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Experimental Study for Wind Velocity Profiles in and around a Rice Canopy at Different Growing Stages

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(*Received November 10, 2006 and accepted December 1, 2006*)

Vertical profiles of wind velocity in and around a rice canopy at three different growing stages were experimentally investigated using a wind tunnel. The vertical profiles were measured between rows of rice bunches and above bunches in a rice canopy, and between rows and behind bunches outside the canopy. Each vertical profile was compared with the input profile of wind velocity, and trends in attenuation and acceleration of wind were examined. It was found that wind was accelerated above rice bunches, and the extent of acceleration depended on a growing stage of rice. For vertical profiles between rows of rice bunches, attenuation of wind velocity was found at the area that the rice bunches spread out leaves between rows, and wind was accelerated above and below the area. A peak location of attenuation behind bunches changed depending on a growing stage. For locations below appearance height of a rice canopy, the peak of attenuation appeared right behind the rice bunch 8. The wind velocity decreased by 60 % at the growing stage 2nd and 3rd. For locations above appearance height of a rice canopy, acceleration was prominent at the 3rd growing stage, and the wind velocity increased by 60%.

INTRODUCTION

Environment of wind is one of the important factors for cultivation of rice paddy because of its influence on rice production environment, such as temperature and humidity, and lodging damages. Understanding of wind profiles in and around a rice canopy in a paddy field contributes to farmers' decision making for optimization of the cultivation, which improves yield and quality, and avoids pest damages.

For the above purposes of practical applications to agriculture, some studies have been conducted to investigate environment of wind in a field. Nagano and Sugi (1971) investigated wind velocity profiles above canopies of tobacco, corn and rice. Wilson and Shaw (1977) developed a one–dimensional, nonbuoyant mathematical model of air flow within vegetative canopies using equations of motion. The model was applied to a corn canopy and the accuracy was assessed in results predicted for mean wind velocity, Reynolds stress and turbulent intensities for the region from the soil surface to twice the canopy height. Kotoda and Hayashi (1980) examined relationships between parameters in a formula for the logarithm rule of wind velocity, which are friction velocity, zero–place displacement, and roughness

length, and height of a canopy and a drag coefficient of total canopy. The study focused on wind profiles above plant canopies of grass, corn, and a Japanese larch. Inoue and Uchijima (1979) conducted broad and detailed investigation regarding environment of wind in a field. The variation of wind profiles in a canopy with the growth of crops and the oscillation of the turbulence intensity profiles were investigated for maize and rice. Profiles of mean wind velocity and turbulence intensity in a maize canopy were examined at 4 growing stages, while those in a rice canopy was studied at just one growing stage.

When we consider that the goal of this study is to define wind profiles in and around a rice canopy in a paddy field, studies mentioned above provide limited information for characteristics of wind profiles in a field and insufficient to define the profiles depending on a rice growing stage. Also, from a practical aspect, it would be general to define wind profiles in a paddy field from field observations, which gives wind velocity at a specific location. Considering these situations, in this study, vertical profiles of wind velocity against input wind velocity were investigated experimentally using a wind tunnel at three different growing stages of rice paddy. Each vertical profile was compared with the input profile of wind velocity, and trends in attenuation and acceleration of wind were examined. Finally, attenuation and acceleration ratios of wind for above a canopy, between rows of rice bunches, and behind rice bunches were presented at each growing stage as reference to define wind profiles in a paddy field.

