Wind Engineering Joint Usage/Research Center
FY2023 Research Result Report

Research Field: Wind Hazard Mitigation
Research Year: FY2023
Research Number: 23233001
Research Theme: The effects of Reynolds number on the aerodynamic characteristics of retractable dome

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Budget [FY2023]: 240,000Yen

*There is no limitation of the number of pages of this report.
*Figures can be included to the report, and they can also be colored.
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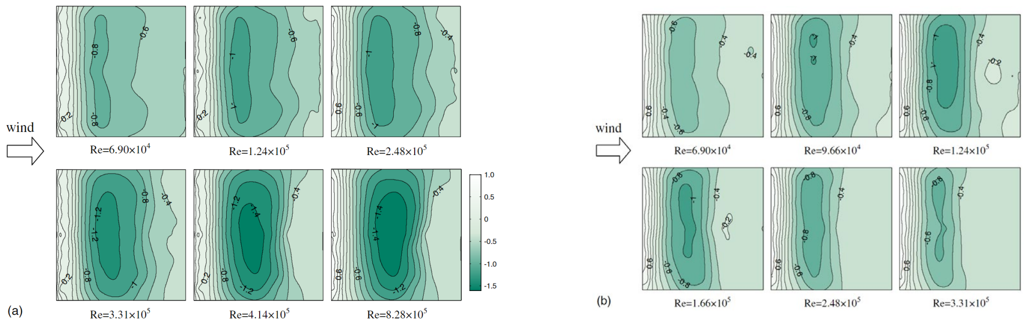
1. Research Aim

There are relatively fewer studies on wind load for retractable dome roofs than for general dome roofs, and a wind load code has yet to be established. Therefore, study on retractable dome roofs has been conducted jointly with the Wind Engineering Research Center Joint Usage/Research Center since 2018. Previous studies have focused on the shape of the roof, the retractable type, the opening ratio, the height-span ratio (hereafter called as H/D), the rise-span ratio (hereafter called as f/D) and various wind environments. However, previous studies did not consider the Reynolds number and surface roughness, which has a significant effect on the distribution of wind pressure. Cheng and Fu (2010) conducted a series of wind tunnel test to investigate the effect of Reynolds number on the aerodynamic characteristics of hemispherical dome in smooth and turbulent boundary layer flows. In the study of Cheng and Fu (2010), the Reynolds number varies from 5.3×10^4 to 2.0×10^6. They confirmed the following from their research results. In smooth flow, the transition of separation flow occurs in-between Re=1.8×10^5–3.0×10^5 and pressure distributions become relatively stable after Re > 3.0×10^5. In turbulent flow, the transition of separation flow occurs at lower Reynolds number, Re < 1.1×10^5, while the pressure distributions become Reynolds number independent at Re=1.0–2.0×10^5.

As the results of the previous study mentioned above, the Reynolds number is an important factor influencing the wind pressure distribution. Wind load or flow patterns acting on buildings usually vary depending on the location of the separation point, and in the case of objects with curved surfaces such as cylinder, the location of the separation point varies greatly by the number of Reynolds, so the effect of Reynolds number cannot be ignored. The Reynolds number is difficult to match the actual Reynolds number in a wind tunnel test using a reduced model. In case of buildings with sharp angles, such as square shape, are less affected by the Reynolds number because the location of the separation point is fixed to the edge, but the curved roof such as the dome roof is greatly affected by the Reynolds number. Therefore, the actual Reynolds number flow state should be reproduced by allowing the Reynolds number in the wind tunnel test to reach the super-critical Reynolds number by installing roughness elements on the surface of model in the case of curved roofs (Merrick and Bitsuamlak (2008)).

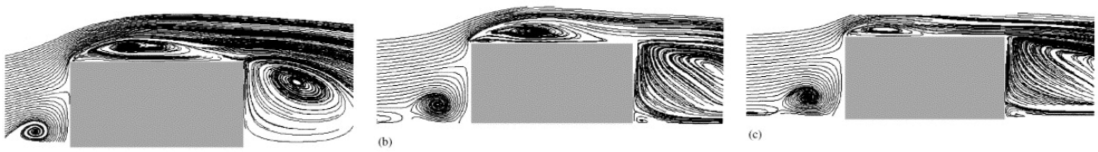
Figure 1 shows the mean pressure contours for the smooth and the rough surface of cylindrical roofs depending on Reynolds number, which is the previous study of Qiu et.al (2018). For smooth surface, the distribution of wind pressure is stable when the Reynolds number is Re < 3.31x105, but for rough surface, it is confirmed that the distribution of wind pressure is not stable at the same Reynolds number. In addition, the separation point of the flow also approaches the windward side (Separation occurs quickly, so separation point moves to the windward side.), and the negative pressure overall decreases.



