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HEAT BALANCE OF AN URBAN RIVER -OBSERVATION AT ARA RIVER ON A SUMMER DAY-

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SYNOPSIS. Field observations were conducted at Ara River, which flows in the east part of Tokyo Metropolitan district, in 1993 summer to evaluate the heat balance in a tidal river. The observation in the river course consists of measurements on long wave and short wave radiations, sensible heat and vapour fluxes at the water surface, vertical distributions of water temperature and saline concentration, flow velocity and transmissivity of solar radiation through the water body. The development of thermocline in the water body associated with the absorption of solar radiation was observed, and it was found that the short wave solar radiation is much influential on the balance of heat. However, it was found that the heat convectively transported by flowing water is much larger than the heat generated by the net radiation.

INTRODUCTION

Recently, heat of flowing water in Ara River has been used as energy resources collected by heat pumps. The water warmed by heat exchangers is discharged into the flowing water, and it will increase the surrounding air temperature in summer. This situation is unfavourable to the heat environment in Tokyo where heat island is remarkably formed. The heat balance of air blowing across Ara River was observed by Takewaka et al. (1994), in which it was found that the river course including flood plains behaves like cool island. The increase of water temperature produced by heat exchangers may induce various unexpected effects on wild lives such as vegetation, insects, fishes etc. The use of heat in flowing water as energy resources must, therefore, be limited from the view point of protecting natural environments. On the other hand, the heat contained in flowing water is a kind of clean energies to be used in future.

Few studies have been made on the heat balance of flowing water, and the amount of energy which can be used without influencing seriously the surrounding environments is still not clear.

The present study aims at the measurements of heat balance through the water surface and the heat convectively transported by flowing water. The measurements may contribute to the understanding of heat balance in rivers, which may provide useful basic data for numerical computations to simulate the movement of heat among air, water and power plants which use heat pumps.

OUTLINE OF THE MEASUREMENTS

The site of the field observations locate at 13 km (between Nisiarai Bridge and Senjyu New Bridge) from the mouth of Ara River which flows through the east part of Tokyo and discharges into Tokyo Bay. Ara River takes compound channel cross section at the site, which consists of a main channel with 200 m width and two flood plains with each 100 m width. The flood plains are covered with low height grasses, and there are not any trees. The flowing water there is affected by tide, and the amplitude of the variation of water surface elevation is about 1.2 m at this location. The averaged depth of flow in the main channel is about 8 m.

The measurements were conducted on August 24, 1993, on which Japan Islands were covered with the Ogasawara High Pressure on the Pacific Ocean, and it was a hot and humid day with fine weather typically seen in summer season at Kanto Plain.

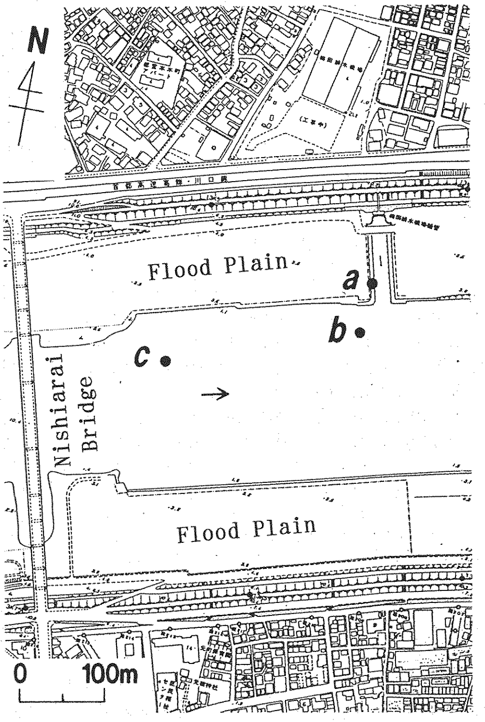

Fig.1 Location of the observation site.

a :flood plain of the left bank.

b :Nishiarai water surface elevation observatory.

c :boat.