EXPERIMENT AND MATERIAL

Experimental system

Vertical profiles of wind velocity in and around a

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rice canopy were measured by the experimental system shown in Fig. 1. This system consists of a wind tunnel, an elevating machine (Sokken, AX–101), a heated thermocouple anemometer (Kanomax, Model 6542), a carriage, and a rice canopy. The width and height of the wind tunnel are 59.5 cm and 125 cm, respectively. A wind fan is located approximately 21.8 m away horizontally from the rice canopy. The elevating machine gives a precise control of the height for a sensor probe of the heated thermocouple anemometer. The sensor probe is attached to a rod of the elevating machine, and the horizontal locations are adjusted by a carriage on which the elevating machine is mounted. The anemometer measures wind velocity at one second of sampling time and calculate the average value for a certain period of setting time. The rice canopy in this experiment represents 9 bunches of rice stems arranged in a wooden box (width: 59.5 cm, length: 93.2 cm, height: 21 cm) filled with water. The location of water surface was arranged at the same level of the bottom of the wind tunnel. Each rice bunch was inserted into a plastic pot and soil was filled tightly to keep an upright condition of the bunch. Bottom of each pot was nailed on plywood in the wooden box.

Experimental material

A rice bunch pulled out of a paddy field was inserted into a plastic pot after measuring physical characteristics of the bunch, which composed a rice canopy. Table 1 presents average values of physical characteristics of a rice canopy used in the experiment, which include values at three different growing stages. Fig. 2 gives an additional explanation for the symbols in table 1. Here, *La*: appearance height of a bunch, *Wbr*: width at the base of a rice bunch in a row direction, *Wbw*: width at the base of a rice bunch in a direction of wind, *Wtr*: width at the top of a rice bunch in a row direction, and *Wbw*: width at the top of a rice bunch in a direction of wind. Appearance height was defined as height from base of a bunch to the fifth highest leaves. The row direction is a direction across a direction of wind. For growing stage 1st, we missed measurements for width of rice bunches.

Experimental conditions

The arrangement of nine rice bunches composing a canopy and measuring locations of wind velocity are shown in Fig. 3. Space between each bunch was 20 cm in a row direction and 30 cm in a direction of wind. Vertical profiles of wind velocity were measured at each location from L1 to L11. Measuring intervals in a vertical direction ranged from 2 to 5 cm depending on the height of measuring points. The lowest height of the measurement ranged from 2 to 6 cm from top of a water surface in a wooden box or bottom of a wind tunnel for the locations of input (L1), between rows (L3, L5, L7, L9, L11), and behind bunches (L6, L8, L10), while the measurement was started above a rice bunch at L2 and L4. Three conditions of wind velocity given in the
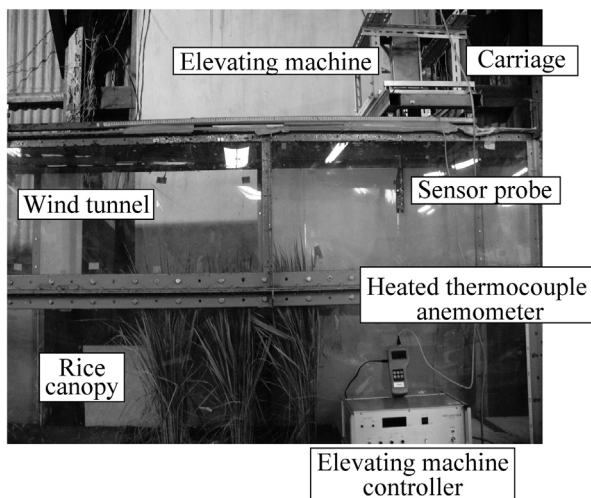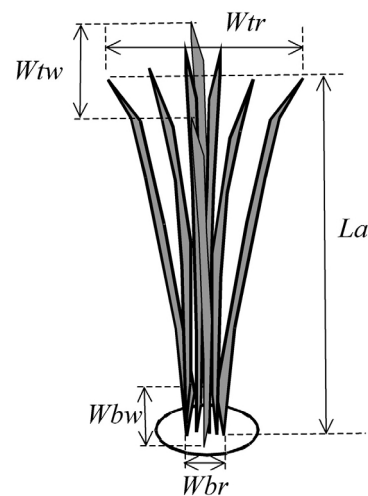

Fig. 1. Experimental system.

