International Journal of Biometeorology
A new causative heat supply for exertional heat stroke on runners in cold air
--Manuscript Draft--

Manuscript Number:	IJBM-D-21-00244R2
Full Title:	A new causative heat supply for exertional heat stroke on runners in cold air
Article Type:	Original Research Paper
Keywords:	aggregation; solar radiation; wet skin; thermal radiation detector; hidden heat inflow
Corresponding Author:	Kazumi Tagami, PhD Physical Education and Sport Science Tsukuba, Ibaraki JAPAN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Physical Education and Sport Science
Corresponding Author's Secondary Institution:	
First Author:	Shenghua Yuan, MS
First Author Secondary Information:	
Order of Authors:	Shenghua Yuan, MS
	Adriana Ota-Kotner, MS
	Kazumi Tagami, PhD
Order of Authors Secondary Information:	
Funding Information:	University of Tsukuba — Professor Emeritus, University of Tsukuba Kazumi Tagami
	Obayashi Foundation — Professor Emeritus, University of Tsukuba Kazumi Tagami

Abstract:

Purpose

Dysregulation in heat balance, the main cause of exertional heat stroke occurs not only in midsummer but also during cold seasons. Possible causes for this are a reduction in convection due to tailwinds and the acceleration of radiant heat inflow. Although radiation on a surface can be estimated, the amount of heat flowing into the body cannot be determined.

Methods

To understand this, a heat exchange detector was mounted on an irradiated surface. This device exhibited almost no surface temperature changes when exposed to thermal radiation. The device outputs included radiation and convection, and they were calibrated and fractionated into two components using a standard radiant heat calibrator, the Leslie cube.

Results

Hidden heat inflow, the output difference between a wet and dry device, was found to be influenced by the surface temperature and room temperature. Multiple regression analysis found the difference to be 10–15%. The hidden heat inflow increased as the surface temperature decreased and the ambient temperature increased. This phenomenon was also confirmed by the wet and dry heat flow meters attached to the surface of the human skin. The latent heat gain by the water vapor aggregation was presumed to be a cause of hidden heat inflow as the surface temperature decreased.

	Conclusion This experiment showed that the water layer on the body surface was involved in latent heat transfer, and it was estimated that an additional heat load of 200 kcal/m ^{2} /h would be sufficient to cause athletes to experience exertional heat stroke or collapse.

A new causative heat supply for exertional heat stroke on runners in cold air

Shenghua Yuan [1], Adriana Ota-Kotner [2], and Kazumi Tagami [3,*]

[1] *Master's Program in Health and Sport Sciences, Graduate School of Comprehensive Human Science, University of Tsukuba, Tsukuba, Ibaraki 305-8574, Japan.* [2] *Doctor's Program in Health and Sport Sciences, Graduate School of Comprehensive Human Science, University of Tsukuba, Tsukuba, Ibaraki 305-8574, Japan* (Current affiliation*: University of Idaho. International Programs Office. 901 Paradise Creek St.LLC Bldg. #3 Moscow, ID 83844*) [3,] *Professor Emeritus, Faculty of Health and Sports Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8574, Japan.*

Corresponding author: Kazumi Tagami, Prof. Emeritus, University of Tsukuba

E-mail address: tagami.kazumi.fn@u.tsukuba.ac.jp

[*]Tel: +81-29-862-5614: Fax: No Fax

Mobile: +81-90-8310-5925

Postal address: Takaoka 2386-10, Tsuchiura, Ibaraki 300-4117, Japan.

Abstract

Objective: The dysregulation in heat balance, the main cause of exertional heat stroke, occurs not only in midsummer but also in the cold season. Possible causes of this are a reduction in convection and evaporation due to tailwinds and an acceleration of radiant heat inflow. Although the amount of radiant heat that reaches the surface can be estimated, the actual amount of heat flows into the body cannot be specified yet. This paper made an experimental attempt for this.

METHODS: A device is made up of a temperature controllable heat sink and heat flow detector, which keeps the surface temperature constant and has a heat exchange coefficient comparable to that of the human body surface. The output of this device (total heat exchange) was divided into radiant heat exchange and other heat exchange using a standard radiant heat calibrator, Leslie Cube.

RESULTS: A phenomenon, in which a wet surface while the surface temperature was low absorbed larger heat than that of the dry surface, was found. And authors named this "hidden heat inflow". As a result of multiple regression analyses, both radiant heat exchange and other heat exchanges are closely related to the surface temperature, and the maximum difference in total heat exchange during the experiment reached 200 kcal/m^2/h. It has been suggested that this phenomenon may also occur on the surface of human skin.

