Soil Phys. Cond. Plant Growth, Jpn.
土壌の物理性
No. 79, p. 41～47 (1998)

Heat and Dissolved Oxygen (DO) Transfer Phenomenon in Ponded Paddy Field

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Abstract

An understanding of the transfer of heat and gases into and out of water is critical to understand the function of surface water layer in a low land paddy field. This study is intended to clarify the phenomena of heat and dissolved oxygen (DO) transfer in the paddy field water layer. Field experiment was conducted for temperature profile and DO concentration. The result was then verified with a lab-scale model under natural solar and artificial infrared radiation which were convective and non-convective system, respectively.

The continuous higher temperature at the soil surface indicated that the soil surface acts as the plane from which the heat is conducted upward and downward to water and soil, respectively. The heating at the bottom of water layer imposes the buoyancy forces that brings the convection current. Rayleigh and Prantdl numbers also confirms the turbulent convection in the water layer. The heat that is accumulated in the soil layer during the heating phase of the day is transferred to the soil surface during the cooling phase. Then the heat transfer from the water to the atmosphere is regulated by convection.

The diurnal variation in DO concentration indicated that there is an excess supply of oxygen in the day time and an over consumption in the night time. In the day time the DO generated by micro algae is transferred from the water to the atmosphere. In contrast, during the night time the oxygen transferred from the atmosphere into the water layer by reaeration. But, there was no distinctive concentration gradient in the ponded water either from the water surface or from the soil surface throughout the day. The corresponded temperature data confirmed the existence of a convection current in the water layer. This convection resulted in a uniform DO concentration throughout the profile regardless of reaeration or deaeration.

The resulting temperature and DO profiles generated under the convective system was compared with the profiles generated in a non-convective system. This comparison lead to the conclusion that convection plays a significant role in the heat and DO transfer in the ponded paddy field.

Key words : Paddy Field, Water Layer, Temperature and Heat Regime, Dissolved Oxygen (DO), Convection

Introduction

Rice is grown mostly under ponding conditions as a lowland cultivation. The shallow ponded water layer acts as an interface between the atmosphere and the soil for the transfer of heat and mass and forms the crop environment accordingly. An understanding of the transfer of heat and gases (dissolved) into and out of water is critical to understand the phenomena of surface water layer in a lowland paddy field.

The thermal regime is an important factor for the growth and development of rice plants. It also influences almost all physical, chemical and biological processes in the ponded fields, thus it effects indirectly the productivity of the land and the crop. But studies on this physical phenomena, so far, were more based on macro than micro levels (Uchijima, 1961, 1976). Hence it is necessary to characterize the thermal regime for the whole system of soil and water, for a proper management of a paddy field environment.

Submerged paddy fields are characterized by an anaerobic condition, in terms of the lack of oxygen in the soil. This affects the plant growth and other biological and chemical processes such as microbial activity, nutrient availability and oxidation-reduction reaction in the soil. Oxygen is a critical factor for the germination of paddy particularly in direct seeding. The rice plant consumes oxygen available in both the water and the soil until the plant matures enough to develop a system of interconnected internal air spaces which allow the plant to make use of atmospheric oxygen. However, the studies on dissolved oxygen (DO) found in the literature are much focused on water quality determination (Gordan *et al.*, 1996) than a crop environment such as paddy field. The dynamics of DO in the ponded water of a paddy field and influence of those dynamics on other phenomena in a crop environment have yet to be clarified.

Hence this study is intended to clarify the transfer of heat and DO in the water layer of a paddy field, taking into account the convective phenomenon.

Method

Field Experiment :

A paddy field lysimeter of $1.8 \times 1.8\,m^2$ surface area and 1.8 m depth was used for the field experiment. Ponded water level was maintained at the depth of 10 cm. The water was limpid and the downward flow of water was zero.

