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Academic Article

Performance Evaluation of Convective Heat Transfer on Leaf Surface by Model Specimens

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ABSTRACT

Urban vegetation is considered to be one of the countermeasures to urban heat island. A recent study highlighted that approximately 50% of the net radiation absorbed by an isolated plant is transferred to the atmosphere as sensible heat flux. This suggests that the surfaces of leaves have a high sensible heat transfer performance. Since the sensible heat transfer in forced convection depends upon the size of the heating surface and the direction of wind, the heat transfer coefficient of a leaf's surface is greater than that of a flat plate with the same area as total area including in a tree crown. The angle of attack of the leaf surface and the oscillatory motion in response to wind speed fluctuations are also potential factors affecting the heat transfer coefficient. In this study, the influences of these factors on the heat transfer coefficient of leaf surfaces are evaluated using the heating flat plate model specimens. The evaluation of heat transfer coefficients for flat plates is performed in a wind tunnel, which is connected to an induced draft fan.

Key Words : Urban heat island, Urban vegetation, Sensible heat transfer on leaf surface, Heat transfer coefficient, Model specimen, Experiment, Wind tunnel

1. Introduction

Urban vegetation, such as trees planted along streets, building rooftops, and walls, is considered to be a countermeasure to the effects of urban heat island. Urban vegetation has many benefits, notably, it causes atmospheric cooling by absorbing net radiation through transpiration, due to the latent heat of moisture. As the mitigative effect of urban vegetation on the thermal environment in urban areas has been identified(1, 2, 3), several studies on the heat exchange performance between tree crowns or green belt areas and the surrounding air have been conducted(4, 5). It can be asssumed that a leaf surface within a tree crown is much smaller than the scale of an entire tree, and has superior characteristics of heat and mass transfer to the atmosphere on its own. In the field of mechanical engineering, empirical and theoretical relationships for turbulent heat transfer coefficients on a flat plate have been established previously(6, 7). In the agricultural or architectural fields, the heat and mass transfer characteristics of a leaf's surface have also been experimentally and numerically evaluated(8, 9, 10, 11). In a recent study, it was shown that approximately 50% of the net radiation absorbed by an isolated plant in an urban area is transferred as sensible heat flux into the atmosphere(12). Asawa et al. evaluated the convective heat transfer coefficient of the entite crown of an isolated tree under outdoor conditions, by measuring the whole tree heat balances of two individual trees that differed in their traspiration rate(13). In both of these studies, the resulting heat transfer coefficients of isolated plants are larger than those found using existing empirical formula such as Jürges's formula. This suggests that the leaf surface of a plant has a high performance of sensible heat transfer. The tree crown is an aggregate of small leaf surfaces contained within it, and the heat transfer performance of the entire crown is considered to be due to the heat transfer performance of individual leaves and the interactions between them. Since the sensible heat transfer in forced convection depends on the size of heating surface and the direction of wind , the heat transfer coefficient of the leaf surface is larger than that of a plate with the same area as total area including in a tree crown. The angle of attack of the leaf surface and the oscillatory motion in response to wind speed fluctuations are also potential factors that affect the sensible heat transfer.

In this study, the influences of these factors on the heat transfer coefficient of leaf surfaces are evaluated by heating flat plate model specimens. The effect of the specimen size, angle relative