DISCUSSION: One of the causes of this “hidden heat inflow” is considered to be the decrease in evaporative cooling due to the decrease in surface temperature. However, this alone cannot explain all of the phenomena, so water vapor aggregation may also be involved. A "hidden heat inflow" as a sufficient heat source for exertional heat stroke or collapse during a marathon race on a cold day was evidenced experimentally.

Keywords: aggregation; solar radiation; wet skin; thermal radiation detector; hidden heat inflow

Introduction

Exertional heat stroke (EHS) is a medical emergency caused by excessive heat accumulation and lack of heat dissipation during physically strenuous activities, such as distance running and occupational activities. This is a major threat to athletes during summer. EHS reduces the willingness to compete and at the same time reduces awareness and impedes the performance of the competition. Young (1979) and Roberts (2000, 2006) suggested that symptoms of EHS can also develop during marathon races on cold days below ambient temperatures less than 10 °C. And Jones et al. (1983) analyzed all the symptoms experienced by participants of the Boston Marathon held in October and those of other races in warmer season, reported that there is no significant difference between the two results. Laitano et al. (2019) reviewed the association between the onset of EHS and magnitude of environmental heat load, and they pointed out that it was different from our conventional understanding. In the Tokyo-Hakone Ekiden (200 km Sash Relay) race in winter, a condition called "BRAKE" is well-known among Japanese fans, and it is very similar to EHS. These facts suggest that heat stroke is a common phenomenon among long-distance runners, and that other important factors besides air temperature and humidity can influence its occurrence.

The body heat balance of a runner during a sunny day is expressed by the following equation.

$$M + R_{short} = W + R_{long} + (C_{res} + E_{res}) + C + E$$

The metabolic heat production (M) of marathon runners is considered to be 400 kcal/m^2/h, and there is no controversy (Costill, 1972; de Freitas and Ryken, 1989; Kyröläinen et al., 2000; Nielsen, 1990, 1996). The solar or short-wavelength IR radiation (R_{short}) is estimated to be 200 kcal/m^2/h in Tokyo (N36, at noon on January 1; Blazejczyk, Nilsson, and Holmer, 1993; Krys, and Brown, 1990). The physical workload (W) of running is 80 kcal/m^2/h, the long-wavelength radiant heat dissipation (R_{long}) is 70 kcal/m^2/h, and the inhaled air humidification and warming (C_{res} + E_{res}) consumes 80 kcal/m^2/h. When the remaining 370 kcal/m^2/h can be dissipated by sweat evaporation and convection, their heat balance will be completed. Convection (C) on their skin surface depends on the temperature difference between skin surface ($T_{surface}$) and ambient air ($T_{ambient}$), and the airspeed or the verosity. Evaporation from the skin surface (E) depends on the water vapor pressure difference between their skin surface and ambient air, and airspeed. The maximum cooling capacity of ambient air, evaporation plus convection (E+C), can be estimated 1000 kcal/m^2/h or more while a runner running at 20 km/h in calm and windless air with 1 atm, 10 °C, and 60% relative humidity (%RH) by the methods of Gagge and Nishi (1977), and Nishi (1981). However, if the tailwind speed is the same as the runner's ground speed (airspeed=0), C+E drops to 370 kcal/m^2/h, and the cooling capacity will be lost completely (Blazejczyk, Nilsson, and Holmer, 1993; Krys, and Brown, 1990). Usual runner's limbs move faster than the airspeed of the torso, the actual (E+C) is considered to be greater than this estimation, and the runner is unlikely to be placed in a negative heat balance. So how did marathon runners running in cold weather develop EHS, as Young (1979) and Roberts (2006) recorded? It must be considered that there is an unknown factor that has not been described so far in the onset of EHS by a marathon running in cold air. The principle of cooling the body by thermal sweating is well understood (Kerslake and Waddell, 1958; Gagge and Nishi, 1977; Nag, 1984), but this principle may not be applicable to runners running in cold air.

This study experimentally explores how the negative heat exchange balance that causes EHS occurs, using the runner in cold weather as a computational model.

