Improvement of High-Temperature Treatment Method using Solar Radiation under Unstable Wind Conditions

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Abstract: Open-top chambers (OTC) equipped with solar-heated double funnels (SDF) were tested for high-temperature treatments under unstable wind conditions. OTC-SDFs have two types of funnel-shaped tunnels attached on opposite ends; OTC-SDF-A had SDFs of the same width, and the OTC-SDF-B had SDFs that were twice the width of the open end. The temperature rise in these OTC-SDFs were compared with that in OTC with solar-heated air introduction tunnel (OTC-SAT). The temperature increase in the OTC-SAT during the daytime was small and not flat, whereas that in OTC-SDF-A was higher than in OTC-SAT and almost flat. The temperature rise was further enhanced in the OTC-SDF-B. An increase in air exchange ability at the intake may account for this enhancement. The drop in temperature at night observed in OTC-SAT was less prominent in OTC-SDFs. Based on these data, OTC-SDFs are considered useful in areas where the wind speed and direction are unstable.

Key words: High-temperature treatment, Paddy field, Rice (\textit{Oryza sativa} L.), Wind condition.

The increase in temperature due to global warming, particularly during the growing season, causes serious damage in both the quality and quantity of crop production (IPCC, 2013). For example, high temperatures during the ripening stage of rice (\textit{Oryza sativa} L.) results in the production of grain that is chalky and cracking (Nagata et al., 2004; Kondo et al., 2006). Furthermore, high temperatures during the flowering stage of rice increases the percentage of sterile grains and decreases grain yield (Matsui et al., 2001; Mohammed and Tarpley, 2009). The development of heat-tolerant cultivars, as well as improvement in cultivation systems, is required for stable and high-quality grain production under global warming conditions. Therefore, an effective and simple method of dealing with imposing high temperatures is needed to screen heat-tolerant genetic resources, which should be complemented by cultivation systems that contribute to crop adaptation to heat stress.

In our previous paper, we developed a high-temperature treatment method (Chiba and Terao, 2014). The method uses an open-top chamber (OTC) attached to a solar-heated air introduction tunnel (SAT), which uses solar radiation to warm the air (Fig. 1). Because the OTC has no cover, shading in the OTC-SAT is less than that in plastic greenhouses. Furthermore, the airflow system of the OTC-SAT might reduce confounding stresses related to the limited rate of gas exchange and variation in humidity typical of closed greenhouse environments.

The OTC-SAT method was effective at locations where the wind direction was stable, such as at Joetsu, Niigata. However, this system might not be suitable where wind conditions are variable, since the system is optimal when the wind blows in just one direction. Efficiency of imposing warming conditions might be affected by the speed of airflow through the SAT, although we did not check the OTC-SAT at that location. We evaluated the performance of the OTC-SAT at Fukuyama, where the wind direction and strength are inconsistent. Furthermore, we developed and evaluated the new types of equipment for the high-temperature treatment that uses the OTCs attached to solar-heated double funnels (SDFs) at the opposite side of the OTC to accommodate multiple wind directions. In addition, increasing the width of the entrance of the SDF was assessed to improve warming efficiency.
Materials and Methods

1. Location

The experiment was conducted at the NARO Western Region Agricultural Research Center (34°50' N, 138°38' E), National Agriculture and Food Research Organization, in Fukuyama, Hiroshima, Japan. Weather data, including wind direction, wind speed and solar radiation measured at the field of the Center, were provided by the Crop Management Group of NARO Western Region Agricultural Research Center. The hourly wind speed over the 10 min preceding the top of each hour. The hourly wind direction is the mode direction over the 10 min preceding the top of each hour. The hourly solar radiation is the integration over the 1 h preceding the top of each hour.

2. OTC-SAT and OTC-SDF design

An OTC-SAT was positioned in the field so that south-southeast (SSE) wind was introduced into the OTC. The dimensions of the OTC was 5.4 m wide, 3 m long and 1.4 m high, which was attached with SAT consists of three scmicircular tubes of 1.8 m wide, 0.65 m high, and 2 m

