Wind Pressure Coefficient of a Pipe-Framed Greenhouse and Influence of the Side Gable Openings Using a Wind Tunnel

Hideki MORIYAMA*2, Sadanori SASE*2, Yasushi UEMATSU*3 and Tomoharu YAMAGUCHI*4

*1 Partially presented at the Joint Conference on Environmental Engineering in Agriculture 2006
*2 National Institute for Rural Engineering, Tsukuba 305-8609, Japan
*3 New Industry Creation Hatchery Center, Tohoku University, Sendai 980-8579, Japan
*4 Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba 305-8572, Japan

Abstract

The wind pressure coefficients $C_p$ on a pipe-framed greenhouse (or simply 'pipe house'), whose shape consists of two or more curvatures, have been evaluated with a 1:20 scale model in a turbulent boundary layer. The length/width ratio of the model was 8.3. The $C_p$ distribution was evaluated at various cross-sections of the model for various wind directions $\theta$ from $0^\circ$ (normal to the ridge) to $90^\circ$ (parallel to the ridge). The evaluated $C_p$ distribution for $\theta = 0^\circ$ was compared with the specifications for greenhouses with gable and circular arc roofs in the current design standard for greenhouse structures, and a significant difference was observed. The $C_p$ distribution changed significantly with wind direction. The largest negative $C_p$ value was about -3.5 near the ridge corner when $\theta = 25^\circ$. The influence of side gable openings on the external pressure coefficient $C_{pe}$ and internal pressure coefficient $C_{pi}$ were also investigated. It is found that the $C_{pe}$ distribution was not affected by the openings. On the other hand, the influence of openings on the $C_{pi}$ value was significant. When $\theta = 0^\circ$, the value of $C_{pi}$ was as low as -0.9, which sifted the net wind force coefficient $C_f$ to a positive value. The value of $C_{pi}$ depended on the location of the openings as well as on the wind direction. When $\theta = 90^\circ$, the value of $C_{pi}$ varied from -0.2 in the leeward opening case to +0.5 in the windward opening case.

Keywords: pipe-framed greenhouse, wind pressure coefficient, wind tunnel test, side gable openings

Introduction

Plastic film clad greenhouses are widely used in the agricultural and horticultural industries. Such greenhouses are designed to a lower level of structural safety than are conventional building structures, because of the need to minimize initial costs, the demand for higher level of light transmission and so on. Consequently, they are very lightweight structures that are vulnerable to wind loading. In practice, they often experience damage during windstorms, such as typhoons and unseasonable strong winds. The wind resistance is one of the greatest concerns of structural engineers, when designing these structures. An essential cause for wind disasters of greenhouses may be a lack of knowledge in the wind resistance performance and wind loads on such structures.

Pipe-framed greenhouses (or simply 'pipe houses'), whose frames consist mainly of arch pipes, are very popular because of low construction cost. In fact, pipe houses account for approximately 80% of the total area of greenhouses in Japan. Therefore, pipe houses play an important role in agricultural and horticultural industries in Japan. However, it is also a fact that most of the wind damage to greenhouses is restricted to pipe houses. It is necessary to improve the design wind resistance for pipe houses. In particular, the wind pressure coefficients $C_p$...
Several researchers have studied the wind loads for plastic film clad greenhouses. Hoxey and Richardson (1984) made full-scale measurements of external wind pressures on greenhouses, which were of curved-arch construction, under natural wind conditions. Regarding single-span greenhouses, they tested three configurations, which were representative of commercial greenhouses in the United Kingdom. They showed that the $C_p$ distribution across the central cross-section in a transverse wind depended on the shape of greenhouses significantly. Based on the results, they proposed a set of $C_p$ values for each shape. Their results provided very useful information about the $C_p$ distribution on greenhouses. However, the shapes of the greenhouses they tested are different from typical pipe houses constructed in Japan.