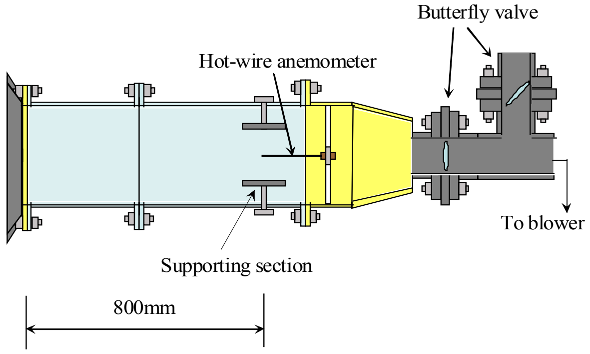


Fig. 1 Technical sketch of the experimental apparatus

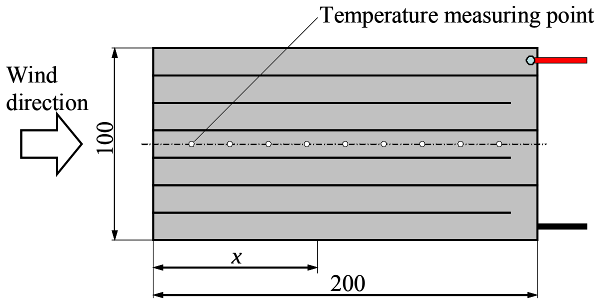


Fig.2 Flat plate model specimen and temperature measuring positions.

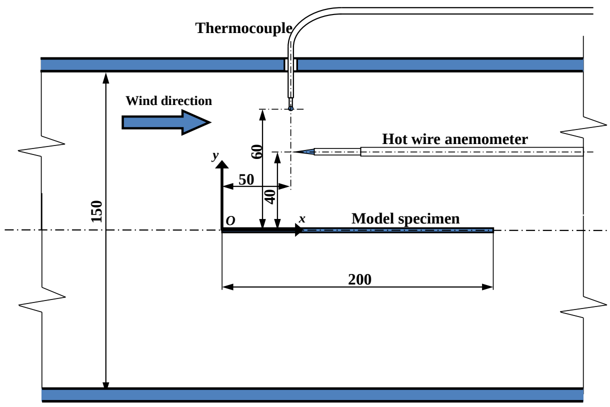


Fig.3 Location of the model specimen and measuring devices.

to wind direction, and wind speed fluctuation on the sensible heat transfer coefficient was parametrically evaluated using a wind tunnel.

2. Experimental wind tunnel apparatus

A suction type wind tunnel, with a blower installed on its downstream side, is used in this study. The cross section of the duct is rectangular, with dimensions of 200 × 150 mm. The mean wind speed can be varied between 0 and 7 m/s by operating two butterfly valves. The model specimen is supported near the center of the duct, and the angle of attack to the mainstream flow direction can be adjusted by rotating it in the pitch direction. Figure 1 shows a technical sketch of the general arrangement of the wind tunnel apparatus. The wind velocity near the model specimen is measured using a hot wire anemometer.

3. Effect of the flat plate size on the heat transfer coefficient

The size of plant leaves differs between plant species. It can be considered that plant crowns consist of small sized flat plates of leaves, and that higher heat transfer coefficients of foliage are due to the size of the leaf.

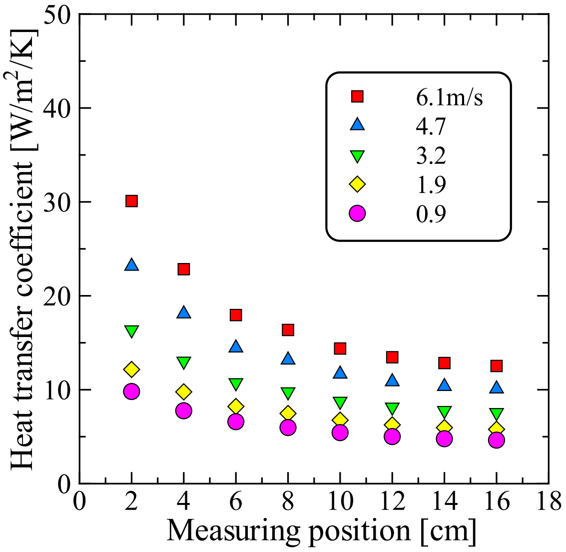
The model specimen is a flat plate of ABS plastic, on which aluminum foil is adhered. It is then heated using electrical resistance heating. The flat plate specimen is installed in the wind tunnel, and the heat transfer coefficient is calculated by recording data for measured wind speed, surface temperature and air temperature. The size of the model specimen is 100 × 200 mm. In order to measure the surface temperature profile, copper constantan thermocouples are located at nine points with a separation of 20 mm, starting from the leading edge. The thermocouples are also located along the center of the specimen, as shown in Fig. 2. It is assumed that heating on the upper and lower surfaces is uniform and of the same amount.