(a) smooth surface (b) rough surface

<Fig. 1> Contours of mean pressure distributions of cylindrical roofs at various Reynolds numbers (Qiu et.al (2018))

Figure 2 shows the flow patterns for flat roof depending on various surface roughness, which are the result in previous study of Nozawa and Tamura (2002). In the Figure 2, as the surface roughness increases, reattachment of the flow occurs quickly. Additionally, as reattachment occurs quickly, the pattern of flow occurring on the leeward side also changes, so the wind pressure is greatly affected by the Reynolds number and surface roughness.



(a) smooth (b) rough A (c) rough B

<Fig. 2> Streamlines of the mean flow projected onto the symmetry plane of the building

Based on the above results, it can be expected that Reynolds number and surface roughness of roof will have a significant impact on the wind pressure of retractable dome roofs. Therefore, this research aims to analyze the wind pressure characteristics of retractable dome roofs depending on the Reynolds number (including surface roughness of roof).

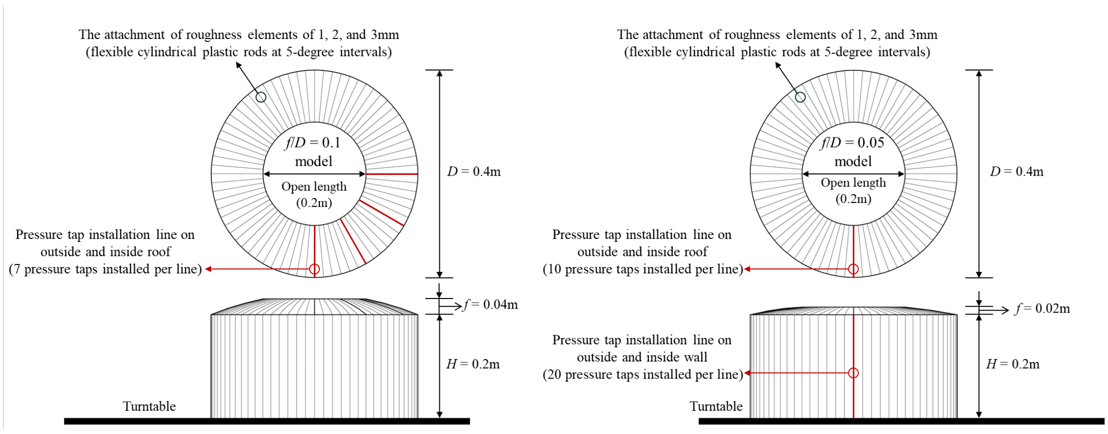
2. Research Method

The model used in the experiment simulated a hemispherical dome with a low rise and an opening at the center. The rise-to-span (f/D) ratios of the models were determined to be 0.1 and 0.05, with an opening ratio of 50%. In Figure 3, the models are presented. In the case of the opening ratio, it is defined as the ratio of the dome's diameter to the diameter of the opening.

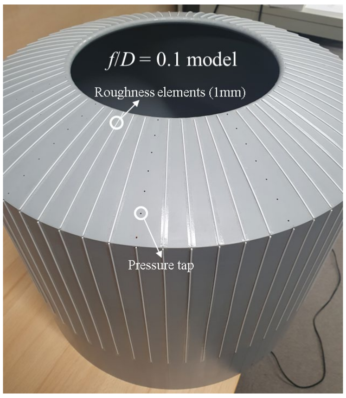
(a) f/D = 0.1 (b) f/D = 0.05

<Fig. 3> Models used in the experiment

Figure 4 shows the dimensions of the model, the locations of the pressure taps, and the roughness elements attached for surface roughness. The red lines indicate where the pressure taps are installed. For the model with an f/D of 0.1, pressure taps were placed in four lines at 30-degree intervals on both the outside and inside roof surfaces, totaling 80 taps. In the case of the model with an f/D of 0.05, pressure taps were installed in a single line on both the outside and inside roof and wall surfaces, with a total of 20 taps on the roof surface. Surface roughness was constructed using flexible cylindrical plastic rods, each with heights of 1, 2, and 3 mm, respectively. These rods were attached to the outside roof and wall surface at 5-degree intervals. Figure 5 shows the wind pressure taps and roughness elements installed on the actual model.