Full-scale measurements are very useful for investigating the wind pressures on structures, because they represent actual situations. If the measurements and data processing are made properly, we can obtain useful information. However, it is difficult to obtain steady conditions in natural winds; wind velocity and direction often change quickly. Furthermore, full-scale measurements are generally expensive and time-consuming. At present, wind tunnel experimentation is regarded as the most reliable and convenient method for investigating the wind loads on structures. Several researchers have investigated the wind loads on pipe frame houses in wind tunnels. For example, the wind tunnel test considering the wind profile was started by Nara (1983) in Japan. Hagura and Fujino (1992) conducted a wind tunnel experiment with a gable-roofed greenhouse model both in a uniform flow and in a turbulent boundary layer. They showed that the distribution of the $C_p$ on the leeward roof and wall for a transverse wind were not considerably affected by the flow condition. However, the $C_p$ values on the windward surfaces depended significantly on the flow condition. This result shows the importance of correct simulation of the flow in wind tunnel experiments. Recently, Robertson et al. (2002) have made a wind-tunnel study of the wind pressures on permeably and impermeably clad greenhouses using large-scale models in a large wind tunnel. The model was similar to one of the three models Hoxey and Richardson (1984) used in their full-scale measurements, i.e. a model with circular arc roof. They measured the displacements of the covered film and wind pressures on the surface of the model. The values of the $C_p$ on the windward surface obtained from the wind tunnel experiment agreed well with those obtained from the full-scale measurement. However, regarding the value of the $C_p$ near the ridge and on the leeward surface, there existed a significant difference between the wind tunnel experiment and full-scale measurement. They pointed out that this discrepancy was due to an early flow separation on the curved surface in the wind tunnel experiment.

Some researchers have tried to obtain the distribution of the $C_p$ by using a computational fluid dynamics (CFD) technique. For example, Mathews and Meyer (2002) simulated the flow around the greenhouses tested by Hoxey and Richardson (1984). The $C_p$ distribution for a transverse wind was computed. The $C_p$ values on the leeward surface were lower, i.e. more negative, than those of the full-scale measurement. Mathews and Meyer suggested that this difference was due to the deformation of the structure in the full-scale measurement, which was not considered in the CFD analysis. Furthermore, Mistriotis and Briassoulis (2002) computed the distribution of the $C_p$ on a semicircular greenhouse with ventilators on the gable walls for a transverse wind. They showed that the ventilators had a significant influence on the internal pressure coefficient $C_p$ but no influence on the external pressure.

The net wind force acting on a pipe house is given by the difference between the external and internal pressures. Therefore, the internal pressure plays an important role in estimating the wind loads, in particular, when ventilators are installed on the gable wall and rooftop. Sase et al. (1980) carried out a wind tunnel experiment to investigate the $C_p$ value for a single span gable-roofed greenhouse. They showed that the value of the $C_p$ depended on the wind direction but was almost independent of the opening ratio of ventilators. The value of their result was generally smaller than that specified in the current standard (Japan
Greenhouse Horticulture Association, 1999). Furthermore, it was shown that the Reynolds number affected the C_p value when the wind velocity is quite low.

Although several investigations have been made of the wind loads on greenhouses, no study has been made for the pipe houses that are popular in Japan. The cross-section of the pipe house consists of slant walls, curvature at the eaves and a pointed arch. The shape is more complicated than those tested in the previous studies, which results in a different pressure distribution.

In the previous wind tunnel studies, models with relatively small length-to-width ratio (L/W) were used, probably because of the limitation in wind tunnel size. For example, the ratio was 2.3 in Huang et al. (1993) and 1.9 in Lee and Lee (1996). Frequently pipe houses are constructed with L/W > 4. When the L/W ratio is small, the C_p distribution in the middle part for a transverse wind may be different from that for long pipe houses because of a three-dimensional effect. In order to obtain exact distribution of C_p on actual pipe houses, longer model should be used. The distribution of the C_p in the transverse direction depends on the distance from the gable wall. Furthermore, the C_p distribution is also affected by wind direction. These effects should be taken into account for estimating the design wind loads. The specifications in the standard are determined mainly on the C_p distribution across the central cross-section for a transverse wind. However, the C_p distributions in the edge region for oblique winds are quite different from the specified one, which may result in a critical condition for frames near the gable wall.