Figure 3 shows the location of the model specimen and the measuring devices located within the wind tunnel. The wind speed is set at various speeds, approximately 1, 2, 3, 4, and 5 m/s. A thermocouple and a hot wire anemometer are located 50 mm downstream from the leading edge of the model specimen and 60 mm and 40 mm above the specimen surface, respectively, in order to measure the wind temperature and speed as reference values for the evaluation of the heat transfer coefficient.

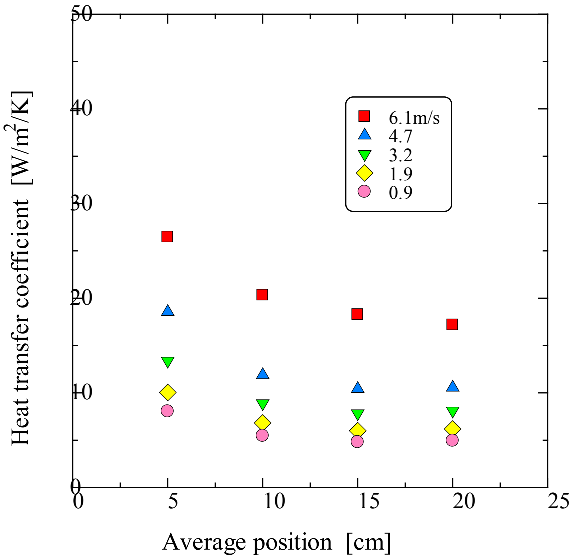
Figure 4 shows the effect of the wind speed on local and average heat transfer coefficients. The local heat transfer coefficient increases as the distance from the leading edge of the specimen decreases, and as wind speed increases. The average heat transfer coefficient is calculated by integrating the temperature profile from the leading edge to position x, which corresponds to the effect of the model specimen size on the heat transfer coefficient. As shown in Fig. 4, it is found that the heat transfer coefficient increases as the size of the model specimen, which corresponds to leaf size, decreases.

4. Effect of the angle of attack on the heat transfer coefficient

The effect of variations of the angle of attack on the heat transfer coefficient of the leaf surface is evaluated by heating the flat plate model specimen in the wind tunnel. Measurements are taken at a range of different angles for the heating flat plate model specimen. Figure 5 shows the location of the measuring



(a) Local heat transfer coefficient



(b) Average heat transfer coefficient

Fig. 4 Effect of wind speed on the heat transfer coefficient.

specimen and measurement devices, which is similar to that found in the previous section. The size of the model specimen is 100 × 100 mm. The horizontal plane is set as the base, and the angle between the specimen surface and the plane is θ. Measurements are taken in seven conditions from θ = +30° to -30°, at 10° intervals. The wind speed for the condition of θ = 0 degrees is set as the base, and this value is used for calculating the heat transfer coefficient. The thermocouple is located on the surface of the lower side, and θ is controlled such that the wind is directly impinging against the surface and is positive. The base wind speed is set to approximately 5 m/s.

Figure 6 presents the experimental results. For the condition of a positive angle, the local heat transfer coefficient shows a similar tendency to that of the horizontal location case , and decreases as it approaches the trailing edge of the specimen. However, for the condition of a negative angle, the opposite outcome appears in