Table 1 Instrumentation of the observation

Location: flood plain "a"

Term	Elevation in m	Instrumentation	Period of measurement	Data Analysis
WD	3.0	arrow type	continuous	15 min average
Wind Vel.	0.1~5(5points)	3 cup type wind velocimetry		
S↓	3.0	solar radiation meter	"	"
L↓	3.0	ultrared radiation meter	"	"

Location: Water elevation observatory "b"

Term	Elevation	Instrumentation	Period of measurement	Data Analysis
S↑	1.0	solar radiation meter	continuous	15 min average
U	-1.5, -2.5	electro-magnetic currentmeter	"	"
R_{net}	2.0	Net radiation meter	"	"
T_s	0.0	radiation temperature meter	every 15 min	instantaneous
T	-0.01,-0.02 -0.05,-0.10 -0.25,-0.50 -0.30,-0.50 -1.0, -2.0 -3.0, -3.5	thermister	"	"

Location: Boat "c"

Term	Elevation	Instrumentation	Period of measurement	Data analysis
T	-0.02,-0.05 -0.10,-0.25 -0.50	thermister (fixed)	continuous	15 min average
T	-0.02~-6.0	thermister(moved)		
Tranmissivity of solar radiation	-0.1~-6.0	echo-probe	"	"
Saline concentration		"	"	"
Wind velocity	1.2	3 cup meter	"	"
Air temperature and humidity	1.2	platinum temperature and humidity meter	"	"

The measurements were performed at three locations, i.e. (a)at flood plain of the left bank, (b)at Nishiarai Water Surface Elevation Observatory, and (c)on a boat anchored 200 m downstream from Nisiarai Bridge. The plan view of the site of the observation is shown in Fig. 1. At these locations the following measurements were conducted:

(a)at the flood plain: wind deirection, vertical distribution of wind velocity up to 5 m from the ground, solar radiation, long wave radiations from the sky and the ground.

(b)at the water surface elevation observatory: reflection of solar radiation from the water surface, net radiation which includes both solar radiation and long wave radiations, water temperature from the free surface to 6 m below it, and flow velocity.

(c)on the boat: wind velocity, humidity, vertical distribution of water temperature, saline concentration and transmissivity of solar radiation through the water body.

The instruments used in the observations are listed in Table 1. All data obtained by these devices were stored in data loggers (Model CR10, Campbell Scientific, Inc., USA) at each location, and they were digitized and stored in a computer for analysis.

RESULTS OF MEASUREMENTS

(1) Water Environments

As described in the above, the water at this location is affected by tide. The variation of the water surface elevation is depicted in Fig. 2, in which the elevation is taken from the Tokyo Pale. At the commencement of measurements early in the morning the tide was low, and it became high tide at 11 a.m. Corresponding to the variation of water surface elevation, the flow velocity changed as seen in Fig. 3. The water moved upstream until 10 a.m., and subsequently the direction of flow changed downstream after 10 a.m. until about 3 p.m. The flow velocities measured by electro-magnetic currentmeters at two elevations show good agreement except the time from 12 a.m. to 3 p.m., during which the direction of flow is downstream and the flow velocity is slightly large near the free surface.

The quality of water was measured by using a multi-purpose water quality measuring device (Echo-Probe, ME Meerestechnik-Elektronik GmbH Inc., Germany). The temporal variation of the vertical distribution of saline concentration is depicted in Fig. 4. It is shown that the concentration is fairly uniform vertically, and it varied only between 130 ppm and 170 ppm throughout the measurement, indicating that the water was well-mixed by turbulence of flowing water and saline wedge was not formed on the day. However, it should be reminded that the guaranteed accuracy of the device used for the measurement is 0.01% (100ppm), and therefore the measured values include considerable amount of errors.

(2) Atmospheric Environments

Fig. 5 shows the temporal variations of wind direction (denoted by WD) at the location "a" (flood plain), the wind velocity, U, air temperature, T, vapor density, q, at the location "c" (boat). The wind blew from the North, i.e. from Kanto Plain toward Tokyo Bay, early in the morning, and it changed to the South before noon, which implies that the wind direction was governed by local land and sea breeze system on the day. The wind became strong before noon and it reached almost 4 m/s. The content of vapor exhibited the maximum of about 22 gr/m^3 at noon, and then it decreased to 19 gr/m^3 at 5 p.m. The variation of the vapor content in air observed in this location was similar to that observed at the Office of the Weather Bureau of Japan which locates in the central part of Tokyo.