Vertical temperature profile was measured at different depths of water layer and of soil layer with Cu-Co thermocouples at the middle of the lysimeter. A thermocouple attached to a float was used to measure the temperature at the water surface. Air temperature was measured at the height of 1.5 m above the ground surface.

DO concentration at the middle of the water layer was measured continuously in the paddy field using DO meter with membrane electrode (DDIC, TOA Co. Ltd.). The water at the depth in concern was pumped using a micro tube pump. The DO probe was mounted on the water sampling tube and the data was continuously recorded. Solar radiation was measured with a pyranometer (MS-42, EIKO Co., Ltd.)

Lab scale model experiment :

A model experiment was performed in a small acrylic tank with 55 cm long, 35 cm wide and 35 cm deep. The bottom and sides were insulated with Styrofoam to form one dimensional (vertically) heat flow. The model was filled with sieved (paddy field) soil up to 20 cm depth. Water was added and the soil was puddled and left for several weeks. Thermocouples were installed in the middle of the model at different depths of water and soil. A thermocouple float was used to measure the temperature at the water surface. Air temperature was measured at the depth of 3 cm above the water surface. Water level was maintained at 10 cm depth. The model was exposed to natural solar radiation and artificial infrared radiation on separate days. An infrared lamp (100 V/400 W-Kett Co. Ltd.) was set at the height of 45 cm from the water surface. In each situation 24 hours data for the vertical distribution of temperature were measured.

In order to measure the DO profile in the water layer, sampling tubes and thermocouples (Cu-Co) were set horizontally through a stand at depths of 3, 6, and 9 cm from the water surface, at the middle of the model. DO was measured with the azide modification of the Winkler method (American Public Health Association, 1955) for individual water samples collected in oxygen bottles by suction at the time of measurements. The experiment was conducted for 24 hours under convective and non-convective conditions on separate days. During the infrared study, radiation period was for 10 hours, and this was followed by 14 hours of darkness.

Results and Discussions

Temperature Profile and Heat Transfer

The basic requirement to understand the thermal behavior of an environment is the measurement of temperature. Figure 1 shows the temperatures of soil surface, water layer (at the middle) and air in a paddy field over a three consecutive days. A detail profile of temperature for the water and soil in the paddy field model was shown in Fig. 2. The figures show that the temperature at the soil surface is always higher than that of the water layer throughout the day. Moreover, temperatures within the water layer at different depths were almost the same except at the soil surface and water surface. The high temperature at the soil surface indicates that the soil surface is the primary site of reception of energy directly from solar radiation. Then the heat is transferred upward and downward to the adjacent water and soil layer, respectively. As a result of this heating process the density of water in the proximity of the soil surface is decreased

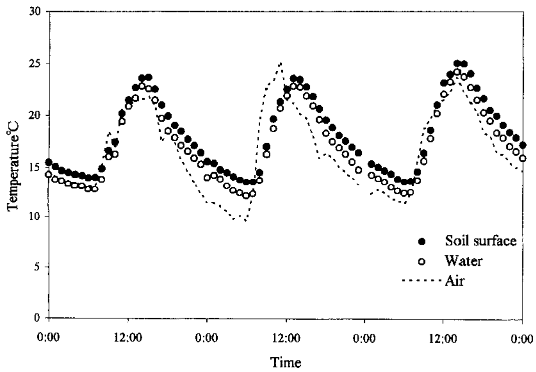

Fig. 1 Temperature of soil surface and water layer in the paddy field over a three consecutive days.

and imposed the buoyancy forces on the water. Because of this buoyancy forces the water moves up and down as "thermals" (buoyancy-driven masses of fluid moving away from the boundary surfaces) as explained by Chu *et al.* (1973) and Hollands *et al.* (1975). This free convection process brought temperature the same within the water profile and transfers the heat from soil surface to water surface (Mowjood *et al.* 1997).