It is widely accepted that the openings on the walls affect the internal pressure significantly, depending on the size and location of the openings. Pipe houses generally have doors on the gable walls. The doors are often destroyed by strong winds during a severe storm. When the doors are destroyed, the internal pressure and the resultant wind forces change suddenly. The opening may increase the wind forces on the frames significantly and cause a collapse of the pipe house. In the previous studies the influence of openings on the external and internal pressure coefficients, C_pe and C_pi, has not been investigated in detail.

Based on the above-mentioned discussion, the distributions of C_p, both external and internal, were evaluated in detail using a typical pipe house model in a turbulent boundary layer correctly simulating natural winds over typical open-country exposure. Focus was on the influence of wind direction and opening condition on the gable walls.

**Experimental arrangement and procedures**

1. **Wind simulation**

The experiments were carried out in an Eiffel-type wind tunnel at the National Institute for Rural Engineering, which has a working section 20 m long, 4 m wide and 3 m high. A turbulent boundary layer, which simulates natural winds over typical open-country exposure, was generated with a standard spire-roughness arrangement on the wind tunnel floor (Fig. 1). The profile of the mean wind velocity up to a height of 1000 mm, measured by a three-dimensional hot wire anemometer (model IFA300, TSI Inc.), is shown in Fig. 2, which was approximated by the following equation (logarithmic law):

\[ U = 1.08 \ln \left( \frac{z}{z_0} \right) \]

where U = mean wind velocity (m/s); z = height above wind tunnel floor (mm); and z_0 represents the roughness length and was estimated as 0.43 mm. Assuming a boundary layer scale of 1:20, the full-scale value of z_0 was approximately 1 cm, which was somewhat small but within the range of full-scale measurements for flat open-country exposures (for example, Tieleman 2003). Note that a geometric scale of 1:20 was used for the wind tunnel model, as will be described below. The turbulence intensity in the main direction of the flow at a height of z = 158 mm (the level of rooftop of the wind tunnel model) was 0.13.

2. **Wind tunnel model**

A pipe house with the following dimensions was chosen as the subject of the present study as one of the most typical pipe houses constructed in Japan; length L = 50 m, width W = 6.0 m, ridge height H = 3.16 m, and eaves height h = 1.75 m. The L/W was 8.3, large enough to achieve a nearly two-dimensional flow in the middle
part of the model for a wind normal to the ridge. The house has a door 2.4 m wide and 2.0 m high on each gable wall, which can be removed.

The wind tunnel model was made with a geometric scale of 1:20 (Fig. 3). The blockage ratio of the model with respect to the wind tunnel cross-section was approximately 3.3%. For such a small value, the blockage effect on the wind pressures is considered insignificant (Jensen and Frank, 1965 and Ishizaki, 1981). Therefore, no correction was applied to the results. The model consists of a sandwich structure constructed of two ABS resin plates. The thickness of the model was 8 mm. Seventy-seven pressure taps of 0.8 mm diameter were drilled on the roof, side and fifteen on the sidewall and gable wall, respectively. Five pressure taps were also installed inside the model. These pressure taps were all distributed on a quarter part of the model, considering the symmetry of the model.

Wind direction $\theta$ was defined as shown in Fig. 4 and varied from $0^\circ$ to $90^\circ$ at increments of $5^\circ$; $\theta = 0^\circ$ represents a wind direction normal to the ridgeline. Four $C_p$ distributions of each quarter part of the model corresponding to the same wind direction were measured and integrated as the values of the $C_p$ of the whole model.

Four cases listed in Table 1 were tested with respect to the influence of side gable openings on the value of the $C_{pe}$ and $C_{pi}$. Case 1 corresponds to an enclosed structure, for which many standards provide the design $C_p$ distribution. In Case 3 where the model has openings on both gable walls, the wind blows inside the model. When $\theta = 90^\circ$, in particular, the wind speed inside the house is likely to be high.