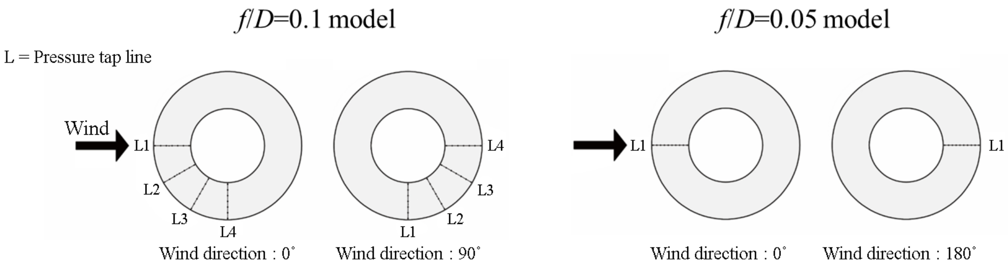


<Fig. 4> Dimensions of the model, pressure taps, and surface roughness elements



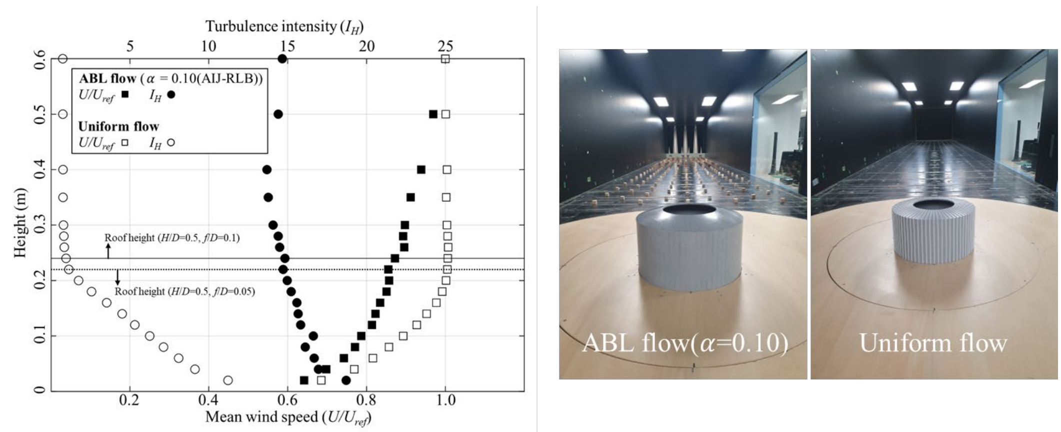
<Fig. 5> The roughness elements attached to the actual model

Figure 6 shows the experimental wind directions. Considering the wind pressure taps installed on the model, the *f/D* of 0.1 model adjusted the wind directions from 0 to 90 degrees at 10-degree intervals, while the *f/D* of 0.05 model adjusted the wind directions from 0 to 180 degrees at 10-degree intervals.



<Fig. 6> Experimental wind direction

Figure 7 shows the characteristics of the oncoming flow. Two oncoming flow characteristics were considered in this study. ABL flow represents turbulent flow corresponding to Flat Terrain category 1 based on Japanese wind load standards (The power-law index alpha is 0.10). Additionally, uniform flow was simulated in the empty wind tunnel floor without roughness elements. For uniform flow, the turbulence intensity at the roof height of the model is about 1%.



<Fig. 7> Characteristics of oncoming flow

Table 1 represents the range of Reynolds numbers considered in this study. The Reynolds number (Re) was defined by the diameter of dome (D=0.4m) and the mean wind speed (U) at the height of model roof ($H+f$ = 0.24m and 0.22m).

<Table 1> The range of Reynolds numbers

f/D= 0.1				f/D= 0.05			
ABL		Uniform		ABL		Uniform	
U(m/s)	Re	U(m/s)	Re	U(m/s)	Re	U(m/s)	Re
2.37	6.32x10^{4}	3.17	8.44x10^{4}	2.28	6.08x10^{4}	3.15	8.39x10^{4}
5.02	1.34x10^{5}	7.18	1.92x10^{5}	4.99	1.33x10^{5}	7.17	1.91x10^{5}
7.91	2.11x10^{5}	11.17	2.98x10^{5}	7.64	2.04x10^{5}	11.15	2.97x10^{5}
10.44	2.78x10^{5}	15.14	4.04x10^{5}	10.4	2.77x10^{5}	15.12	4.03x10^{5}

Table 2 summarizes the conditions of the experiment. The k/D was defined by the height of the roughness elements and the diameter of the dome. The k/D values are 0.0025, 0.0050, and 0.0075, respectively. These values align closely with those found in previous studies.