Fig. 1. Schematic diagram (side view) of the OTC-SAT and OTC-SDFs, and top view, and a picture of the OTC-SAT, OTC-SDF-A, and OTC-SDF-B. The width of the OTC-SAT was 5.4 m.
long on one side and an exhaust tunnel of 1.2 m long, 5.4 m wide, and 0.45 m high at the OTC junction and 1.3 m high at the exhaust end on the opposite side (Fig. 1). The OTC-SAT design was the shortened version of the OTC-SAT-DW; wider version of OTC-SAT-D which had larger exhaust tunnel to reduce the temperature gradient (5.4 m wide and 4.5 m long OTC with 3 m long SAT and 2 m long exhaust tunnel) (Chiba and Terao, 2014). The OTC was built with plastic film (0.1 mm thick, Nobi-ace-mirai, Mitsubishi Plastics Agri Dream Co., Ltd., Tokyo, Japan). The height of the SAT opening was 0.2 m higher than that of the previous paper (Chiba and Terao, 2014) due to 0.2 m high concrete levees at the inlet and outlet of the SAT. The sloping wall was attached to the OTC over the SAT. The exhaust tunnel was attached to the north-northwest (NNW) side of the OTC. The surface of the ground inside the SAT and the exhaust tunnel were covered with black weed suppression sheets.

In 2013, we used two types of OTC-SDF that had SDFs on the SSE and NNW sides (Fig. 1). The size of OTC was 1.8 m wide, 3 m long and 1.4 m high. The OTC-SDF-A was equipped with a SDF 0.65 m high at the OTC junction, 1.4 m high at the end, and 1.8 m wide from the junction to the end. The OTC-SDF-A was basically the same type but the shorter version of the OTC-SAT-E that had 3 m long SDF at both sides of the OTC whose length was 4.5 m (Chiba and Terao, 2014). The width of the SDF at the end was increased to 3.6 m in the OTC-SDF-B, but the width at the junction remained 1.8 m. The floor inside the SDF was covered with black plastic film-lined plywood panels to keep the floor even with the concrete levee to reduce the effect of the levee.

3. Temperature measurement and cultivation

Medium-size seedlings of the rice cultivar ‘Hinohikari’ were transplanted on 5 June 2012 and 4 June 2013. The heading date was 18 August in both years.

From 17 August to 26 September 2012 and from 20 August to 29 September 2013, we measured the air temperature inside the OTC 0.9 m above the ground and at different distances from the SSE side air intake using a temperature data logger (Thermochron SL type, KN Laboratories, Inc., Osaka, Japan) that was attached to the radiation shield housing, which was made of 5 layers of white plastic dishes. Measurements were taken at 0.45 m, 1.15 m, 1.85 m and 2.55 m from the end of OTCs at SSE side in 2012 and 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m in 2013. Eight ambient points in 2012 and five ambient points in 2013 were set outside the OTC. Temperatures were measured at 20 min intervals in 2012 and 15 min intervals in 2013.

Results

1. Wind direction and wind speed in the field

The distribution of wind direction and the wind speed were analyzed every 3 hours in August and September in
In the early morning (0600 /0700 /0800), the wind mainly blew from the northeast (NE), with a relatively low average wind speed of approximately 2 m s$^{-1}$. However, the wind direction was erratic at 0900 /1000 /1100. The main wind direction changed to SSE in the afternoon (1200 /1300 /1400 and 1500 /1600 /1700); thus, the directions of the SAT and SDF were set to this direction. The average wind speed of the afternoon SSE wind was approximately 3 m s$^{-1}$. Overall, the main wind direction changed from east to south, and the wind speed increased during the day. The wind speed in the night was low, except at 1800 /1900 /2000, when the daytime effect remained. There was no north wind due to a hill at the northern end of the experimental field.

2. Diurnal temperature rise variations

The average diurnal temperature profiles in the OTC-SAT in 2012 and in the OTC-SDF-A and OTC-SDF-B in 2013 are shown in Fig. 3A. The maximum temperature rise in the OTC-SAT was the lowest, approximately 1.3°C, followed by OTC-SDF-A and OTC-SDF-B, which were approximately 2.0°C and 2.2°C, respectively. Another conspicuous point for the OTC-SAT was that the temperature rise was depressed (– 0.46°C) before the morning temperature rise. This depression decreased in the OTC-SDF-A and disappeared in the OTC-SDF-B. From these temperature profiles, the daytime temperatures were separated into 3 phases: a rising phase, which roughly correspond to the time period from 0600 to before 1000, a stable phase from 1000 to before 1500, and a falling phase from 1500 to before 1800. The diurnal temperature profile of ambient
is shown in Fig. 3B. The pattern of temperature change was similar but the value was 2.1°C higher in 2012. The ambient temperature was lowest at 0520 in 2012 and 0530 in 2013, and increase rapidly from 0600 to 1000. That was highest at 1320 in 2012 and 1315 in 2013, and deceased rapidly from 1600 to 1900.