Fig. 2. Symbols of the physical characteristics for a rice bunch.

Table 1. Average values of physical characteristics of a rice canopy at three growing stages

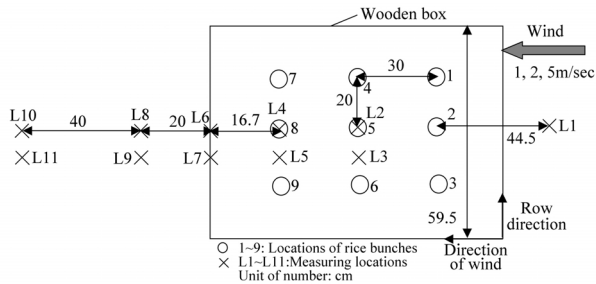| Growing stage	Number of stems	La, cm	Wbr, cm	Wbw, cm	Wtr, cm	Wtw, cm
1st	4.3(0.5)	17.8(1.7)	–	–	–	–
2nd	19.4(2.3)	50.3(3.1)	6.9(1.6)	6.6(1.4)	21.8(4.1)	23.2(4.0)
3rd	24.6(2.5)	81.0(2.2)	5.8(1.1)	6.3(0.7)	26.3(5.9)	25.3(3.4)

* Figures in parentheses represent standard deviation

Fig. 3. Arrangement of rice bunches and measuring locations of wind velocity.

Fig. 5. Vertical profiles of wind velocity at L4 (above the rice bunch 8).

experiment were 1, 2, and 5 m/sec. The uniformity of wind velocity was confirmed before the experiment. The wind velocity was measured at one second of sampling time and the average value for 30 sec was calculated.

EXPERIMENTAL RESULTS AND DISCUSION

Vertical profiles of wind velocity above a rice canopy

Vertical profiles of wind velocity at the location of L1 are shown in Fig. 4. Each vertical profile under wind velocity of 1,2, and 5 m/sec followed the logarithm rule of wind below height of 30 cm and was uniform above the height. The profiles were referred as a criterion (input) to discuss changes in vertical wind profiles in and around a rice canopy. Figure 5 shows vertical wind profiles at L4. Because the profiles were measured above the rice bunch 8, the lowest point of the measurement increased as a growing stage advanced. On the other hand, .the lowest point of measurement decreased as wind velocity increased due to deflection of the rice bunch. Wind was accelerated above a rice bunch at all growing stages, and the extent of the acceleration became prominent at a late growing stage. An inflection point in a vertical profile was found at each wind velocity and each growing stage from Fig. 5 and wind velocity at the point was plotted as shown in Fig. 6. The extent of acceleration in wind velocity increased with a growing stage. Ratios of wind velocity at an inflection point to wind velocity at approximately the same height of L1
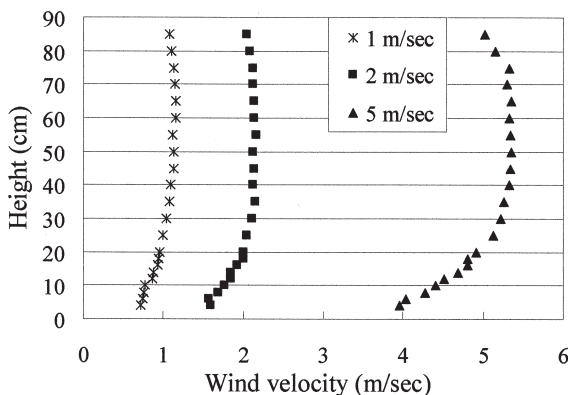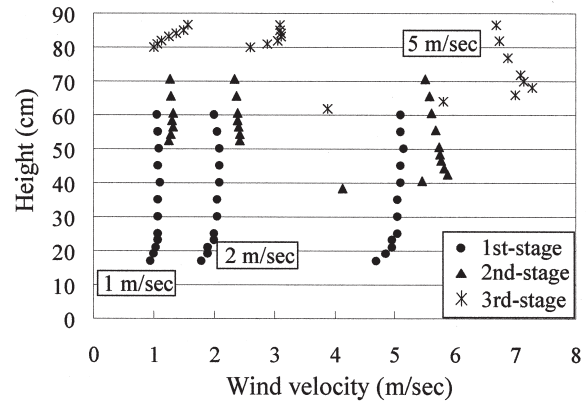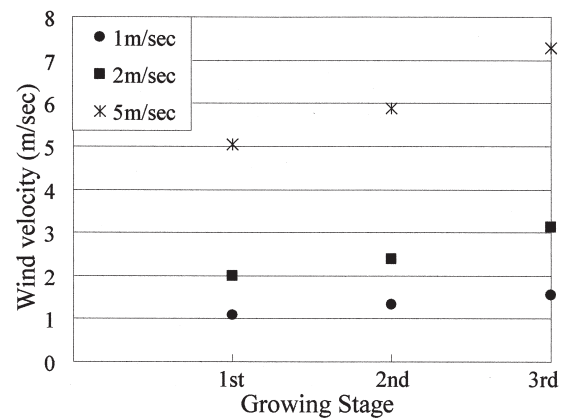