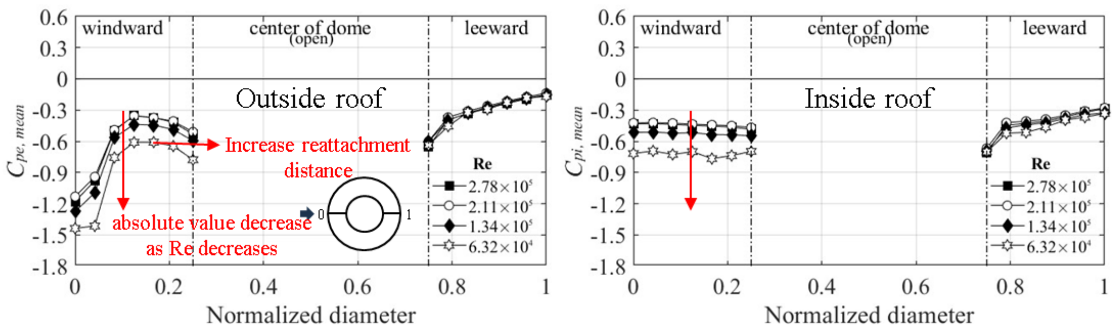
<Table 2> The range of Reynolds numbers

Case No.	f/D	Flow type	Reynolds number range	Roughness type	Roughness diameter(k)	
					k (mm)	k/D
1	0.1	ABL	6.32x10^{4} to 2.78x10^{5}	Flexible cylindrical plastic rod	1	0.0025
					2	0.0050
					3	0.0075
				smooth	0	0
2	0.05	ABL	6.08x10^{4} to 2.77x10^{5}	Flexible cylindrical plastic rod	1	0.0025
					2	0.0050
					3	0.0075
				smooth	0	0
3	0.1	Uniform	8.44x10^{4} to 4.04x10^{5}	Flexible cylindrical plastic rod	2	0.0050
					3	0.0075
				smooth	0	0
4	0.05	Uniform	8.39x10^{4} to 4.03x10^{5}	Flexible cylindrical plastic rod	2	0.0050
					3	0.0075
				smooth	0	0

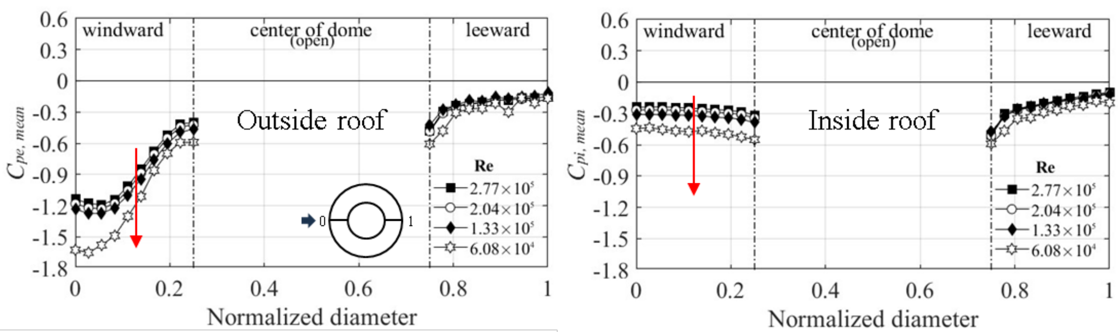
3. Research Result

3.1 Characteristics of wind pressure distribution

Figure 8 shows the mean pressure coefficient of the outside and inside roofs relative to the Reynolds number in ABL flow. The significant observation in these figures is the increase in absolute values on the windward side as the Reynolds number decreases. The increase in absolute values observed on the outside roof likely results from relatively low wind speed. Lower wind speed implies reduced turbulent flow components. This reduction in turbulence increases reattachment distance and renders the roofs more influenced by separation bubbles, thus increasing the absolute value of the mean pressure coefficient on the outside roof. The increase in absolute values on the inside roof is attributed to the phenomenon where the mean pressure around the opening becomes similar for both the outside and inside roofs. While the wind pressure magnitude somewhat varies with Reynolds number, the position of the separation point remains unchanged on the leeward side (normalized diameter at 0.75).