(3) Radiations

The balance of radiations at free surface of water is described by

$$R_{net} = S\downarrow - S\uparrow + L\downarrow - \sigma T_s^4 \tag{1}$$

in which R_{net} is the net radiation, $S\downarrow$ is solar radiation, $S\uparrow$ is the reflection

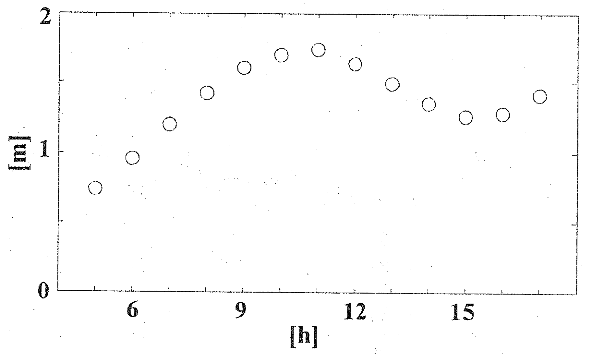

Fig.2 Temporal variation of the water surface elevation taken from Tokyo Pale at the location "b".

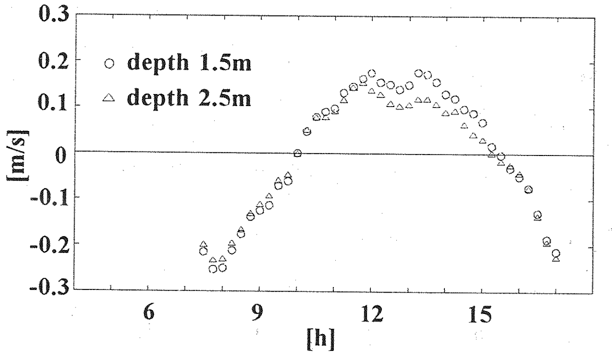

Fig.3 Temporal variation of the flow velocities at the location "b".

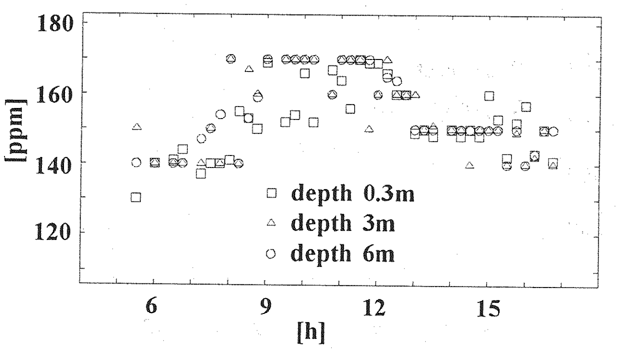

Fig.4 Temporal variation of the saline concentrations at the location "c".

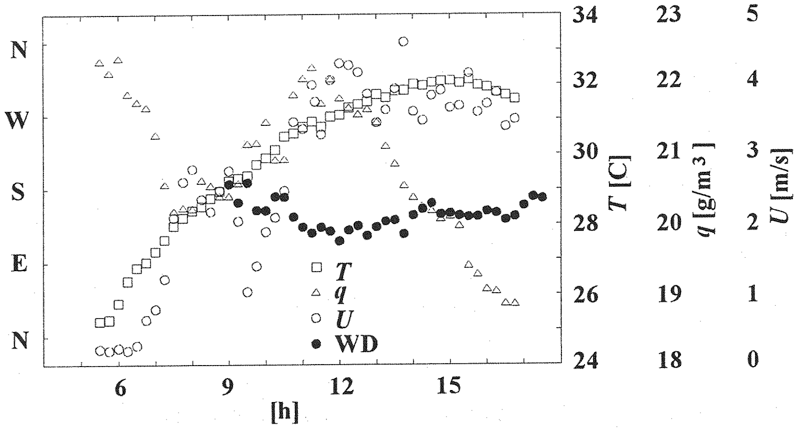

Fig.5 Temporal variations of wind direction (WD) at the location "a", wind velocity (U), air temperature (T), vapor density (q) at the location "c".

