REYNOLDS NUMBER EFFECTS ON HEMISPHERICAL DOMES IN SMOOTH FLOW

C. M. Cheng\(^1\)  C. L. Fu\(^2\)

\(^1\) Director, Wind Engineering Research Center, Tamkang University
Taipei County 251, Taiwan, cmcheng@mail.tku.edu.tw
\(^2\) Department of Civil Engineering, Tamkang University
Tamsui, Taipei County 251, Taiwan, fcl@mail.tku.edu.tw

ABSTRACT

This article investigates the Reynolds number effects on pressure distribution and the wind load pattern of hemisphere dome in smooth flow. The flow visualization scheme and pressure measurements were used to study dome’s aerodynamic characteristics. It is found that the mean meridian drag coefficient decreases with Reynolds number for \(\text{Re}<3.0 \times 10^5\), and then increase monotonically; RMS meridian drag coefficient shows maximum and minimum values at \(\text{Re} \approx 1.5 \times 10^5\) and \(\text{Re} \approx 3.0 \times 10^5\), respectively. The transition of separation flow occurs near \(\text{Re}=3.0 \times 10^5\) and the pressure distributions become relatively stable at \(\text{Re}=2.0~3.0 \times 10^5\).

KEYWORDS: WIND LOAD, HEMISPHERICAL DOME, WIND TUNNEL, SMOOTH FLOW, REYNOLDS NUMBER

INTRODUCTION

This article investigates the Reynolds number effects on pressure distribution and the wind load pattern of hemisphere dome in smooth flow. There exist only few previous works on the aerodynamics of hemispherical domes (Maher\([1]\), Taylor\([2]\), Ogawa et al.\([3]\), Toy et al.\([4]\), Letch-ford and Sarkar\([5]\)). In light of the past works on this issue, it is believed worthy to accumulate more data and better understanding on the aerodynamics of hemispherical domes.

EXPERIMENT DESIGN

Three acrylic hemispherical pressure models with diameters of 120 cm, 50 cm, and 20 cm, were used in this investigation; the corresponding Reynolds number varies from \(5.3 \times 10^4\) to \(2.0 \times 10^6\). During wind tunnel tests, base plate elevated from floor was used to minimize the boundary layer developed over base floor. The wind tunnel setups are shown in Figure 1. Over 200 pressure taps were installed on each of the dome models. Instantaneous wind pressures were sampled simultaneously at 300 Hz to investigate the pressure pattern in different testing conditions. The blockage ratios of the tests were 0.0015 –0.054. In addition to the pressure coefficients, pressure contours and spectral characteristics, spatial correlation analysis and flow visualization were adopted to provide better interpretations of the flow patterns. The wind tunnel testing cases are listed in Table 1. Shown in Figure 2 is the coordinate system of the pressure taps on hemisphere dome surface, in which, \(\bar{\phi}\) denotes the angle of longitude and \(\bar{\theta}\) is the angle of center meridian; for the contours of pressure coefficients, \(\bar{\omega}\) is used denoting the angle of latitude.
<table>
<thead>
<tr>
<th>Model</th>
<th>Diameter</th>
<th>Reynolds number</th>
</tr>
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<tbody>
<tr>
<td>Dome S</td>
<td>20 cm</td>
<td>6.6x10^4 - 3.4x10^5</td>
</tr>
<tr>
<td>Dome M</td>
<td>50 cm</td>
<td>1.6x10^5 - 8.7x10^5</td>
</tr>
<tr>
<td>Dome L</td>
<td>120 cm</td>
<td>5.3x10^5 - 2.0x10^6</td>
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**EXPERIMENTAL RESULTS**

In order to explain these phenomena, flow visualizations were conducted in a smaller wind tunnel with the smoke technique. The Reynolds number used was 7.6x10^4 to 3.0x10^5. The side view photos shown in Figure 3(a) - 3(c) clearly indicate that there exist three distinct patterns of flow separation, which corresponds to three Reynolds numbers. Although the point of separation cannot be pinpointed from the side view photos, it is evident that separation point moves downstream with the increase of Reynolds number. At Re= 7.6x10^4, surface shear flow separates well before 90°; when Re=2x10^5, separation point moves downstream at about 90°; at Re=3x10^5, separation point moves further downstream. The concentrated smoke line in the top view photos shown in Figure 4(a) to 4(c) is the line of separation. Similar to the side view photos, this two-dimensional line of separation moves downstream with the increase of Reynolds number. Unlike the side view photo, the location of separation line can be clearly read from the top view photos. At Re=7.6x10^4, the separation line is very unstable, mainly oscillating in-between 80°~85°. When Re=2x10^5, the separation line moves slightly downstream and oscillating at about 90°; at this Reynolds number, a second weakly concentrated line would intermittently appear around 105°. At Re=3x10^5, two rather stable lines of separation-reattachment would appear around 95° and 110°. Combined with the latter pressure data discussion, this dual separation line observation can be attributed to the
separation-reattachment phenomenon. In other words, due to the separation-reattachment, a separation bubble is intermittently formed at $Re=2 \times 10^5$, and firmly established at $Re=3 \times 10^5$.