(a) $f/D = 0.1$

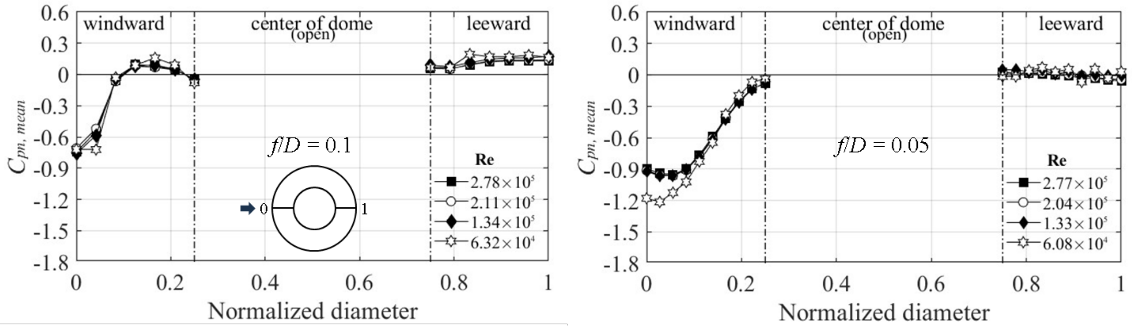


(b) $f/D = 0.05$

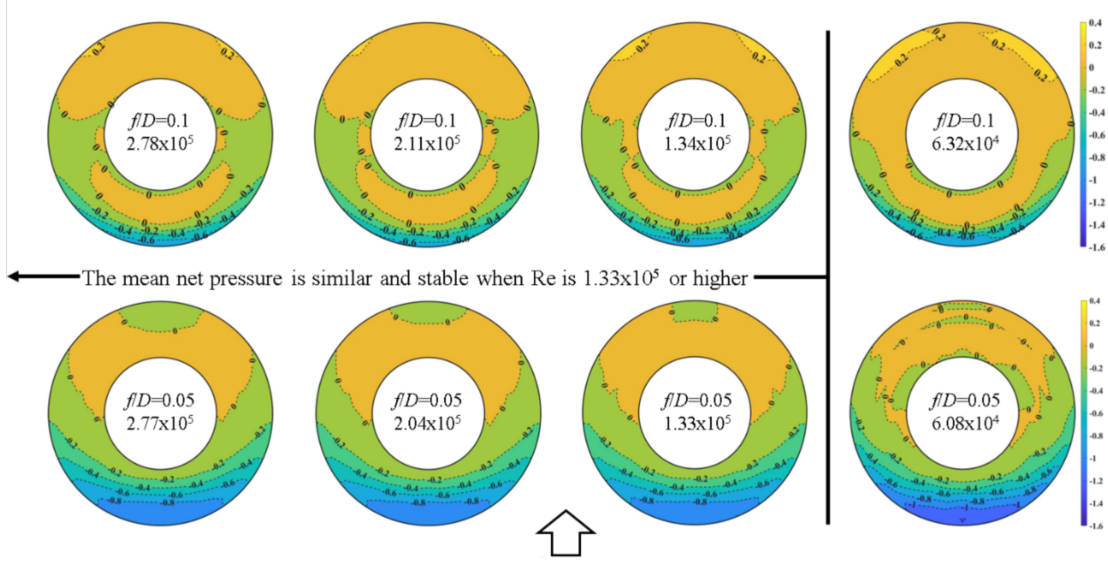
<Fig. 8> Mean pressure coefficient according to Reynolds number in ABL flow

Figure 9 shows the mean net pressure coefficient according to the Reynolds number in ABL flow. In the mean net pressure coefficient, the difference in absolute values with Reynolds number is somewhat reduced compared to the outside roof. This phenomenon is attributed to the offsetting of negative pressure on the outside and inside roof surfaces. Moreover, the absolute values show significant similarity when the Reynolds number exceeds 1.3 x 10^5. Therefore, when exceeding this Reynolds number 1.3 x 10^5, the pressure distribution is deemed to be stable in turbulent flow conditions.

Figure 10 shows the overall mean net pressure coefficient distribution of the roof, and the distribution of pressure is very similar when the Reynolds number exceeds 1.3 x 10^5.

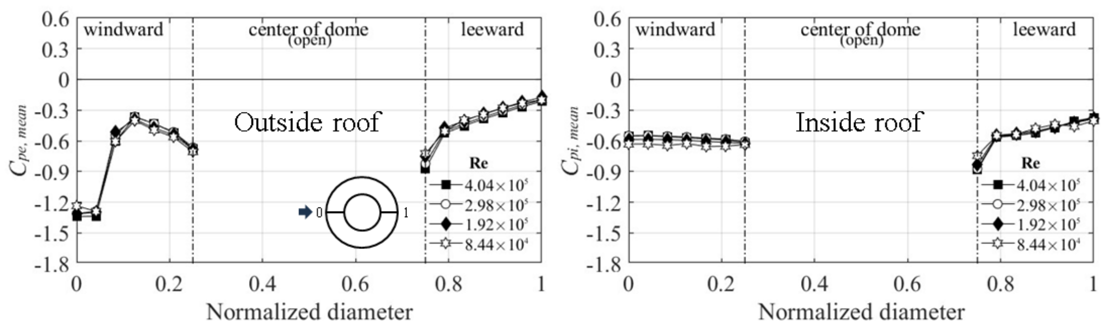


<Fig. 9> Mean net pressure coefficient according to Reynolds number in ABL flow

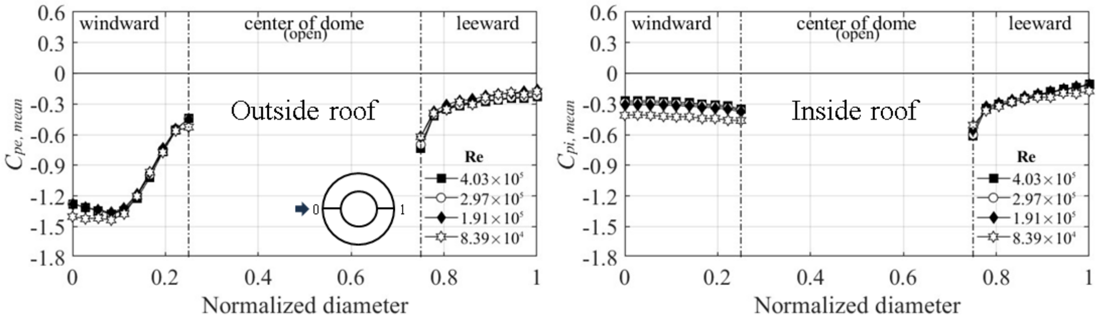


<Fig. 10> Distribution of mean net pressure coefficient according to Reynolds number in ABL flow

Figure 11 shows the mean pressure coefficient of the outside and inside roofs relative to Reynolds number in uniform flow. Compared to ABL flow, the variation in pressure coefficient depending on Reynolds number is very small. This is likely due to the low turbulence intensity of the oncoming flow and the shape of the roof. In uniform flow, the position of the separation point on the leeward side remains unchanged, as observed in ABL flow.