Fig. 6. Wind velocity at an inflection point in a vertical profile of L4.

(input) were 1.03, 1.18, and 1.56 for the 1st, 2nd, and 3rd growing stage, respectively under 1 m/sec, 0.98, 1.11, and 1.61, respectively under 2 m/sec, and 1, 1.11, and 1.47, respectively under 5 m/sec.

Vertical profiles of wind velocity between rows of rice bunches

Vertical profiles of wind velocity at the location of L5 are shown in Fig. 7. The measuring points are located between rows of rice bunches (between the rice bunches of 8 and 9). The wind was attenuated a little below the average appearance height of 17.8 cm at the 1st stage, but the vertical profiles were almost the same as those at L1. At the 2nd stage, the attenuation of wind velocity was found around the height of 30 cm under 1 m/sec, and the height of the attenuation became low as wind velocity increased. The height where attenuation of wind velocity was found was the area that rice bunches spread out leaves between rows, and the height of attenuation became low as wind velocity increased due to deflection of rice bunches. Wind was accelerated below and above the area of attenuation. The trend was similar at the third growing stage, and the extent of attenuation and acceleration was prominent compared to other growing stages.
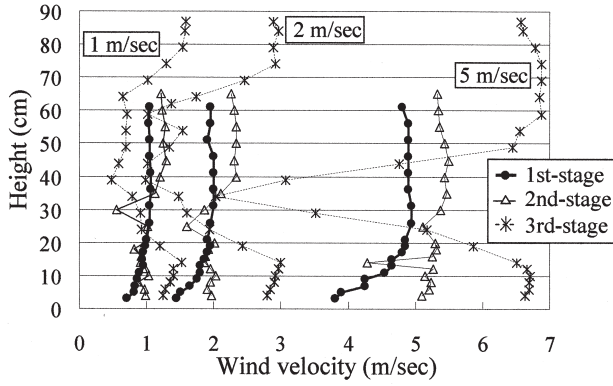

Fig. 4. Vertical profiles of wind velocity at L1 (input).

Fig. 7. Vertical profiles of wind velocity at L5 (between rows).