The values of the $C_p$, both external and internal, were defined as follows:

$$C_p = \frac{P - P_s}{\frac{1}{2} \rho U_i^2}$$

where $P$ = pressure acting on the model (Pa); $P_s$ = static
pressure in the wind tunnel (Pa); \( \rho \) = air density (kg/m\(^3\)); and \( U_H \) = wind velocity at the ridge height (m/s). The static pressure \( P \) was measured by a pitot tube located at a point 3.5 m ahead of the center of the turn table (Fig. 1).

### 3. Pressure measurement

All pressure taps were connected to an electronic pressure scanning system (F98-6149, Kyowa Dengyo co. Ltd) via 300 cm lengths of flexible vinyl tubing of 1.37 mm inside diameter. The tubing was installed between the two ABS resin plates. The wind pressures at 97 taps were sampled in parallel at a rate of 200 Hz for a period of 40.96 s.

The pressure measurements were made at a wind velocity of 7.7 m/s at a height of \( z = 500 \) mm (10 m in full scale). Accordingly, the wind velocity \( U_H \) at the ridge height \( H \) was 6.3 m/s. The corresponding Reynolds number \( R_e \), defined in terms of \( U_H \) and \( H \), was approximately \( 6.6 \times 10^4 \). Although the roof of the pipe house consisted of two or more curvatures, the ridge has a sharp edge and the flow may separate at the ridge even for a wind normal to the ridgeline. Therefore, the effect of \( R_e \) on the pressures seems fairly small (Japan
1. **C_p** distribution for a wind normal to the ridgeline

Fig. 5 shows the **C_p** distributions at four sections \( \xi = 40, 100, 300 \) and \( 600 \) mm and at the central cross-section \( \xi = 1250 \) mm of the enclosed model (Case 1) when \( \theta = 0^\circ \), with \( \xi \) being the distance from the gable wall. Regarding the central cross-section, the **C_p** value was 0.45 at the mid-height of the windward wall. The value on the windward roof was generally negative, gradually increasing in magnitude from 0 at the windward edge to -0.6 at the ridge. On the leeward roof and wall, the value was almost constant over the whole area; the value was approximately -0.6 on the roof and -0.54 on the wall. The **C_p** distribution at the section 600 mm from the gable wall was similar to that for the central cross-section. However, as the distance of the cross-section from the gable wall decreased, the difference in the **C_p** distribution became more significant; in particular, on the leeward roof and wall. That is, the **C_p** distributions of the cross-section in the middle part of the pipe house were independent of the distance from the gable wall. For the part closer to the gable walls, as the distance of the cross-section from the gable wall decreased, the difference in the **C_p** distribution for the pipe house became more significant; in particular, on the leeward roof and wall. This feature is related to a three-dimensional effect of the flow due to the gable walls. It is found that the wind tunnel model with \( L/W > 4 \) should be used in order to obtain the correct **C_p** distribution for longer pipe houses in the fields.

Fig. 6 shows a comparison for the wind force coefficient \( C_f = (C_{pe} - C_{pi}) \) between the experimental result and the specifications in the current standard (Japan Greenhouse Horticulture Association, 1999). In practice, no specification is provided in the standard for a pipe house such as tested in the present study. Therefore, two similar configurations, e.g. greenhouses with circular arc and gable roofs as shown in Fig. 7, were used for comparison. Furthermore, the value of the **C_p** was assumed to be -0.2 (Sase et al., 1995). The **C_f** distribution for the pipe house was the same as that of the **C_{pe}** distribution in Fig. 5 but shifted to the positive side by 0.2. The specifications for the two types of greenhouse were different from the result of the present experiment; in particular, the difference was substantial for the arched greenhouse. The distribution for the pipe house was, if anything, similar to that for the gable-roofed greenhouse. This may be related to a similar flow pattern around the structure; that is, the flow separates at the location of the ridge in both cases. However, the slant of the wall and the curvature of the roof affect the flow along the windward surfaces. The **C_f** value on the windward wall for the pipe house was smaller than that for the gable-roofed greenhouse, which is due to the
slant of the wall, as mentioned by Hoxey and Richardson (1984). A vertical wall strongly intercepts the wind flow and the wind collides with the wall, resulting in large positive $C_p$ value on the wall. By comparison, when the wall is slanted a little, the wind flows more smoothly along the surface of the wall, which reduces the positive value of the $C_p$. Furthermore; the $C_p$ values on the windward roof are larger in magnitude for the pipe house. This feature may be related to the more accelerated flow along the roof of the pipe house; higher wind speeds make the pressures more negative.