The vertical thermal profile under convection as in the fig. 2 can be distinguished with three regions that are upper and lower conductive water layers where the temperature gradient was observed (air-water and water-soil boundaries) and a isothermal inner core between them as illustrated by Chu *et al.* (1973) and Hollands *et al.* (1975). The lower conductive water layer was formed because of the conductive heat transfer from the warmed soil surface. The convective circulation of the water brought the isothermal inner core. The top boundary layer was due to the heat loss from the inner isothermal core to the water surface. The thickness of the each layer depends on the temperature difference between the soil surface and the water surface.

The characteristics of the convection flow can be explained by a set of dimensionless parameters, such as Prandtl (Pr) and Rayliegh (*Ra*) numbers, that were calculated from the temperature difference between the soil surface and the water surface and the thermal parameters of water using the equations below (Holman, 1992).

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{1}$$

$$Ra = \frac{g\beta\,(T_{s.s} - T_{w.s})d^3}{\nu\alpha} \tag{2}$$

where,

ν-kinematic viscosity of water (m^2/s), α-thermal diffusivity of water (m^2/s), g-gravitational acceleration (m/s^2), β-thermal expansion coefficient of water (K^{-1}), d-depth of water (0.1 m in this study), $T_{s.s}$-temperature at soil surface and $T_{w.s}$-temperature at water surface.

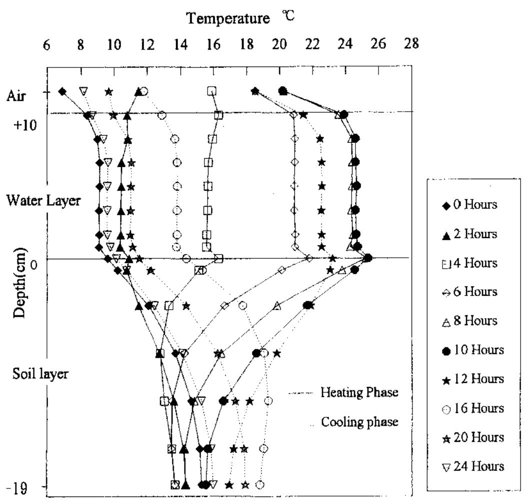

Fig. 2 Temperature profile in the lab-scale model of paddy field under convection.

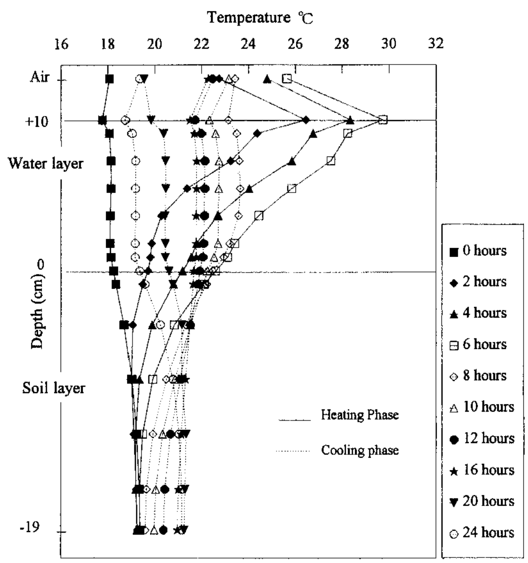

Fig. 3 Temperature profile in the lab-scale model of paddy field under non-convection.

The Rayliegh number ranges greater than the power of 10^6 throughout day. The Prandtl numbers was around 7. The temperature difference was found minimum in the morning and maximum in the mid day. This confirms the convection in the water layer of paddy field to be in turbulent and the degree of turbulent may varies with time within a day.

The temperature difference between soil surface and water surface maintained through out the day. This can be explained as follows. In the day time solar radiation heats the soil surface and instantaneously the heat is transferred downward by conduction efficiently. Because the soil is saturated under ponded condition and has low resistance to heat conduction compared with that of upland. In the late evening and night the heat, stored in the soil underneath, is conducted upward to the soil surface until the next day morning. Further the temperature at the water surface was lower mainly due to the latent heat loss and out flux of heat to the air. The evaporation process at the water surface not only transfers the heat from the water surface but also accelerates the convection current by increasing the temperature difference between the soil surface and the water surface by its cooling effect. From these facts, it is quite evident that convection is a continuous process in the paddy field water layer and it will be prominent if there is a cool night followed by a sunny day.