Vertical profiles of wind velocity behind rice bunches

Vertical profiles of wind velocity at the location of L6 are shown in Fig. 8. The measuring points are located behind the rice bunch 8. At the 1st growing stage, wind was attenuated relatively around the height of 10 cm. The average appearance height at the growing stage is 17.8 cm, and it was examined that density of leaves was high around 10 cm. The trend was similar at the 2nd stage, and the peak of attenuation was in the height between 20 cm and 30 cm. Also, the peak became low due to deflection of rice bunches as wind velocity increased. The variation of wind velocity was large at the 3rd growing stage. General trend in attenuation of wind was similar to other growing stages, and the peak of attenuation was in the height between 30 cm and 40 cm. Wind was accelerated significantly above appear-
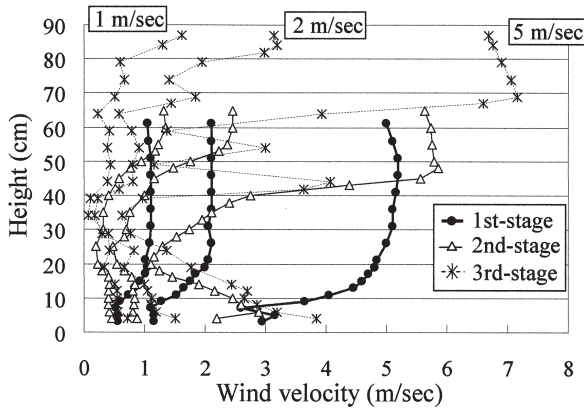

Fig. 8. Vertical profiles of wind velocity at L6 (behind the rice bunch 8).

ance height of the rice bunch.

Attenuation and acceleration ratios of wind below and above appearance height of a rice canopy

Attenuation and acceleration ratios of wind below and above appearance height of a rice canopy at each measuring point were calculated by following equation (1).

$$R_i \quad \frac{\left\{\int_{hl_i}^{hu_i} V_i dy \Big/ (hu_i - hl_i)\right\}}{\left\{\int_{hl_1}^{hu_1} V_1 dy \Big/ (hu_1 - hl_1)\right\}} \tag{1}$$

where, R: ratio of attenuation or acceleration, hl: lower height limit of integration, hu: upper height limit of integration, V: wind velocity, and y: an arbitrary height. The subscript i of each variables represents a measuring location. Because L2 and L4 were measuring locations above a canopy, those locations were excluded from the calculation for attenuation ratio of wind below appearance height of a canopy. For the attenuation ratio, the lower limit of integration was the lowest point of measurement. The upper limit of integration was determined by finding attenuation range of wind. The attenuation range was found by comparing vertical wind profiles between L1 and L6. For the acceleration ratio, the lower and upper limit of integration was determined by finding acceleration range of wind. The acceleration rage was also found by comparing the vertical wind profiles between L1 and L6. The ranges of attenuation and acceleration (integration range) at each growing stage and under each condition of wind velocity are shown in table 2. In table 2, "LOW" and "High" represents lower and higher limit of attenuation or acceleration range (integration range). Also, "LP" and "HP" represents the lowest measuring point and the highest measuring point in the experiment, respectively. For the wind velocity of 2 and 5 m/sec at the 2nd and 3rd growing stages, acceleration range continued within range of the measurement, and the highest measuring point was taken as the upper limit of acceleration range.

Figure 9 shows attenuation ratios of wind below appearance height of a rice canopy. Wind velocity slightly increased by 20 % at the location of L3 and L5, which were located between rows of rice bunches in a canopy. The peak of attenuation appeared at the location of L6, which was right behind the rice bunch 8

Table 2. Attenuation and acceleration range (integration range)

	Attenuation range						Acceleration range					
	1 m/sec		2 m/sec		5 m/sec		1 m/sec		2 m/sec		5 m/sec	
Growing Stage	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
1st	LP	21	LP	21	LP	21	21	30	21	30	21	30
2nd	LP	50	LP	50	LP	43	50	HP	50	HP	43	HP
3rd	LP	80	LP	80	LP	67	80	HP	80	HP	67	HP