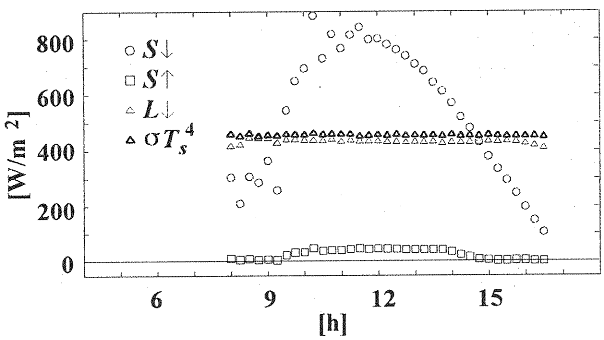

Fig.6 Temporal variation of each radiation.

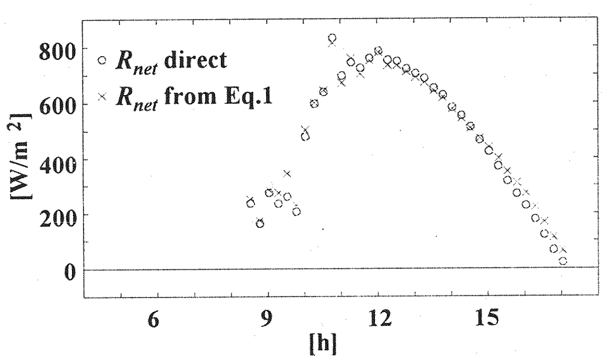

Fig.7 A comparison between the net radiation calculated from Eq.1 and that observed directly by using a net-radiationmeter.

of solar radiation from the free surface, L↓ is the long wave radiation from the atmosphere, σ is the Stefan-Boltzman constant which has a value of 5.67×10^{-8} W/m^{2}K^4, K is the Kelvin temperature, and T_s is the Kelvin temperature at the free surface.

In the present data analysis, the values of S↓ and L↓ measured at the location "a" (flood plain) were used, and S↑ and $\sigma T_s{}^4$ were observed at the location "b" (water surface elevation observatory). Fig. 6 shows the temporal variation of each radiation during 9 a.m and 5.30 p.m. The solar radiation takes the maximum value of 800 W/m^2 at noon. The reflection of the solar radiation, S↓, is about 40 W/m^2, which indicates that the albedo (=S↑/S↓)is about 0.05. The value of albedo for flat free surface of clear water can be calculated by using Fresnel's law, if the height of the sun is specified. The height on the day was 66 degrees, and the Fresnel's law predicts a value of 0.02. The calculated value is somewhat smaller than the observed value, one reason of which is that waves were generated on the free surface by wind and ships moving on the river. The other reason is turbidity of water at this reach, which increases the reflection rate. The long wave radiations from the atmosphere and from the water body are nearly equal, taking a nearly constant value of about 400 ~ 500 W/m^2 throughout the day. Therefore, the energy balance at the free surface is almost governed by the solar radiation.

Fig. 7 shows a comparison between the net radiation calculated from Eq. 1 and that observed directly by using a net-radiotionmeter placed at the location "b" (water surface elevation observatory). Both agree well at any time, which indicates that the accuracy of the measurements on radiations is satisfactory.

ENERGY BALANCE

(1) Vertical One-Dimensional Energy Balance

The net radiation flux expressed in Eq. 1 is usually distributed to sensible heat flux, H, latent heat flux, ℓE, and heat flux transferred toward the water body, G. The energy balance at the free surface of still water is then described by

$$R_{net} = H + \ell E + G \tag{2}$$

in which ℓ is latent heat of evaporation (=583 cal/gr = 2240 J/gr at 25 degrees in Celsius).