Materials and Methods

1. Surface heat-exchange detector (SHED)

The skin surface temperature of a human at rest or during training is the most important factor governing heat exchange with the external environment. All modes of heat exchange, conduction, convection, and radiation were calculated using the skin-surface temperature as an essential factor. A SHED, shown in Figure 1, Panel 1A, is a temperature-variable heat sink coupled with a heat flux meter. It was assembled with a Peltier's cooler (40 × 40 mm^2; Type SL-2F, Nippon Blower Co., Ltd., Tokyo, Japan) and a heat flux meter (42 × 20 mm^2; Type MF-180, EKO Instruments, Tokyo, Japan), similar to that described by one of the authors of this paper in his earlier work (Tagami, 2011). A flux flow meter was mounted on the surface of Peltier cooler with a positive output when heat flowed into the SHED. Because the surface of the heat flow meter was not hydrophilic, it could not retain water. Therefore, an approach was devised to increase its water retention capacity by covering the surface of the heat flow meter with a layer of commercially available tissue paper. By spraying 100 µL of distilled water onto a 3 × 3 cm paper, the effect of the saturated paper on heat flow into the SHED could be investigated and shown as verification data.

Figure 1 insert near here.

The SHED analog output (mV) was scanned every 30 s, digitized, and stored in a data logger (CR800, Campbell Scientific, Ink, Logan, Utah). The stored data were downloaded to a personal computer via the RS232C interface and further processed using Microsoft Excel. The output values (mV) were converted to heat flow rate (W) by multiplying by the sensor-specific calibration value. Heat flow rate (W) was then divided by the unit conversion constant (1.163) to convert W/m^2 to kcal/m^2/h. Spectrophotometry of layers of commercial tissue paper was performed at the Shimane Prefectural Industrial Technology Center using a UV-VIS-NIR spectrophotometer (V-670, JASCO Corporation, Tokyo). The results showed that wet tissue paper promoted light transmission or solar heat absorption only slightly more than dry tissue paper.

The heat exchange (**Q**) of the vertically located surfaces of the SHED at 30 °C and 35 °C, was measured in a climate chamber set at 25 °C, 40%–80%RH, and windless (under natural convection). The device-specific $\boldsymbol{\kappa}$ value of the total heat transfer coefficient was obtained by dividing the **Q** by the difference between the SHED surface temperature (T_{surface}, °C) and the temperature of the paper surface placed on the SHED surface (T_{paper}, °C). $\boldsymbol{\kappa}_{\text{dry}}$ and $\boldsymbol{\kappa}_{\text{wet}}$ were derived similarly as $\boldsymbol{\kappa}$ from dry paper covered **Q** ($\mathbf{Q}_{\text{dry}}$) and wet paper covered **Q** ($\mathbf{Q}_{\text{wet}}$), respectively. The surface temperature of the paper on the SHED surface was obtained by analyzing thermograph images with software ‘Research IR ™’ (FLIR Systems Japan, Tokyo).

2. Calibration

Each heat flux meter was calibrated individually at the time of shipment from the manufacturer. The Leslie cube (Hardy, 1934; Figure 1, Panel 1B) was a radiant heat calibrator and could also be used as a radiant heat source. In this case, the output value of SHED (**Q**) was divided into two categories: radiant heat exchange (**R**) and convection heat exchange (**C**). The **R** between the cube and the SHED was calculated by incorporating the water temperature (T_{water}, °C) of the cube and the surface temperature ($T_{surface}$, °C) of the SHED into the Stefan–Boltzmann equation. The water temperature is changed stepwise from 25 ° C to 50 ° C, and each time the water temperature changes, dry paper covered **Q** ($\mathbf{Q}_{dry}$), wet paper covered **Q** ($\mathbf{Q}_{wet}$), and $T_{surface}$ were measured at each time of the cube water temperature change. The residual amount of **Q** ($\mathbf{Q}_{wet}$ or $\mathbf{Q}_{dry}$) minus **R** is equal to **C**, because conduction was negligible while the heat flux meter was not in contact with any other solid material. In SHED measurements, evaporative heat dissipation is included in convective heat dissipation.

3. Experiment 1: Effect of surface wetness and temperature on heat exchanges or its flow rate onto the SHED surface

The T_{water} of the Leslie cube installed in a room (8m L x 6m W x 3.5m H) at 25°C was fixed at 50°C in Experiment 1, and the outputs of the $\mathbf{Q}_{wet}$ and $\mathbf{Q}_{dry}$ were continuously recorded. The experiment was repeated with the $T_{surface}$ of the SHED varying from 20°C, 25°C, 30°C, 35°C, to 40°C. The $\mathbf{Q}_{wet}$ and $\mathbf{Q}_{dry}$ obtained were further classified into **R** and **C** using the method described in the calibration.