* Figures in parentheses represent standard deviation

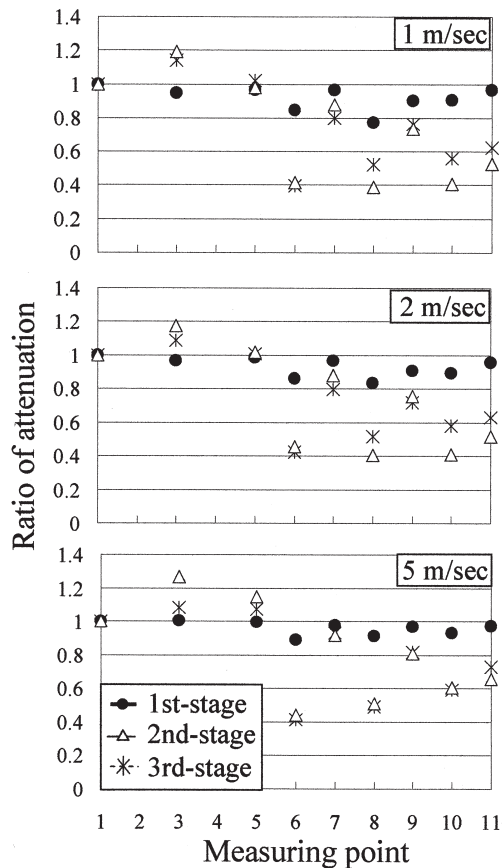**Fig. 9.** Attenuation ratios of wind below appearance height of a rice canopy.

Fig. 10. Acceleration ratios of wind above appearance height of a rice canopy.

outside a canopy. The wind velocity decreased by 60 % at the growing stage 2nd and 3rd, the wind velocity slightly decreased at the 1st growing stage. The extent in attenuation of wind velocity outside a canopy became low behind rice bunches (L6, L8, L10) as measuring points were apart from a rice canopy. On the other hand, the extent in attenuation of wind velocity outside a canopy became high between rows (L7, L9, L11) as measuring points were apart from a rice canopy. As the results, difference in attenuation of wind velocity between the locations behind bunches and between rows became small. Figure 10 shows acceleration ratios of wind above appearance height of a rice canopy. The extent in acceleration of wind velocity was low at the 1st and 2nd growing stage. The acceleration was prominent at 3rd growing stage, and the wind velocity increased by 60%. The variation of the acceleration ratios was large under 1 m/sec while the peak of the acceleration ratio
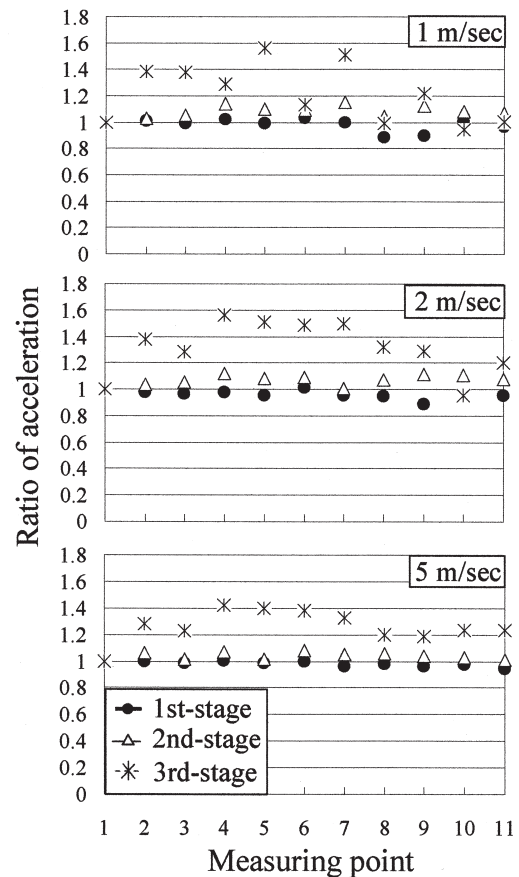
was almost constant under 2 and 5 m/sec.