3. Performance of the OTC-SAT in Fukuyama

The temperature change at each point in the OTC-SAT was analyzed by separating daytime into the above-mentioned three periods (0600 – 0940, 1000 – 1440, 1500 – 1740) (Fig. 4A). At 0600 – 0940, the temperature near the SAT was lower than ambient, and it increased with increasing distance from the SAT. At 1000-1440, the temperature rise increased to more than 1.2°C and was almost flat. At 1500-1740, the temperature rise at the center of the OTC decreased but at both sides was still greater than 0.5°C. Consequently, the temperature rise in the daytime (0600 – 1740) was only 0.55 – 0.89°C and was not flat (Fig. 4B). At night (1800 – 0540), the temperature was lower than the ambient temperature (0.14 – 0.29°C), except near the SAT (Fig. 4B). The average temperature rise at all points was 0.68°C in the day and – 0.15°C during the night.

4. Performance of the OTC-SDF on the temperature in Fukuyama

The temperature rise in the OTC-SDF-A during the three daytime periods is shown in Fig. 5A. At 0600 – 0945, the temperature rise close to the NNW SDF was greater than at other points did. At 1000 – 1445, the temperature rise at the SSE side was 1.3°C and increased with greater distance from the SSE SDF; it reached 2.1°C at the NNW side. The temperature rise at 1500 – 1745 at 0.5 m and 1.0 m from the SSE SDF was almost equal to the temperature rise at 0600 – 0945. However, the temperature rise at other points at 1500 – 1745 was approximately 0.3°C greater than that at 0600 – 0945. Overall, the temperature rise throughout the daytime (0600 – 1745) was 0.92 – 1.46°C (Fig. 5B). The highest temperature rise of 1.46°C occurred at the NNW end. At night (1800 – 0545), the temperature
fell 0.05 – 0.25ºC below ambient, except at the SSE end (Fig. 5B). The average temperature rise was 1.10ºC in daytime and –0.13ºC at night.

The temperature change in the OTC-SDF-B during the three periods is shown in Fig. 5C. At 0600 – 0945, the temperature rise was almost flat, but it was highest near the SSE SDF and lowest at the next point. From 1000 – 1445, the temperature increases at 1.5 m, 2.0 m and 2.5 m away from the SSE SDF were approximately 2.0ºC and approximately 0.4ºC higher than those at 0.5 and 1.0 m away from the SSE SDF. The temperature rise from 1500 – 1745 was similar to that at 0600 – 0945, with the temperature rise increasing slightly with a greater distance from the SSE SDF. Consequently, the temperature rise in the daytime (0600 – 1745) was almost flat, except at 1.0 m away from the SSE SDF, which was slightly low with an average of 1.30ºC (Fig. 5D). At night (1800 – 0545), the temperature fell 0.06 – 0.19ºC below ambient, except at the SSE end (Fig. 5D). The average temperature rise was 1.30ºC in daytime and –0.07ºC at night.

5. The effect of wind conditions on the temperature rises in the OTC-SAT and OTC-SDFs

We analyzed the effect of wind speed on temperature before and after noontime (Table 1). Wind direction in the forenoon was mainly from NE the side of the OTC-SAT and OTC-SDFs, and was particularly erratic 0900 – 1100. Wind direction became stable and to the direction of air intake (SSE) in the afternoon (Figs. 1, 2A).

Correlation coefficients between solar radiation and the temperature rise in the OTC-SAT and OTC-SDFs were calculated using the average values of forenoon and afternoon, under a weak wind condition, with lower than the median wind speed, and a strong wind condition, with winds higher than the median wind speed (Table 1).

In the weak wind condition, the correlation coefficient computed between solar radiation and the temperature rise in OTC-SAT in 2012 was not significant throughout the day. However, in strong wind conditions, the correlation coefficient was significant at the 5% level, both in the forenoon and afternoon. The correlation coefficients of solar radiation with the temperature rise in OTC-SDF-A and -B in 2013 were statistically significant in both forenoon and afternoon irrespective of wind speed. Particularly high correlation coefficients were computed under weak wind conditions in both the forenoon and afternoon, and under strong wind conditions in the forenoon when wind direction was unstable (Fig. 2A). The correlation coefficients significant even in the afternoon under strong wind conditions, although the significance level declined.