Room conditions ($T_{ambient}$ and %RH) were recorded every 30 sec during this experiment. Environmental data were logged into a logger (TM-188D, Mother tool Co., Ueda, Nagano Pref. Japan) for the further theoretical convection estimation.

4. Experiment 2: Effect of water on lamp-radiated heat flow onto the SHED surface

The lamp-radiated **Q** in the SHED was determined directly using a heat flux meter. The wet, white paper absorbed 0%–3% less heat than the wet, black-stained tissue paper at surface temperatures of 20°C, 25°C, and 30°C with 880-kcal/m^2/h lamp radiation. Thus, the wetness and paper color had little effect on the emissivity of the SHED surface, presumably because of its thickness or higher transparency.

Whilst the $T_{surface}$ was regulated to varied temperatures (15, 20, 25, 30, and 35°C), it was irradiated with a reflector lamp (RF110V, 180 W, Panasonic, Osaka) in a room maintained the $T_{ambient}$ at 12.2±1.4, 17.3±0.9, 21.1±1.7, 27.1±1.4, and 30.6±1.7°C. The differences in heat flux induced by water (Δ**Q1**), and induced by radiation(ΔQ2) were subjected to multiple regression analyses for the SHED surface temperature and ambient temperature. The experiments were conducted in an isolated room, in which the ambient temperature changed naturally without air conditioning. The exterior surfaces of the walls did not come in direct contact with ambient air. Measurements were performed at midnight to minimize the effects of diurnal temperature changes on ambient temperature. %RH was not shown in Table 2, however, Δ**Q1** fully reflected the influence of %RH.

The testing time was chosen to maintain a minimal temperature change between the midnight and early morning. The room conditions (ambient temperature, black-globe temperature, wind velocity, and RH) were measured and recorded every 10 s using a data logger (LR8402, Hioki, Tokyo) connected to a temperature/humidity meter (HN-CLN, Chino, Tokyo). These instruments were placed in a multi-plate radiation shield (41003-2, Young Company, Michigan), with a pyranometer/solarimeter (Eko, Tokyo, Japan), a hot-wire anemometer (6036-A0, Nippon Kanomax, Osaka, Japan), and Bernon's black globe with a Pt100 resistance thermometer (NR: JIS class B, Chino, Tokyo, Japan). The stored records were downloaded from a microSD and processed on a personal computer.

5. Experiment 3: Effect of water on lamp-radiated heat flow in human skin

Eight, active college league players (sex, male; age, 22 ± 2; height, 178 ± 6 cm; weight, 78 ± 12 kg; sports experience, 11 ± 4 years) were included in this study. They performed on an ergometer cycle, with a load of 30-40 W and 30 min maximum duration. They underwent two measurements, before exercises and after exercises (until sweating) at temperatures of 22.0 °C ± 0.9°C and 12.8 °C ± 0.9. The subjects' left lateral thighs were irradiated with a reflector lamp, resulting in an elevation of skin temperature from 30 °C to 40°C. Two heat flux meters (MF180, EKO, Tokyo, Japan) bound to two thin-filmed thermocouples were fixed side-by-side, 5 cm apart, on the skin of the thighs using paper tape (Micropore ™, 3M Health Care, Tokyo, Japan). The skin and the heat flux meter were covered with a layer of tissue paper similar to that used in Experiment 2 and irradiated with a reflector lamp, same type as used in Experiment 2, placed 35 cm away. Warm water was sprayed on, or applied to one side of the flux meter covered with tissue paper. The outputs of these flux meters were thermally saturated within 1 min under experimental thermal conditions, which included the processes of water spraying and lamp irradiation. The analog output signals (in mV) were digitized using an A/D converter (NR-250, KEYENCE, Tokyo, Japan). The values were recorded on a computer and converted to heat flow (kcal/m^2/h) by dividing them by sensor-specific calibration factors. After confirming a stable flow value (A') and heat flow rate (B') with water spraying, the skin temperature of each subject (rapidly elevated by irradiation) was monitored until it stabilized. The skin-surface temperature (S) was measured at 10-s intervals using a thermocouple placed between the heat flux meter and the skin (Supplement 5). The differences in heat flux (forced heat flow by water = B' – A') were subjected to multiple regression analyses with the S (Table 3).