Another possible reason for the difference between experiment and specifications in the standard is the difference in the flow condition used in the wind tunnel experiments. In the present study, we used a turbulent boundary layer that properly simulated natural winds over open-country exposures. On the other hand, less-turbulent flows (smooth flows in some cases) were used in the experiments, the results of which were used for providing the specifications in the current standard.

When a frame of the pipe house is subjected to a distributed wind force as shown in Fig. 6, the windward wall is pushed by the positive wind forces, and negative wind forces acting on the leeward roof and wall generate uplift and drag forces. The wind force on the windward roof was negative but small in magnitude. Therefore, it does not alleviate the positive force on the windward wall. Consequently, the windward wall is subjected to a push in the wind direction and may collapse due to excessive bending stresses. The collapse of pipe houses in the wind direction during a severe storm may be caused by such a large drag. Damage investigations of pipe houses often show such a collapse as shown in Fig. 8, in which the windward eaves were pushed down by strong winds. The $C_p$ distribution obtained from the present experiment corresponds well with the actual collapse mode of pipe houses.

2. Variation of $C_p$ distribution with wind directions

Fig. 9 shows typical $C_p$ distributions on the enclosed model (Case 1) for several wind directions. When $\theta = 0^\circ$, larger suction occurred in a roof area near the leeward gable wall. This is probably due to a three-dimensional effect of the flow at the gable wall. The largest negative $C_p$ value was -1.03 at the leeward ridge corner (Fig. 9(a)). The magnitude of the largest negative value increased and the area of larger suction expanded along the ridgeline as the wind direction
increased. When $\theta = 25^\circ$, the maximum negative value was -3.46 at a point near the gable edge ($s = 40$ mm) as shown in Fig. 9(b). Fig. 10 shows the variation of the $C_p$ distribution at a cross-section with the distance $s$ from the gable wall. For the comparative purpose, the distribution at the central cross-section for $\theta = 0^\circ$ is also plotted in the figure. The distribution at the central cross-section for $\theta = 25^\circ$ was almost the same as that for $\theta =$
The value on the windward wall and roof did not change so much with a decrease in $\xi$. However, that on the leeward roof and wall changed significantly, and the distribution was quite different from the distribution at the central cross-section, in particular, for $\xi < 300$ mm. For $\xi > 900$ mm, the $C_p$ distribution changed only slightly with $\xi$ (Fig. 9(b)) and was similar to that of central cross-section for $\theta = 0^\circ$. Similar features of the $C_p$ distribution were observed for wind directions up to $35^\circ$.

As $\theta$ increases further, the area of high suctions shrinks. For example, when $\theta = 75^\circ$, high suctions occurred only in an area near the windward gable wall (Fig. 9(c)). In the other region, the $C_p$ values were generally small in magnitude, approximately -0.2 to 0. Similar features of the $C_p$ distributions were observed when $\theta = 90^\circ$ (Fig. 9(d)).

Fig. 11 shows the influence of side gable openings on the distributions at the central cross-section and $\xi = 20$ mm when $\theta = 25^\circ$. The results on the distributions for four opening conditions (Cases 1 to 4 listed in Table 1) are plotted in the figure. It suggests that the distribution was not affected by the opening condition on the gable walls. In Case 3 where there are openings both on the windward and leeward gable walls, wind can blow inside the pipe house, which may result in a decrease in the magnitude of negative pressures acting on the outside of the pipe house. In practice, however, there was no significant change in the distribution. This suggested that the distribution is not affected by the existence of openings on the gable walls.