The sensible heat is tranferred by the difference of temperatures between air and water. It is usually estimated by a bulk method expressed by

$$H = \rho C_p C_{H1.2} U_{1.2} (T_{sw} - T_{1.2}) \tag{3}$$

in which ρ is mass density of air (=1.205 kg/m^3), C_p is specific heat of air at constant pressure (=1.006 J/gr·K), $C_{H1.2}$ is a bulk transport coefficient which takes a value between 0.3×10^{-3} and 1.4×10^{-3} according to the stability of the atmosphere and the height of measurement (the details for the calculation of $C_{H1.2}$ is described by Kondoh, 1992), $U_{1.2}$ is the wind velocity at the height of 1.2 m from the free surface of water, T_{sw} is the temperature of the surface water, and $T_{1.2}$ is the temperature of air at elevation of 1.2 m from the free surface.

The latent heat flux is estimated in a similar manner, using the following equation:

$$\ell E = \ell C_{E1.2} U_{1.2} (q_{sw} - q_{1.2}) \tag{4}$$

where $C_{E1.2}$ is a coefficient for the transport of vapor which takes a value between 0.3×10^{-3} and 1.5×10^{-3} (Kondoh, 1992), q_{sw} is the vapor content very close to the free surface, in which it is assumed that the vapor is saturated at the free surface (at the water temperature at the free surface), and $q_{1.2}$ is the vapor content at the elevation of 1.2 m.

The energy transferred toward the water body, G, is decomposed into two parts, i.e. transmission of radiations into water and transport of sensible heat mainly by turbulence. The transmissivity is affected by the turbidity of water. For clear water such as water in ocean, the solar radiation becomes 10 % of the incident value at 20 m deep below the surface. The water at the observation area of Ara River is somewhat polluted, and therefore the transmitted radiation into water is absorbed in the layer close to the free surface. Fig. 8 is the transmitted solar radiation for 670 nm wavelength observed by the Echo-Probe, which indicates that the strength of the radiation reduces itself to 10 % of the incident radiation at 1 m below the free surface. The transmitted ray therefore warms the water only close to the surface. The transport of heat by turbulence will play an important role in distributing the heat and in determining the distribution of water temperature. The details of the distribution will be described later.

Fig. 9 shows the vertical one-dimensional energy balance at the free surface, in which the energy flux toward the water body, G, is calculated by

$$G = R_{net} - H - \ell E \tag{5}$$

Therefore, G is not a measured value but an inferred one from the residual of the measured values. The value of G thus estimated will be compared later with the value calculated from the temporal variation of vertical distribution of water temperature. The figure indicates that the sensible heat is transferred toward the water body from the air, which reveals that the air is cooled while it blows over the water surface. Takewaka et al. (1994) reported that the temperature of air is reduced by 1.5 degrees in Celsius while it blows across the river at this place. However, both H and ℓE are very small, showing orders of 30 and 50 W/m^2, respectively. The latter value is somewhat smaller than the value observed in August, 1992, at which ℓE was about 120 W/m^2 in the afternoon (see Ref. 1). This indicates that almost all net radiation is stored in the water body.

(2)Vertical Distribution of Water Temperature

The stored heat can be estimated from the temporal variation of the vertical distribution of water temperature. The temporal variations at three elevations, i.e. 2cm, 50 cm and 6 m below the free surface, are depicted in Fig. 10.

The figure suggests that the water temperature increases in the morning until 10 a.m., during which it is almost uniform along the vertcial. Therefore, this rise of water temperature can be assumed to be associated with the tidal transport of warm water from Tokyo Bay. The water temperature near the free surface begins to deviate from that of bottom water from 10 a.m., and it increases very rapidly until noon. This indicates that the water near the free surface is warmed by transmitted solar radiation, as described in the above. The water temperature at each location shows a similar fluctuation corresponding to the movement of flowing water induced by tide. When the water flows downstream toward Tokyo Bay, the water temperature is decreased by cool water coming from upstream. The water temperature at this location is thus strongly affected by both solar radiation and convective heat transport by flowing water.

Fig. 11 shows the vertical distribution of water temperature at each time. It is found that the water temperature is fairly uniform compared with strong stratification usually generated in still water, such as in reservoirs and lakes (e.g., Tanaka and Ishikawa, 1989). This implies that the water at this location is strongly mixed by turbulence in flowing water, as seen for the vertical distribution of saline concentration (Fig. 4), the situation of which is quite different from that observed in reservoirs and lakes where the thermocline remained until night (Tanaka and Ishikawa, 1989).