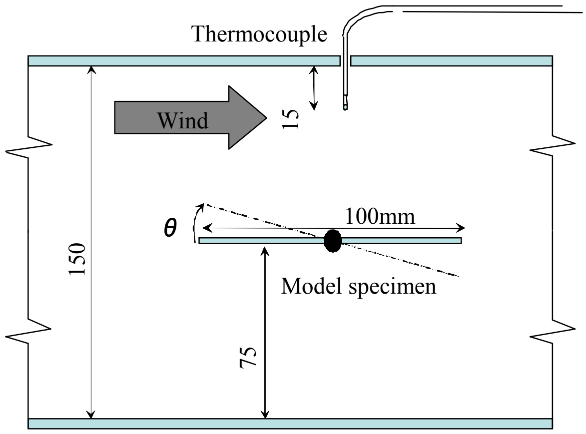
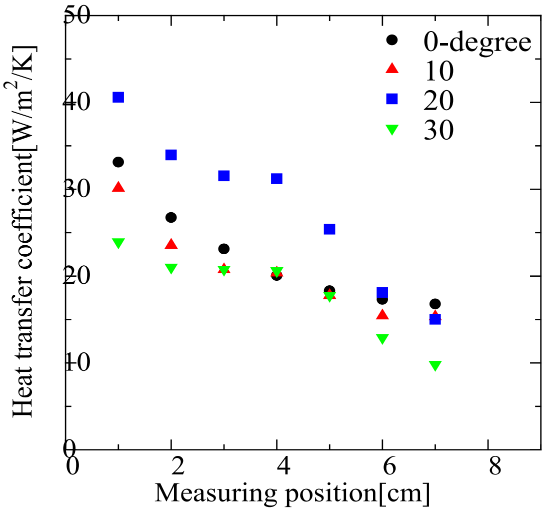
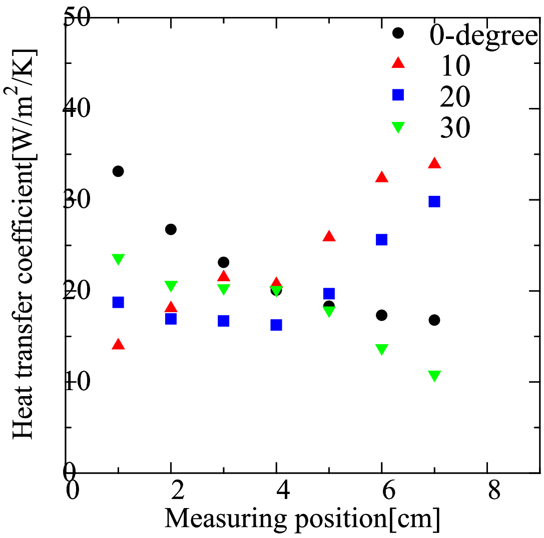


Fig. 5 Location of model specimen for evaluation of the effect of angle of attack.



(a) Positive angle



(b) Negative angle

Fig. 6 Local heat transfer coefficients in the condition changing the angle of the specimen.

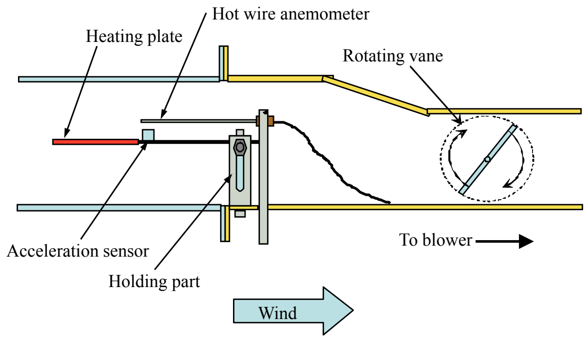


Fig.7 Location of model specimen for the evaluation of oscillatory motion effects.

certain cases, and the overall tendency is complicated.

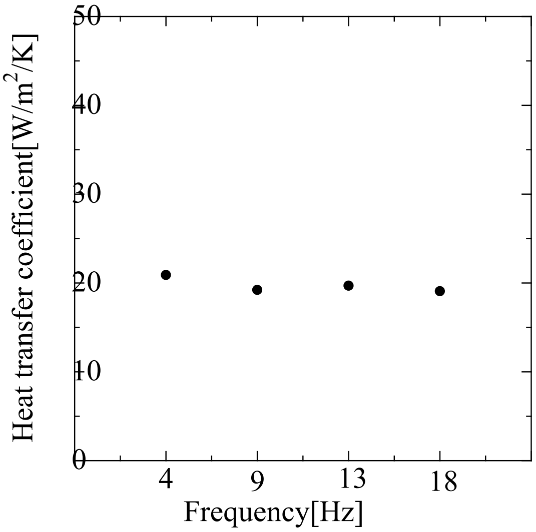
5. Effect of oscillatory motion on the heat transfer coefficient