To clarify the phenomenon of convection in relation to the thermal regime in a paddy field, the effect of non-convective system that is under infrared radiation was examined using the model. The infrared (long wave) radiation is absorbed at the water surface efficiently, thus a decreasing temperature gradient as shown in Fig. 3 was established from the water surface to the soil surface during the radiation. The temperature gradient shows that the lower-density water was above the higher-density water and no convection currents was occurred. In this case the heat transfer across the water was by conduction alone. This comparison made it clear that the convection determine the thermal behavior of the water and soil in a paddy field.

DO dynamics in a Paddy Field :

The DO concentration variations with time in the ponded water of the paddy field over a three consecutive days is shown in Fig. 4. The DO concentration changed remarkably

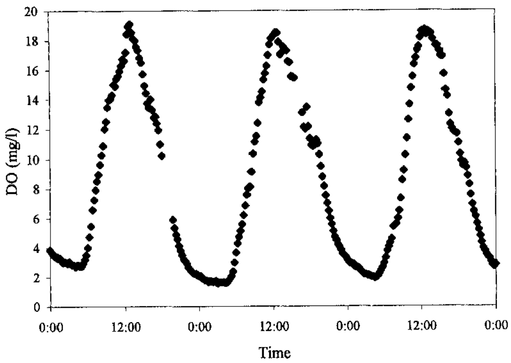

Fig. 4 DO concentration in the water layer of the paddy field over a three consecutive days.

with time. It shows peaks in the late afternoon and lowest levels just before sunrise. The maximum DO concentration was greater than the saturated concentration of plain water under atmospheric conditions, which is typically about 8 mg/*l* at 25℃. This is due to the photosynthetic activity of micro algae that is closely related to the factors of radiation and temperature (Mowjood, *et al.*, 1998). During the night time, the DO decreased far below the saturation level. The only source and sink of oxygen at the night is atmosphere and soil surface, respectively. Therefore the lowering of oxygen level below the saturated concentration is a sum of oxygen consumption and reaeration. Unfortunately, the excess oxygen generated during the day cannot be stored for the use in the night, as it is expelled to the atmosphere to maintain equilibrium. Therefore, the transfer of oxygen across the water layer is important to understand the behavior of soil environment related to the oxygen dynamics in the paddy field.

We have confirmed the existence of convection current in the water layer throughout the day from the temperature profile. The convection mechanism may affect the DO distribution within the water layer of a paddy field. In an effort to further explore the relationship between the DO dynamics and the convection mechanism within the water layer, we continued the investigations with a lab-scale model of a paddy field as described above.

DO distribution

Figure 5 shows the vertical profile of DO concentrations in the water layer of the lab-scale paddy field model. The DO concentrations at different depths in the water layer were almost uniform during the day and during the night time. There was no distinctive concentration gradient either from the water surface or from the soil surface. As in the paddy field, oxygen in the shallow stagnant water layer diffuses from the atmosphere by the process of reaeration as explained by the two-film theory of mass transfer (Peavy *et al.*, 1985). Then the reaerated oxygen is transferred to the bulk water layer by molecular diffusion.

If diffusion was the only mechanism at work, one would expect a concentration gradient from the water surface to the soil surface, because the diffusion process is very slow since the oxygen diffusion coefficient is low in water, about $2.51 \times 10^{-9}\,m^2/s$ at 25℃. However, the reaeration/diffusion concept does not adequately explain the results that were obtained. This suggests that convection plays a significant role in the DO transfer throughout the water layer.