### 3. Internal pressure

The internal pressures were evaluated at five points for Cases 2 to 4; regarding the location of the measuring points, see Fig. 3. It was found that the $C_p$ value did not depend on the tap location significantly, except the location where the wind blows directly at it. This feature agrees with the analytical result obtained by Mistriotis and Briassoulis (2002). Therefore, the mean of the values evaluated at the five points will be used in the following discussion.

Fig. 12 shows the variation of the $C_p$ values with wind direction $\theta$ for Cases 2 to 4. In all cases, the value

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*Fig. 11 Influence of side gable openings on the $C_p$ distribution for $\theta = 25^\circ$: (a) Central cross-section, (b) $\xi = 20$ mm*

*Fig. 12 Variation of the mean value of the $C_p$ with wind direction*
was approximately -0.9 when $\theta = 0^\circ$. This value was much larger in magnitude than the specification for enclosed greenhouses in the current standard (i.e., -0.2). With this value, the resultant $C_r$ value was as large as 1.35 (=0.45-(-0.9)) on the windward wall (Fig. 5). Similarly, $C_r$ values on the windward roof ranged from 0.8 to 0.3, and those on the leeward roof and wall were approximately 0.3 and 0.4, respectively. That is, the frame is subjected to positive wind force in any part. In particular, the magnitude of $C_r$ is large on the windward wall and roof, which may cause a collapse of pipe houses with openings as shown in Fig. 8.

The results of Fig. 12 indicate that the $C_p$ value was strongly dependent on the wind direction as well as on the condition of the side gable openings. The value increased almost gradually with an increase in $\theta$ in all cases. In Case 2 where only the windward gable wall has an opening, the value was larger for $\theta > 0^\circ$ compared with the other cases. This is because the internal pressure was mainly affected by the wind pressure at the location of the opening. The value was approximately 0.5 when $\theta = 65^\circ - 90^\circ$. When $\theta = 90^\circ$, the value was 0.46. A large value of the $C_p$ of approximately -0.9 occurred in an area close to the windward gable wall, particularly on the roof. High suction combined with $C_n$ and $C_p$ cause large uplift forces on the frames near the windward edge. This feature is important for the design of foundations.

In Case 3 where both gable walls have openings, the behavior of $C_p$ with $\theta$ was similar to that in Case 2. However, the value was generally smaller than in Case 2. When $\theta = 90^\circ$, for example, the value was 0.14 in Case 3 and 0.46 in Case 2. This is because the wind blows inside the pipe house in Case 3, while the air is stagnant in Case 2. Judging only from the magnitude of $C_n$, the possibility of destruction for pipe houses is likely to be lower in Case 3 than in Case 2. When the door on the windward gable can be destroyed by strong winds, it will be effective to open the door on the leeward gable wall to protecting the frames of pipe houses from destruction by reducing the wind forces.

In Case 4 where only the leeward gable wall has an opening, the $C_n$ value was always negative for all wind directions from $0^\circ$ to $90^\circ$. For a wind direction range from 45$^\circ$ to 90$^\circ$ the value of $C_n$ was almost constant, approximately -0.25, which is nearly equal to that in Case 1.

As mentioned above, it is clear that the $C_r$ distribution on pipe houses were strongly affected by the wind direction as well as by the condition of openings on the gable walls. Such features should be considered appropriately in the wind resistant design of pipe houses, or in the specifications of $C_r$.

**Conclusions**

The $C_p$ distributions on a pipe house have been evaluated with a 1:20 scale model in a turbulent boundary layer. The results can be summarized as follows:

1. At the central cross-section, the $C_p$ value of the pipe house was 0.45 at the mid-height of the windward wall. The $C_p$ value on the windward roof was negative, gradually increasing in magnitude from 0 at the windward edge to -0.6 at the ridge. On the leeward roof and wall, the values of the $C_p$ were -0.6 and -0.54, respectively.

2. The $C_n$ distribution of the pipe house was different from that of the specification for a greenhouse with a circular arc roof. However, the distribution was similar to that for the gable-roofed greenhouse, while the $C_r$ value on the windward roof for the pipe house was larger in magnitude than that of the gable-roofed greenhouse.