Plant leaves oscillate as the wind blows. It has been reported that the thickness of the boundary layer on a leaf's surface becomes thinner owing to this oscillation than it would otherwise be in a stationary condition. It is also understood that the efficiency of photosynthesis improves as the wind blows, due to the reduction of resistance in gaseous species exchanges. The effects of leaf oscillation are evaluated within this study by subjecting the flat plate to an oscillatory air current(14). In this section, the effect of oscillatory motion on sensible heat transfer performance is evaluated.

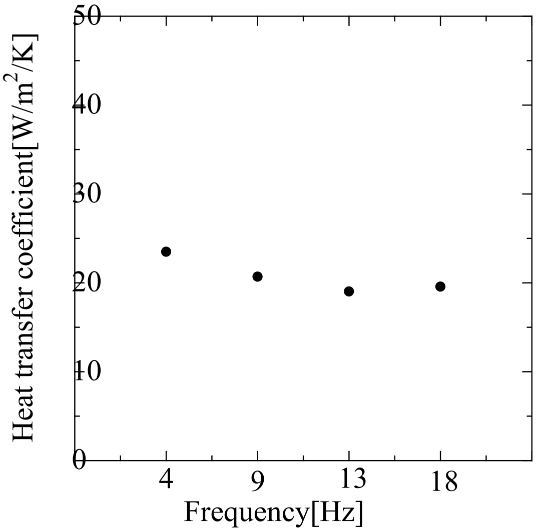
Figure 7 shows the experimental apparatus. A heating flat plate model specimen is installed at the end of a flexible beam of ABS plastic, which extends from the downstream side to the upstream side of the wind tunnel, and wind speed is varied using a rotating vane located on the upstream side of the blower. The frequency and acceleration of the flat plate oscillation are measured using an acceleration sensor. The fluctuation frequency can be controlled within the range of 4 to 60 Hz, by altering the speed of the rotating vane. The size of the specimen is 100 × 100 mm.

Experiments are performed for two cases relating to the support apparatus of the model specimen; rigid arms connected to the wind tunnel wall as shown in Figs.1 and 3, and the flexible plastic beam described above. Four cases of air current oscillation frequency are applied; 4, 9, 13, and 18 Hz. 4 Hz corresponds to the characteristic frequency of the flexible beam.

Figure 8 shows the experimental results for the average heat transfer coefficients. In the case of the 18 Hz air current oscillation frequency experiment, the oscillatory motion of the specimen is found to be negligible, and the difference of heat transfer coefficients between the fixed plate specimen and movable one is minor. In the case of the 4 Hz air current



(a) Support with rigid arm



(b) Support with flexible beam

Fig. 8 Experimental results for the average heat transfer coefficient in different conditions of air current oscillation.

oscillation frequency experiment, relatively large oscillations of the flexible beam were observed, and a relatively higher heat transfer coefficient of the plate specimen supported with the beam were measured, than that supported with the rigid arm.

6. Summary

In this study, the influences of leaf size, angle of attack, and oscillatory motion on the heat transfer coefficient of a leaf's surface are evaluated using heated flat plate model specimens.

The local heat transfer coefficient increases with an increase in wind speed, and decreases as the measuring position moves along the wind direction from the leading edge.

The influence of the angle of attack of a leaf's surface on the heat transfer coefficient has been evaluated. It was found that the local heat transfer coefficient profile of the specimen becomes complex with an increase in the angle. In addition, the influence of the oscillatory motion in response to wind speed fluctuation was evaluated using the same measurements, by fixing the specimen on the end of a flexible beam. The result is that heat transfer coefficients increase when compared to those measured in a fixed condition.

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