Discussion

1. Performance of the OTC-SAT in the unstable wind

First, we evaluated the OTC-SAT in Fukuyama, where the wind conditions in the daytime were unstable. However, the average temperature rise in the daytime was only 0.68ºC (Fig. 4B). This was approximately half of the temperature rise observed in the OTC-SAT in Joetsu (Chiba and Terao, 2014). This small temperature increase was particularly prominent at 0600 – 0940. This decreased efficiency and lower temperature compared to ambient temperature at the closest end and 1.15 m from the SAT were accompanied by a transient temperature decrease before the temperature rise in the morning (Fig. 3A). This decrease was most prominent at the closest end of the SAT and was less prominent with increasing distance from the SAT (data not shown but see Fig. 4A 0600 – 0940). This temperature drop seems to have occurred because of a delayed temperature rise inside the OTC due to the poor air exchange. It seems that the wind went into the OTC through the exhaust tunnel and that cool air was easily exchanged near the exhaust tunnel, but not in the SAT: the SAT was not a suitable shape for air exhaust because it had a much smaller exhaust in the OTC-SAT (Chiba and Terao, 2014). Because of this, higher solar radiation did not increase the temperature rise of the OTC-SAT in the weak wind condition both in the forenoon and afternoon.

Table 1. The correlation coefficients between solar radiation and temperature rises in the OTC-SAT and OTC-SDFs under different wind conditions.

| Year | High-temperature treatment | Correlation coefficients between solar radiation and temperature rise |
|------|-----------------------------|-----------------------------------------------------------------------|
|      |                             | Forenoon                  | Afternoon               |
|      |                             | Weak wind | Strong wind | Weak wind | Strong wind |
| 2012 | OTC-SAT                     | 0.269 ns  | 0.467 *    | 0.181 ns  | 0.538 *    |
| 2013 | OTC-SDF-A                   | 0.873 *** | 0.863 ***  | 0.898 *** | 0.503 *    |
|      | OTC-SDF-B                   | 0.889 *** | 0.913 ***  | 0.940 *** | 0.588 **   |

Solar radiation at 0600-1200 characterized the forenoon period, while that at 1200-1800 represented the afternoon period. Temperature data at 0600-1140 in 2012 and at 0600-1145 in 2013 denoted the forenoon. Temperature data at 1200-1740 in 2012 and at 1200-1745 in 2013 represented the afternoon. *, **, and *** indicate significant correlations at the 5%, 1%, and 0.1% levels, respectively. ns indicates non-significance.
(Table 1). In addition, the temperature at the center of the OTC-SAT decreased by approximately 0.3°C at night (Fig. 4B). Cool air might accumulate in the OTC due to a high specific gravity and a difficult exchange caused by low wind speed at night in Fukuyama (Fig. 2B) compared to Joetsu, where a stable breeze blows from the south at night (Nakagawa and Yokoyama, 2012).

Another point is that the night temperature near the SAT was higher than near the exhaust tunnel. One reason could be the concrete levee placed between the SAT and the OTC, which may have acted as a heat reserve. Furthermore, the air space between the SAT and the sloping wall insulated heat outflow. These results indicate that OTC-SAT is not suitable for high-temperature treatments in areas where the wind direction and strength are unstable, such as Fukuyama.

2. Performance of the OTC-SDFs

We examined the OTC-SDFs in Fukuyama in 2013, which was a year later than the OTC-SAT was examined (2012). The temperature rise in the daytime in the OTC-SDF-A and OTC-SDF-B was 1.10°C and 1.30°C, which was higher than in the OTC-SAT of 0.68°C (Figs. 4B, 5B, 5D). The greater temperature rise in the OTC-SDFs was obtained in 2013 with an average daily solar radiation energy of 16.2 MJ m⁻². The solar radiation energy in this year was lower than that of 2012, which was 17.2 MJ m⁻². Thus, the greater temperature rise was obtained in a lower solar radiation year. Accordingly, the greater temperature rise in the OTC-SDFs compared with the OTC-SAT may be attributed to the differences in the OTC type.

At 0600-0945, the minimum temperature rise in OTC-SDF-A was 0.3°C, whereas that of OTC-SDF-B was 0.6°C (Figs. 5A, 5C) and was never lower than ambient, in contrast to the OTC-SAT (Fig. 4A). In particular, the temperature rise at 0600 – 0945 of the OTC-SDF-B was almost flat, except near the SSE side of SDF, and was higher than the OTC-SDF-A. The early morning temperature depression was much smaller in the OTC-SAT (Figs. 4B, 5B, 5D). In general, a larger vertical air intake section area results in a smaller nighttime temperature fall.

Conclusions

Based on these results, OTC-SDF-A is generally useful in areas where the wind is slow and uncertain, such as Fukuyama. Increasing the width of the SDF, as in OTC-SDF-B, is an efficient method to increase the daytime temperature rise and decrease the nighttime temperature fall, although constriction may become difficult.

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* In Japanese with English abstract.
** In Japanese with English title.
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