!) (b) (c) (a) (Re=7.6E+4 (b) Re=2.0E+5 (c) Re=3.0E+5)

Shown in Figure 5 and 6 are the distributions of mean and RMS pressure coefficients along the center meridian at Reynolds number between $6.6 \times 10^4$ ~ $3.1 \times 10^5$. At very low Reynolds number, $Re < 1.0 \times 10^5$, the surface shear flow separates at about 80°~90°; when $Re=3.1 \times 10^5$, the beginning of the wake region moves downstream to about 120°. In this Reynolds number region, the negative pressure at dome apex increases, whereas the negative pressure in the wake region decreases with Reynolds number. However, the measurements further indicate that, for Reynolds number between $3.0 \times 10^5$ ~ $2.0 \times 10^6$, the wake suction increases slightly with Reynolds number and the point of separation moves slightly upstream.

As for the RMS pressure coefficients: when $Re<1.8 \times 10^5$, there is one distinct and narrow peak of $C_{p}'$ locate at 80°~90° and a broader lump around 140°; when $Re=1.8 \times 10^5 ~ 3.0 \times 10^5$, a second distinct and narrow peak appears around 110°. Evidences from flow visualization and correlation studies suggest that appearance of double peaks RMS pressure coincides with the separation-reattachment phenomenon.

!) (b) (c) (a) (Re=7.6E+4 (b) Re=2.0E+5 (c) Re=3.0E+5)

Fig. 5 Distributions of mean pressure coefficients, $6.6 \times 10^4<Re<3.1 \times 10^5$

Fig. 6 Distributions of RMS pressure coefficients, $6.6 \times 10^5<Re<3.1 \times 10^5$
Shown in Figure 7 are spectra of fluctuating surface pressure measured along the center meridian of Dome S at Reynolds number Re=1.4−3.0×10^5. For θ<45°, the spectral estimates decrease rapidly with the increase of θ as shown in Figure 7(a1) to 7(a4). This feature is clearly reflected in the measurements of the RMS pressure in Figure 6. Shown in Figure 7(b1) and 7(b2), the trend of spectral decrease is stopped and even reversed. When θ is between 45° to 60°, and Reynolds number is less than 2.4×10^5, the spectral estimates increase slightly with θ in the lower frequency region where the reduced frequency, f_r = fD/U, is less than 0.3. Then, when Re>2.4×10^5 as shown in Figure 7(b3) and 7(b4), the spectral estimates become almost invariant.

The pressure spectra shown in 7(c1) to 7(c4) indicate that, for 60°<θ<90°, the spectral estimates generally increase with θ; and decrease with increase of Reynolds number. These observation are consistent with the characteristics of the RMS pressure distributions that, for Re=1.4−3.0×10^5, the first peak occurs at θ=80°−90° and peak value decreases with Reynolds number. Then for 90°<θ<100°, The pressure spectra shown in Figure 7(d1) to 7(d4) indicate that the spectral magnitude are invariant in the lower frequency region where f_r<0.3; and shows minor increase with θ in the higher frequency region.

Shown in Figure 7(e1) to 7(e4) are the pressure spectra obtained in the region of 100°<θ<120° where the separation bubble appears at Re=2×10^5−3.0×10^5. Figure 7(e1) and 7(e2) indicate that, when Re<2.0×10^5, the spectral amplitude decreases with θ in the lower frequency region, whereas it shows slight increase with θ in the higher frequency region. When Re=2.4−3.0×10^5 where the reattachment observed in the flow visualization study, as shown in Figure 7(e3) and 7(e4), the spectral amplitude shows significant increases with θ in all frequency ranges. This observation is also conforming to the second peak of the RMS pressure distributions. The pressure spectra of the rear part, θ=120°−171°, exhibit only minor variation as shown in Figure 7(f1) to 7(f4).
In order to better interpreting the experimental data, a set of non-dimensional correlation lengths of the fluctuating pressure are introduced in this paper. Let $\lambda_i^-$ denote the upstream correlation length of pressure fluctuations at $\theta_i$. In which,

$$ R(\theta_i,\theta_j) = \frac{\sigma_{i,j}^2}{\sigma_{i} \sigma_{j}} = \text{correlation coefficient between pressure fluctuations at } \theta_i \text{ and } \theta_j \tag{2} $$

$$ r = \text{radius of dome.} $$

Therefore, $\lambda_i^-$ represents the correlation length of the fluctuating pressure considering only the upstream of the reference point $\theta_i$. Similarly, let $\lambda_i^+$ denotes the downstream correlation length that considering only the pressure taps downstream of the reference point $\theta_i$ in which,

$$ \lambda_i^+ = \frac{1}{r} \int_{\theta}^{\infty} R(\theta_i,\theta)d\theta \tag{3} $$

A threshold of $R(\theta_i, \theta) \geq 0.05$ was adopted during integration to avoid the fluctuating nature of correlation coefficient at large spatial separation.
For a pressure tap located immediately upstream of separation or reattachment point, a relatively high upstream correlation length, $\lambda_-$, and a low downstream correlation length, $\lambda^+$, can be expected. On the other hand, for pressure taps located immediately downstream of separation or reattachment point, we can expect to find low upstream correlation length and relatively high downstream correlation length. These upstream and downstream correlation lengths were calculated.