DO transfer

To verify the transfer mechanism of DO, the resulting DO profile generated under a convective system was compared with the profile generated in a non-convective system, which was created using infrared radiation. Figure 6 shows the DO profile of this non-convective system. Because of this non-convective condition, the DO concentrations were not uniform throughout the profile. Instead, a gradient was observed from the soil surface during the radiation period of 10 hours. There was oxygen generation at the soil surface, and the generated oxygen was transferred to the upper water layer by molecular diffusion, not by convection. The cause of the oxygen generation is discussed subsequently. This comparison

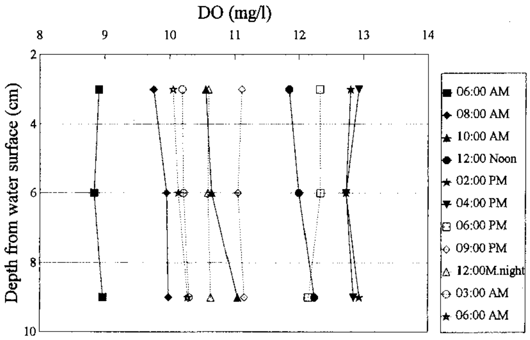

Fig. 5 DO profile in the lab-scale model of paddy field under non-convection.

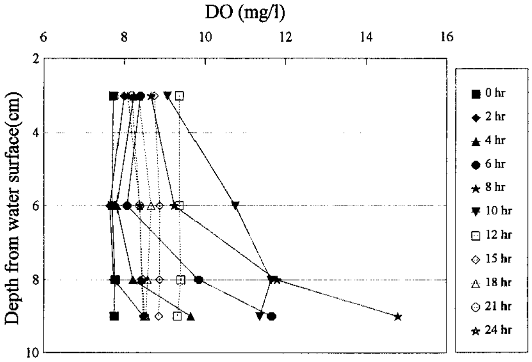

Fig. 6 DO profile in the lab-scale model of paddy field under non-convection.

of infrared and solar radiation systems lead to the conclusion that convection plays a significant role in the DO transfer in the water layer of a paddy field.

The light from the infrared lamp contains mostly the infrared spectrum, but also a small portion of visible spectrum. We quantified the visible spectrum (about 22%) of the light produced by the infrared lamp. Under the infrared radiation the visible portion of the light was used by micro algae found at the soil surface, accounting for the increase in oxygen concentration at the soil surface.

From these results it is clear that in the daytime the DO generated by micro algae is transferred from the water to the atmosphere. In contrast, during the night time oxygen moves from the atmosphere into the water layer by reaeration which depends on the oxygen deficit related to the saturation. Regardless of whether reaeration or deaeration is occurring, convection within the water layer greatly influences the transport mechanism of DO.

Conclusion

In the low land paddy field solar energy is absorbed at the soil surface and the heat is transferred to overlying water by convection and to underlying soil by conduction. The convection process continues even in the night-time due to the temperature difference at the boundaries. Ponded water in the paddy field increases the accumulation of heat in the soil and controls the out flux of heat by the convection process.

The convection process is not only controlling the heat transfer but also the DO distribution in the water layer. Oxygen, produced in the ponded water of a paddy field during the daylight hours by micro algae, is transported within the water layer by convection and then to the atmosphere by deaeration. Eventually the water becomes supersaturated with oxygen. During the night, the reaerated oxygen is transferred to the soil surface by convection in the water layer. Thus convection plays an important role in the thermal regime and DO dynamics within the ponded water of a paddy field. This fact could be correlated with chemical and biological process of interest. Thus convection in the water layer plays an important role in heat and DO transfer between atmosphere and soil in the paddy field.

The future research should be directed to investigate the DO dynamics with related to rice cultivation practices such as use of weedicide (pre-emergence and post emergence) that also inhibit the photosynthesis of algae and fertilizer application. The significance of reaeration, respiration of micro organisms, soil consumption of oxygen on diurnal and seasonal changes of DO in the paddy field also should be studied.

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受稿年月日：1998年 3 月 2 日
受理年月日：1998年 7 月 16 日