The stored energy will be calculated by using the temporal variation of the vertical distribution of water temperature. However, the method includes the effect of convective transport of heat by moving water. Therefore, the stored energy, Q_T, is estimated only for the time when the water is not in motion, i.e. at 10 a.m. and 3 p.m., using the following relation:

$$Q_T = \int_0^{bottom} C_w \rho_w \frac{\Delta T}{\Delta t} dz \tag{6}$$

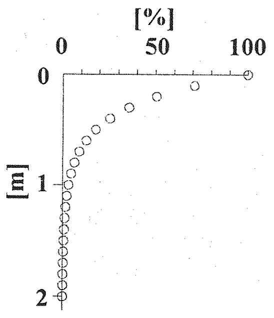

Fig.8 Transmitted solar radiation for 670 nm wavelength at the time 12h.

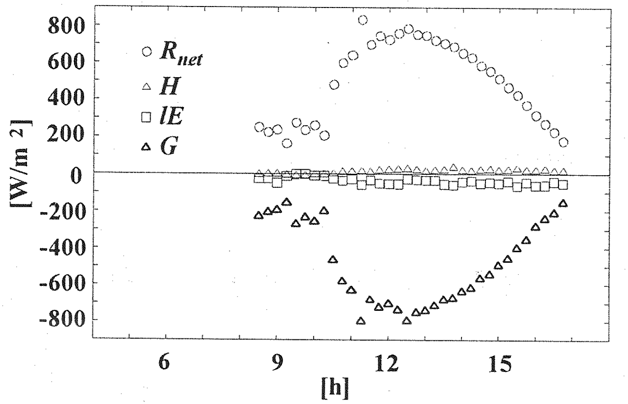

Fig.9 Temporal variation of the vertical one-dimensional energy balance at the free surface. Positive sign indicates energy gain at surface.

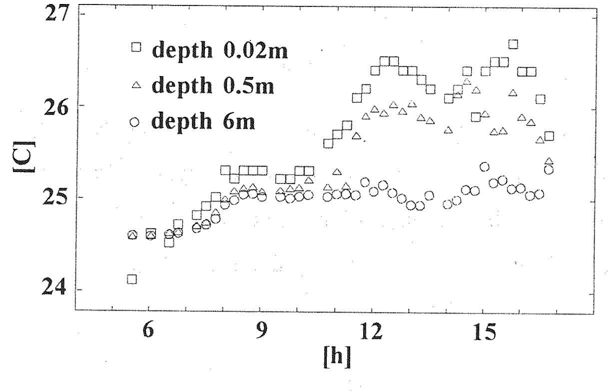

Fig.10 Temporal variation of the water temperatures at the location "c".