Characteristics of wind velocity between rows and behind rice bunches

When profiles of wind velocity in a paddy field are determined from field observations, wind velocity at a specific location outside a paddy field would be used typically. Thus, it is important to understand changes in characteristics of wind velocity against input wind, in order to define profiles of wind velocity in and around a rice canopy. Table 3 and table 4 shows characteristics of wind velocity between rows (L5) and behind rice bunches (L6), respectively. The wind was not attenuated very much between rows even below appearance height of a canopy, while the wind behind bunches was attenuated by 10–20% at the 1st growing stage and by 60% at the 2nd and 3rd growing stage. For above appearance height of a canopy, the acceleration ratio

Table 3. Characteristics of wind velocity between rows (L5)

Location L5	Ratio of attenuation			Ratio of acceleration			Maximum wind velocity, m/sec		
	Below appearance height			Above appearance height					
Growing Stage	1 m/sec	2 m/sec	5 m/sec	1 m/sec	2 m/sec	5 m/sec	1 m/sec	2 m/sec	5 m/sec
1st	0.97	0.98	1.00	0.99	0.99	0.99	1.06	2.00	4.95
2nd	1.02	1.01	1.07	1.10	1.08	1.01	1.29	2.33	5.49
3rd	0.98	1.02	1.15	1.56	1.51	1.40	1.58	3.00	6.88

Table 4. racteristics of wind velocity behind bunches (L6)

Location P6	Ratio of attenuation			Ratio of acceleration			Maximum wind velocity, m/sec		
	Below appearance height			Above appearance height					
Growing Stage	1 m/sec	2 m/sec	5 m/sec	1 m/sec	2 m/sec	5 m/sec	1 m/sec	2 m/sec	5 m/sec
1st	0.84	0.86	0.89	1.03	1.01	1.00	1.11	2.10	5.20
2nd	0.40	0.42	0.41	1.10	1.09	1.08	1.35	2.46	5.86
3rd	0.42	0.46	0.44	1.13	1.48	1.38	1.61	3.19	7.16

was higher between rows than that behind bunches. The acceleration ratio between rows was relatively constant under each wind velocity, while the ration behind bunches was high under relatively higher wind velocity. The maximum value of acceleration was higher behind bunches compared to that between rows. Namely, it was examined that the acceleration ratio behind bunches was high locally just above bunches. Further investigation regarding relationship between growing stages of rice and changes in vertical profiles of wind against input wind is required, while values of average wind velocity can be roughly determined between rows and behind bunches by referring the tables

CONCLUSIONS

For the purpose of defining profiles of wind velocity in a paddy field from field observations, vertical profiles of wind velocity against input wind velocity were investigated experimentally. The following conclusions were drawn from this study

1) For vertical profiles above a rice canopy (L4), wind was accelerated above a rice bunch at all growing stages, and the extent of the acceleration became prominent at a late growing stage.
2) For vertical profiles between rows of rice bunches, the attenuation of wind velocity was found at the area that rice bunches spread out leaves between rows. Wind was accelerated below and above the area of attenuation.
3) For vertical profiles behind bunches, the peak of attenuation was found around 10 cm at the 1st growing stage, between 20 cm and 30 cm at the 2nd stage, and between 30 cm and 40 cm at the 3rd stage.

4) For locations below appearance height of a rice canopy, the peak of attenuation appeared right behind the rice bunch 8 outside a canopy. The wind velocity decreased by 60% at the growing stage 2nd and 3rd. The extent in attenuation of wind velocity outside a canopy became low behind rice bunches (L6, L8, L10), while the extent in attenuation of wind velocity outside a canopy became high between rows (L7, L9, L11) as measuring points were apart from a rice canopy.
5) For locations above appearance height of a rice canopy, the acceleration was prominent at the 3rd growing stage, and the wind velocity increased by 60%.
6) Characteristics of wind velocity between rows and behind bunches were tabulated. Values of average wind velocity in and around a rice canopy can be roughly determined from filed observations by referring the tables.

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