during 1960s–1990s for hyperbolic cooling towers with heights of about 90 m~120 m, and focus has been usually on the average wind pressure distribution. In fact, modern cooling towers taller than 165 m show sensitivity to wind-induced effects under strong wind excitation. The performance of these flexible structures is closely related to the fluctuating wind action in the atmospheric boundary layer. Modeling of these features is underscored by the difficulty in matching supercritical Reynolds number in boundary layer wind tunnels. Accordingly, it has been difficult to accurately establish a relationship between fluctuating pressures on the surface of a cooling tower to inflow conditions. This has caused a bottleneck for enhancements in the state of wind resistant structural design of larger cooling towers. In view of this difficulty, high Reynolds number flows were simulated in the wind tunnel using scaled model with a combination of surface roughness elements to establish a relationship between the inflow turbulence intensity and pressure fluctuations. This was supplemented by a validation using data from long-term measurements of wind pressure around a 166.68 m cooling tower. Wind tunnel experiments were in a general agreement with full-scale observations which offered a relationship between the fluctuating wind pressure distribution and the incoming turbulence intensity at supercritical Reynolds number conditions (Re≥4×10E7).

1. Introduction

The main loads during the life-cycle of hyperbolic cooling tower usually include gravity, wind loading, temperature stress, seismic action, construction loading and uneven settlement of foundation. Tall thin-walled flexible structures are particularly sensitive to wind excitation. Wind actions are dominating loads for structural design of the tower shells under normal circumstances considering various loading combinations. In 1965, three out of eight cooling towers with double-row diamond-shaped arrangements in the British Ferrybridge Power Plant collapsed mainly due to aerodynamic interference effects at an average wind velocity of about 19 m/s. Following this disaster, in 1973, the Scotland Ardeer Power Plant expereinced another cooling tower collapse under strong winds. The International Wind Engineering Society took this opportunity to carry out systematic studies on wind effects on cooling towers (Simiu and Scanlan, 1996), conducting in-situ measurements of wind pressure characteristics over the surface of a cooling tower (Sun and Zhou, 1992) and proposing a testing technique for the measurements of pressures pressure and force fluctuations utilizing a surface roughness to simulated high Reynolds number flows (e.e., Kareem and Cheng, 1999). Investigations focussing on the influence of tower groups and adjacent buildings on the wind pressure distributions of cooling towers (Sun and Gu, 1995; Niemann and Köpper, 1998; Orlando, 2001), buckling stability and ultimate bearing resistance under wind loading conditions (Radwańska and Waszczyszyn, 1995; Noh, 2006), nonlinear performance considering typical structural defects and soil-structure interaction effect (Karisiddappa et al., 1998; Waszczyszyn et al., 2000; Witasse et al., 2002; Noorzaei et al., 2006; Viladkar et al., 2006) and wind-induced stochastic dynamic response for shell structures (Zahlten and Borri, 1998) were conducted.

Prior literatures on full-scale measurements of wind pressure on a cooling tower surface came from the four-tower combination in the British West Burton Power Plant in the 1960s (Armitt, 1980). The height of the measured tower was 113.5 m and there were 6×12=72 external measurement points and 3×12=36 internal ones. A 10 m-high lattice tower was built near the cooling tower for wind environment observation. However, due to the influence of the cooling tower and surrounding buildings, wind pressure from the observation tower could not be directly used as a reference. Since the internal pressure is unrelated to the measurement height and always has a uniform distribution around the circumference, the inner pressure of the

* Corresponding author.
E-mail address: zhaolin@tongji.edu.cn (L. Zhao).

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cooling tower was taken as a reference value during the in-situ observation procedure.

In 1971, Niemann and Propper (1975) measured the 104 m-high Germany Weisweiler cooling tower on the spot. Wind pressure sensors were unevenly installed at a height of 62.53 m with 78 measured points around the circumference. The experimental measurement of the reduced-scale model was also designed to get the circumferential distribution characteristics of average wind pressure.

In 1974, Sollenberger and Scanlan (1974) conducted measurements on Pennsylvania Martin' s Creek cooling tower in the U.S. The tower was 126.8 m high and the throat part was 107.6 m high. Wind pressure sensors were installed on the throat section with 16 measured points around the circumference, and the instrument recorded up to 164 s wind pressure signals each time. Subsequently, Scanlan analyzed the measured data, studying wind pressure spectra and correlation functions between measured points, proposing wind pressure distribution expressions by means of a 2-order auto regressive model and an appropriate auto regression coefficient, thus showing the characteristics of wind pressure distribution on various measured points.