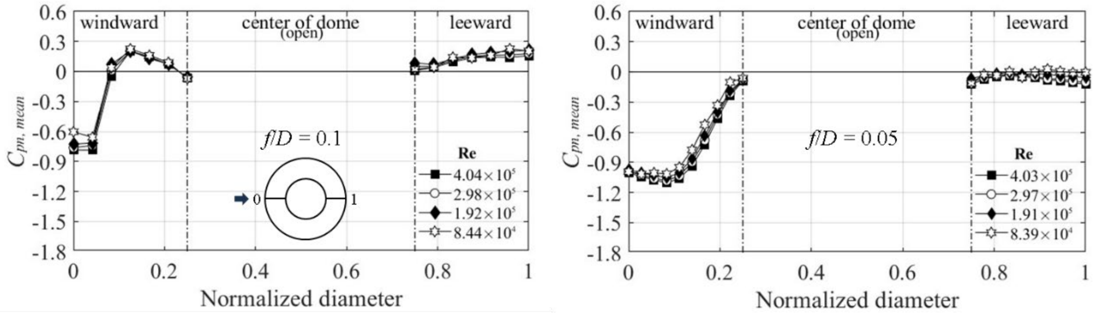
(a) f/D = 0.1



(b) $f/D = 0.05$

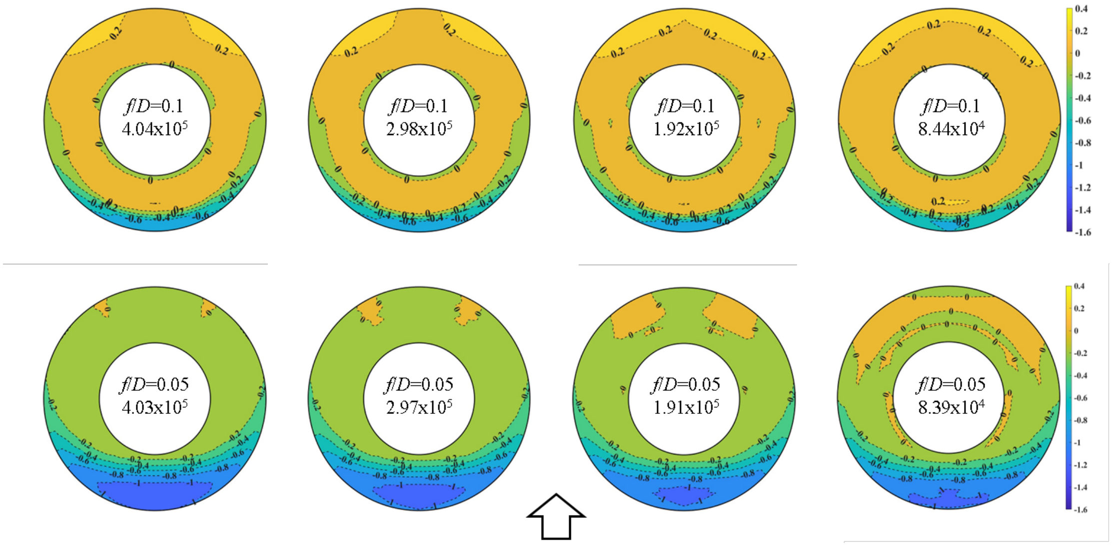
<Fig. 11> Mean pressure coefficient according to Reynolds number in Uniform flow

Figure 12 shows the mean net pressure coefficient for Reynolds number in uniform flow. Overall, no significant change in the mean net pressure coefficient is observed, but the absolute value is slightly more stable when exceeding a Reynolds number of 1.9×10^5.