3. The $C_p$ distributions of the cross-section in the middle part of the pipe house were independent of the distance from the gable wall. For the part closer to the gable walls, as the distance of the cross-section from the gable wall decreased, the difference in the $C_p$ distribution for the pipe house became more significant; in particular, on the leeward roof and wall. This feature was related to a three-dimensional effect of the flow due to the gable walls. It was found that a wind tunnel model with $L/W > 4$ should be used when $\theta = 0^\circ$.

4. When $\theta = 25^\circ$, the maximum negative $C_p$ value was -3.46 at a point near the gable wall. On the other hand, the $C_p$ distribution at the central cross-section was not affected significantly by the gable wall at a range of $0^\circ$ - $35^\circ$ in $\theta$. 

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(5) The $C_{pe}$ distribution was not affected by the existence of openings on the gable wall.

(6) For the pipe house with openings on one or both gable walls, the $C_{pi}$ values were approximately -0.9 when $\theta = 0^\circ$. This value was much larger in magnitude than the current standard of -0.2 for enclosed greenhouses. With this value, the resultant $C_t$ was as large as 1.35 on the windward wall, and may cause a collapse of pipe houses with openings.

(7) For the pipe house with openings on windward gable walls, when $\theta = 90^\circ$, the $C_{pi}$ value was 0.46. A large $C_{pe}$ value of approximately -0.9 occurred in the area close to the windward gable wall, particularly on the roof. High suction combined with $C_{pi}$ and $C_{pe}$ may cause large uplift forces on the frames near the windward edge. This feature is important for the design of foundations.

In this paper, only the time-averaged values were discussed. However, the dynamic load effects of wind pressures have been recently considered important. The effects will be reported in another paper.

Acknowledgement

The authors wish to express sincere thanks to Dr. Atsuo Ikeguchi, National Institute of Livestock and Grassland Science, Dr. Limi Okushima and Dr. Masahisa Ishii, National Institute for Rural Engineering, and Dr. David R. Mears, Rutgers, The State University of New Jersey, USA for their expert advices. This study was supported by the Research Project for Utilizing Advanced Technologies in Agriculture, Forestry and Fisheries.

References


パイプハウスの風圧係数と妻面開口部の影響に関する風洞実験

森山英樹*1・佐瀬勲紀*2・植松 康*1・山口智治*4

*1 農業環境工学関連学会 2006 年春季大会にて一部発表
*2 (独) 農業・食品産業技術総合研究機構農村工学研究所, ℹ 305-8609 つくば市
*3 東北大学未来科学技術共同研究センター, ℹ 980-8579 仙台市
*4 筑波大学大学院生命環境科学研究科, ℹ 305-8572 つくば市

要 旨

一般建築物に比せて複雑な形状を有するパイプハウスの風圧係数を求めるために、乱流境界層中に設置した縮尺1:20の模型に関する風洞実験を行った。模型の開口に対する桁行長さの比は8.3であり、これは従来の風洞実験で使用されてきた模型に比べて大きい。風圧係数の分布は、風向0°（開口方向）から90°（桁行方向）まで、5°間隔の風向において測定した。風向0°に関する風圧係数を、従来の設計基準における両屋根型温室および円弧屋根温室の風圧係数と比較し、両者における風圧係数分布の違いを明らかにした。また、風圧係数の分布は風向に大きな影響を受け、風圧係数の最小値-3.5は、風向25°における妻面近傍の屋根上で生じた。外圧係数および内圧係数に対する表面開口部の影響も調べた。その結果、表面開口部は、外圧係数に殆ど影響を与えない一方で、内圧係数に対する影響は大きかった。風向0°の時、内圧係数の最小値は-0.9であり、風力係数を正の値に大きく移行させた。内圧係数は風向にも影響を受けた。風向が90°の時に、内圧係数は、風下側の開口部がある場合の-0.2から風上側に開口部がある場合の+0.5まで分布した。

キーワード：パイプハウス、風圧係数、風洞実験、表面開口部