Since 1981, Sun and Zhou (1992) have measured two full-scale 90 m-high cooling towers in Maoming of Guangdong and in Shijingshan of Beijing. A fitting equation for average wind pressure distribution was then adopted by Chinese loading Codes (GB/T 50102-2003 and DL/T 5339-2006). Limited to technical conditions, only the circumferential distribution of static average pressure on the external surface was measured.

There are also some basic observation reports (Ruscheweyh, 1976; Sageau, 1979; Nienman, 1969; Nienman and Pröpper 1974; Pröpper and Welsch, 1980; Basu and Gould, 1980) that considered surface fluctuating wind pressure characteristics of cooling towers at supercritical Reynolds number conditions (Re≥10E7). Some of the research results have been adopted by relevant specifications (VGB-R, 2010; BTR, 1990; GB/T 50102-2003; DL/T 5339-2006). In Simiu and Scanlan (1996), a simple comparison between fluctuating pressure measurement of prototype cooling towers from Ruscheweyh (1976) and Sageau (1979) and wind tunnel tests of a reduced-scale model by Davenport (Davenport and Isyumov, 1966) in the monograph "Wind Effect of Structure" was made. It was noted that there were some obvious differences about fluctuating wind pressure distribution observation around the prototype cooling towers, and possible influencing factors have been ignored. Table 1 summarizes developments in the measurement of full-scale cooling towers, in which we can find that the earlier observation involving the fluctuating wind pressure were mainly conducted in the cooling towers in Weisweiler and Schmehausen reported by Nienman (1969) and Nienman and Pröpper (1974). The principal aim was to clarify the effect of high Reynolds number and surface roughness on mean pressures. It was followed by a complete analysis of mean and fluctuating pressures involving RMS, co-variance, spectra, cross-spectra, etc.

It is well known that the interference effect and wind-induced vibration of cooling towers are more closely related to the surface extreme wind load distribution and its dynamic excitation. As a result of the imperfection of Reynolds number criteria concerning surface dynamic aerodynamic loads on reduced-scale testing models, it is often difficult to reasonably reproduce the relation between dynamic wind loads under multi-tower combination conditions and inflow average wind speed, turbulence intensity, and integral scale of fluctuating wind. The dynamic wind pressure distribution characteristics of a super-large cooling tower under supercritical Reynolds number conditions has become the bottleneck for modeling using current wind tunnel test techniques and structural design of cooling towers.

Some measured data relate somewhat to fluctuating pressure distribution (Ruscheweyh, 1976; Sageau, 1979; Davenport and Isyumov, 1966). However, there is no consistent understanding and generally accepted conclusions. Most discussions have been focusing on the average wind pressure distribution. Since 2009, in-situ mea-

Table 1
Previous pressure measurement of cooling towers in various countries.

Time	Site / power plant	Project profile	Measured points arrangement	Motivation
1960s	Britain, West Burton	Four-tower combination, smooth tower, tower height 113.5 m	6×12=72 external measured points 3×12=36 internal measured points	Outer average pressure
1970s	U.S.A, Martin's Creek	Two-tower combination, tower height 126.3 m, ribbed tower with 52 ribs	16 measured points nearby throat part, sampling frequency 2 Hz	Outer average pressure
1967–1970	Germany, Weisweiler	Tower height 104.4 m, ribbed tower with 52 ribs	Circumferential uneven distribution of 78 measured points, sampling frequency 0.67 Hz, maximal Re 6×10E7	Average pressure and surface roughness
1975–1976	Germany, Schmehausen	Tower height 121 m, ribbed tower with 52 ribs	Circumferential uneven distribution of 16 measured points, lack in lee side, sampling frequency 4 Hz, maximal Re 1.36×10E8	Average pressures and pressure fluctuations
1960 s~70 s	Germany, Scholven	Four-tower in-line combination, tower height 113.5 m	8 measured points in single row in one cooling tower, totally 18 measured points in three rows in another cooling tower	Fluctuating pressure and its correlation
1980 s	China, Maoming, Guangdong	Single smooth tower, tower height 90 m	Relative measured height Z/H=0.556, 50 external measured points, 8 internal measured points	Outer average pressure
1990 s	China, Shijingshan, Beijing	Istage, single smooth tower, tower height 120.61 m IIstage, two-tower combination	12 external pressure measured points in 60 m high and 8 internal and external pressure measured points in 96 m for No.1 tower 18 external pressure measured points in 60 m high for No.2 tower, arranged more densely near No.1 tower side	Outer average pressure for interference effect