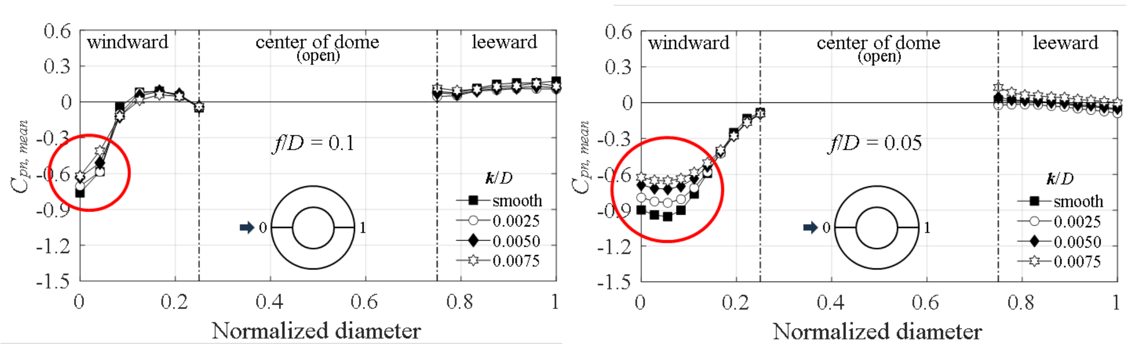
<Fig. 12> Mean net pressure coefficient according to Reynolds number in Uniform flow

Figure 13 shows the overall distribution of the mean net pressure coefficient on the roof in uniform flow. The absence of discernible differences in wind pressure distribution across all Reynolds numbers can be attributed to the similarity in flow patterns near the roof, influenced by the shape of the roof.



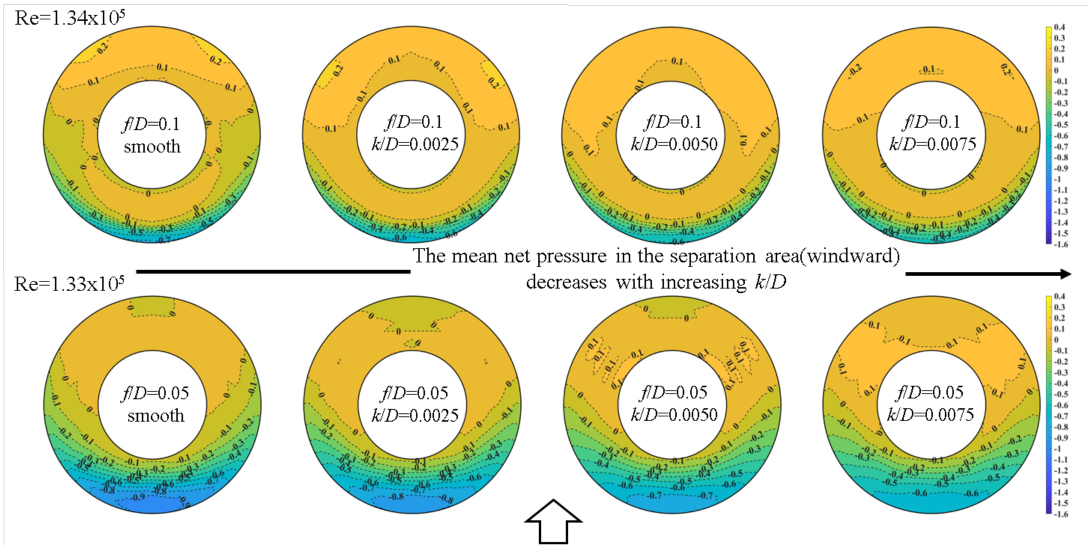
<Fig. 13> Distribution of mean net pressure coefficient according to Reynolds number in Uniform flow

Figure 14 shows the variation in mean net pressure coefficient for the two models with changes in k/D. The installation of roughness elements on the outside roof alleviates the negative pressure exerted on the roof. Specifically, the negative pressure is notably decreased, particularly on the windward side where separation occurs. However, the overall trend of change in mean net pressure was similar for all *k/D*.



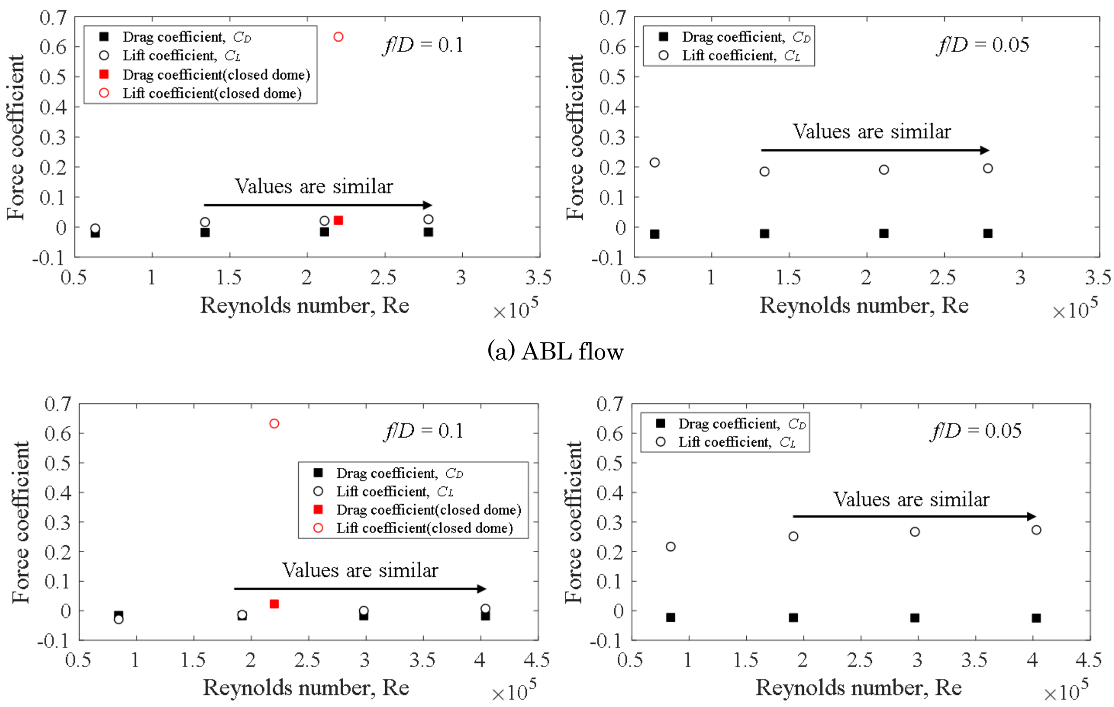
<Fig. 14> Mean net pressure coefficient according to *k/D*