Show in Figure 8(a1) and 8(a2) are the upstream correlation length and downstream correlation length, respectively, of hemispherical models tested in smooth flow and Reynolds number in-between $9.2 \times 10^4$ to $3.3 \times 10^5$. In this region of Reynolds number, the upstream correlation length, $\lambda_-$, increases with the angle of latitude, $\theta$, and reach the highest value of 1.0 near $\theta=100^\circ$; then drops drastically to the minimum value. The point of suddenly appeared minimum value, locates at $\theta=140^\circ$ for Re=$9.2 \times 10^4$ and gradually moves upstream to $\theta=120^\circ$ at Re=$2.0 \times 10^5$. The downstream correlation length, $\lambda^+$, shown in Figure 8(a2), exhibits a similar trend as $\lambda_-$. The minimum value of $\lambda^+$ occurs slightly ahead of $\lambda_-$ at $\theta=110^\circ$~$115^\circ$, and this position is quite consistent for all Reynolds number in this region. Since the position of minimum $\lambda^+$ indicates this particular pressure tap locates upstream of separation point. It is logical to observe the location of minimum $\lambda^+$ appears slightly upstream of $\lambda_-$. For Re=$1.8$~$3.3 \times 10^5$, the averaged location of minimum $\lambda_-$ and $\lambda^+$, $\theta\approx115^\circ$, roughly coincides with the "boundary of wake" that observed in pressure distributions shown in figure 6 and 7. However, the physical meaning of the location change of minimum $\lambda^-$, from $\theta=140^\circ$ to $\theta=120^\circ$ at low Reynolds number is not clear at this stage.

![Fig. 8 Correlation length of pressure fluctuations on center meridian](image)

(a) upstream correlation length    (b) downstream correlation length.

The contours of mean and RMS pressure coefficients of dome were plotted to study the variation of the overall pressure distribution pattern as function of Reynolds number. It is interesting that, the variation of the pressure contour is similar to the mean pressure distribution of the center meridian. It also can be observed that, when the Reynolds number exceeds $2.0 \times 10^5$, the overall mean pressure distribution pattern remains nearly invariant. Shown in Figure 4, for Re<$2.0 \times 10^5$, the RMS of pressure fluctuations in the rear half of the dome in the separation wake, increases with the Reynolds number. Near Re=$3.0 \times 10^5$, a few spots of local maximum RMS pressure can be observed in the low rear part of the dome,. When Re>$3.0 \times 10^5$, the local fluctuating pressure decreases and the fluctuating pressure distribution pattern exhibits only minor variations.
Correlation coefficients between two pressure contours are calculated and presented in Figure 11 to give a quantitative index to the similarity of pressure distribution patterns. The pressure contour at Re=3.0x10^5 and selected to be the reference pressure contour. In Figure 11, ρ_{mean} and ρ_{rms} denote mean and RMS correlation coefficients. The result indicates that the correlation coefficient of mean pressure distribution, ρ_{mean}, approaches 1.0 near Re=2.0x10^5 and remains to be 1.0 afterwards. As for the correlation coefficient of RMS pressure distributions, ρ_{rms} decreases rapidly for Reynolds number less the reference case; the correlation coefficient can be as low as ρ_{rms}<0.5. In the cases of Reynolds number greater than the reference case, i.e., Re>3.0x10^5, the correlation coefficient has a much slower decaying trend and levels-up at ρ_{rms}=0.8 when the Reynolds number reaches 8.0x10^5.
Integrating the pressure along the dome meridian of each testing case, a drag coefficient called the “meridian drag coefficients” can be obtained. Data indicates that, for $Re<3.0 \times 10^5$, the mean drag coefficient decreases with the increase of the Reynolds number, and it recovers gradually thereafter. The maximum RMS drag coefficient occurs at $Re \approx 1.5 \times 10^5$, then decreases rapidly and exhibits a minimum value at $Re \approx 3.0 \times 10^5$.

![Fig 12. Mean and R.M.S. center meridian drag coefficients](image)

**Conclusions**

A series of wind tunnel pressure measurements were performed on hemispherical domes to study the Reynolds number effects on characteristics of wind loads. Following summaries can be made from the tests in the smooth flow condition. In smooth flow, the transition of separation flow occurs near $Re=3.0 \times 10^5$. The mean meridian drag coefficient decreases with Reynolds number for $Re<3.0 \times 10^5$, and then increase monotonically up to $Re=2.0 \times 10^6$; RMS meridian drag coefficient shows maximum and minimum values at $Re \approx 1.5 \times 10^5$ and $Re \approx 3.0 \times 10^5$, respectively. The correlation coefficients of mean and RMS pressure contours indicate that, the pressure distributions become relatively stable at $Re=2.0-3.0 \times 10^5$.

**References**