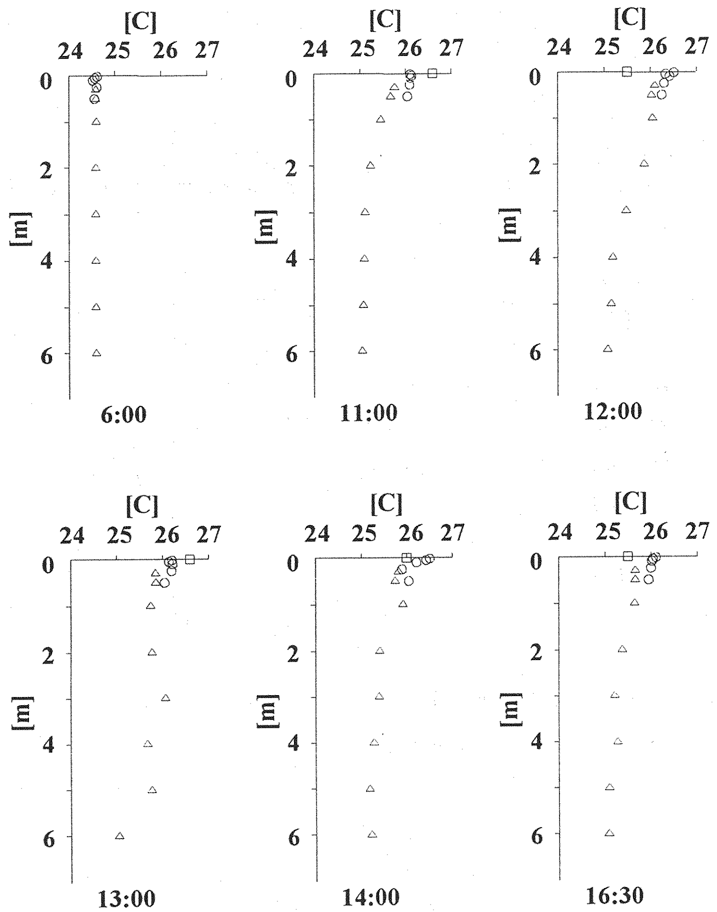

Fig.11 Vertical distributions of water temperature at each time at the location "c".

□ :water surface temperature observed by using an infrared radiometer.

○ :observation by thermistors hung on a float.

△ :observation by a thermistor moved in the vertical direction.

in which C_w is the specific heat of water (=4.186 J/gr·K), ρ_w is the mass density of water, ΔT is the difference of water temperature during a time interval, Δt. In the present analysis, Δt is taken to be 1 hour, and the following values are obtained:

$$Q_T = 370 \text{ W/m}^2 \quad \text{at 10 a.m.} \tag{7a}$$

$$Q_T = 210 \text{ W/m}^2 \quad \text{at 3 p.m.} \tag{7b}$$

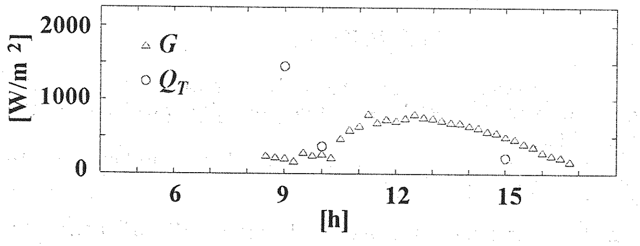

Fig.12 A comparison between the values of G calculated from Eq.2 and the values of Q_T calculated from Eq.6.

These values are plotted in Fig. 12 together with the values of G calculated from the vertcial one-dimensional energy balance which are comparable with Q_T. It is found that both values agree as an order of magnitude. To know the amount of energy transported convectively by flowing water, Q_T is also estimated by using Eq. 6 in the morning at 9 a.m., at which the water temperature is not affected by solar radiation (water temperature is uniform vertically as seen in Figs. 10 and 11). The value of Q_T thus calculated is

$$Q_T = 1{,}400 \text{ W/m}^2 \quad \text{at 9 a.m.} \tag{8}$$

The value is very large compared with the solar energy, G, as seen in Fig. 12. This implies that the convective transport of heat by flowing water is much influential in determining the water temperature, suggesting a possibility of usage of water heat as energy resources by employing heat pump.

CONCLUSIONS

In the present paper, the data obtained in Ara River on a summer day is analysed, and the following results are obtained:

(1)The long wave radiations emitted from the atmosphere and the water surface are nearly equal, and the values of them are constant of about 400 ~ 500 W/m^2. The net radiation at the free surface is, therefore, governed by short wave solar radiation which takes the maximum value of 800 W/m^2 at noon on the observation day.

(2)The sensible heat, H, was transferred from the air toward the water, which cools the air while it blows over the free surface. The latent heat, ℓE, is transported toward the air by evaporation from the free surface. Both values are small compared with the net radiation; H is about 30 W/m^2 and ℓE is 50 W/m^2 at noon.

(3)The net radiation is transmitted toward the water body, and raises the water temperature near the free surface (within 1 m below the free surface). The stored heat, G, calculated by the vertical one-dimensional energy balance supports the value, Q_T, as a order of magnitude, which is estimated by the variation of water temperature at the time when the water was not in motion.

(4)The energy transported by flowing water is larger than the heat stored by the radiation, suggesting a possibility of the use of flowing water as energy resources by heat pump.

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