Figure 15 shows contour of the mean net pressure coefficient for the two models as *k/D* varies. As mentioned earlier, it is evident that negative pressure decreases in the separation-affected area as roughness increases. Furthermore, the same phenomenon was observed in uniform flow, confirmed that the absolute value of the mean net pressure coefficient remains similar.



<Fig. 15> Distribution of mean net pressure coefficient according to *k/D*

Figure 16 shows the drag and lift force coefficients of the two models for ABL flow and uniform flow. Both models show very small drag effects due to their low rise-span ratio(*f*/*D*). Additionally, the lift force coefficient is reduced compared to that of the closed roof (red dot). This reduction stems from the offsetting wind pressure acting on the outside and inside roofs. Overall, both drag and lift coefficients demonstrate insignificant changes with variations in Reynolds number but become more similar when Re exceeds 1.3 x 10^5 and 1.9 x 10^5.



(a) ABL flow

(b) Uniform flow

<Fig. 16> Drag and lift force coefficients

3.2 Conclusions

In this study, we have identified the effect of Reynolds number and surface roughness on the wind pressure distribution for a retractable dome roof. The results are summarized as follows:

(1) In turbulent flow, the pressure distribution becomes relatively stable when the Reynolds number exceeds 1.3×10^5.

(2) In uniform flow, the pressure distribution becomes relatively stable when the Reynolds number exceeds 1.9×10^5.

(3) The Reynolds number within the studied range influences the magnitude of wind pressure and the forces acting on the roof. However, no significant alteration in the surrounding flow was observed because the separation point remained fixed due to the roof's shape.

(4) Surface roughness reduced the negative pressure and lift force acting on the roof. Normally, a decrease in lift force leads to an increase in drag force. However, no change in drag force was observed due to the shape of the roof.

As only one model was utilized in this study, there was a constraint on reproducing a wider range of Reynolds numbers. Future studies should therefore aim to analyze wind pressure distribution by incorporating a broader spectrum of Reynolds numbers.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]
[Published papers]

1. Cheon, D.J., Kim, Y.C., Yoon, S.W., A Proposal of Wind Pressure Coefficients for Structural Frame Design of Dome Roof Structures with Opening, Journal of the Architectural Institute of Korea (Under review).

[Presentations at academic societies]
1.
2.

[Published books]
1.
2.

[Other]
Intellectual property rights, Homepage etc.

5. Research Group

1. Representative Researcher
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2. Collaborate Researchers
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   Ph.D. Dong Jin, Cheon

6. Abstract (half page)

Research Theme

The effects of Reynolds number on the aerodynamic characteristics of retractable dome

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Summary・Figures

In this study, the effects of different Reynolds numbers and surface roughness on the wind pressure distribution of retractable dome roofs were investigated. The Reynolds number applied in the experiment ranged from 6.08x104 to 2.97x105, and k/D, the ratio of dome diameter to roughness element, consisted of 0, 0.0025, 0.0050, and 0.0075. Changes in the Reynolds number within the studied range were found to affect the wind pressure and the magnitude of the force acting on the roof, but the difference was not significant, as the shape of the roof does not lead to significant changes in the surrounding flow. Furthermore, the impact of surface roughness was to mitigate the negative pressure and lift exerted on the roof. In general, a decrease in lift leads to an increase in drag, but no change in drag was observed due to the shape of the roof. Therefore, it is concluded that the wind pressure distribution is independent within the range of Reynolds numbers considered in the study due to the shape of the roof. However, due to the limited range of Reynolds numbers, further studies considering a wider range of Reynolds numbers are needed.