6. Statistical analysis and ethical considerations

The human skin experiment was approved by the Ethical Committee of the Faculty of Health and Sport Sciences at the University of Tsukuba (Tai25-7, 2014). The subjects were provided with sufficient information about the contents of this experiment and participated in it after agreeing to its terms and conditions. Correlation and multiple regression analyses were performed on the conductive heat afflux forced by surface water and data obtained from the two experiments on instrumental and human body surfaces. The coefficients were considered significant if they contributed substantially ($\alpha = 0.05$) to the predictive equation.

Results and Discussions

The basic data measurements for SHED's surface temperature at 30 or 35°C, placed vertically in the air, were performed under climate chamber conditions (less than 0.1 m/s wind, 25°C air temperature, and 40, 60, and 80% RH). The $\boldsymbol{\kappa}_{\mathrm{dry}}$ and $\boldsymbol{\kappa}_{\mathrm{wet}}$ values are listed in Table 1. $\boldsymbol{\kappa}_{\mathrm{dry}}$ showed -10 kcal/m^2/h/°C regardless of the humidity and SHED surface temperature, $\boldsymbol{\kappa}_{\mathrm{wet}}$ decreased with increasing humidity and converged at -30 kcal/m^2/h/°C regardless of the surface temperature of the SHED. The $\boldsymbol{\kappa}_{\mathrm{wet}}$ indicates that heat exchange on the wet surface will be more complex. ΔQ, derived $\mathbf{Q}_{\mathrm{wet}}$ minus $\mathbf{Q}_{\mathrm{dry}}$, showed direct correlation with T_{surface}, but not with RH%. T_{surface} is considered to be a major regulator of evaporative heat dissipation when T_{ambient} is lower than the T_{surface} (Table 1).

Figure 2 shows the results of calibration using the Leslie cube. Since the SHED did not touch an object, its total output (**Q**) did not include the conduction heat exchange at all and consisted solely of **R** and (**C+E**). A minor effect of thin paper on each slope and section was observed (data not shown). These regression equations could be used within the calibrated **Q** range (-500 to +200 kcal/m^2/h).

Table 1 and Figure 2 insert near here.

The environmental condition during this experiment was followed; T_{ambient}: 25.4 ±0.5; %RH: 35.5 ±3.1. Figure 3, Panel 3A shows seven **Q** values obtained by changing the surface temperature of the SHED in the order of 8.2, 13.2, 13.4, 18.4, 18.5, 28.8, and 34.5°C. When the SHED is covered with dry paper, $\mathbf{Q}_{\mathrm{dry}}$ is constantly flowing onto SHED. However, when it is covered with wet paper, $\mathbf{Q}_{\mathrm{wet}}$ only flows into SHED when the surface temperature is below 30 °C. The two **Q**s coincide at a surface temperature of around 13.5 °C. When these data are fractionated by our calibration (Figure 2), the $\mathbf{C}_{\mathrm{wet}}$ (= $\mathbf{Q}_{\mathrm{wet}} - \mathbf{R}_{\mathrm{wet}}$) is not fully explained by the theoretical estimate of convection caused by temperature differences between the surface and the ambient air plus evaporative cooling (Figure 3, Panel 3B). This is in agreement with a geoscientific theory that states that wetlands absorb more solar radiation than dry lands (Budyko, 2008). This is a simple experiment, but it shows that surface temperature has a strong influence on heat exchange and that humidity or water vapor partial pressure is the determinant. I would like to show the whole picture under the environmental conditions of a wider temperature and humidity range.

Figure 3. insert near here.

In a room with the temperature of 12 °C, a tissue paper-covered and thermally radiated SHED with surface temperatures of 15, 20, 25, 30, and 35 °C gained more heat than the dry surface with additional water and sustained these values until the water dried up (Figure 4). The device gained heat when radiated by a lamp; however, it absorbed additional heat (~100 kcal/m^2/h) when water was added to the radiated surface. Another SHED, which was not covered with paper and non-radiated (dashed line in Figure 4), exhibited more heat loss (HL) as the surface temperature increased. Similar measurements were performed in rooms at 17, 21, 27, and 31 °C (Supplement 1. – 4.), and the results are summarized in Table 2.

Table 2 and Figure 4 insert near here.

In summary of Experiment 2, multiple regressions of $\Delta\mathbf{Q}1$, and $\Delta Q2$ listed in Table 2 are provided. This shows that both the $T_{surface}$ and $T_{ambient}$ are important factors in determining the amount of absolute radiated heat afflux on a wet surface. The inclusion of $T_{surface}$ and $T_{ambient}$ variables explains 74% of the data fluctuation.

A multiple regression equation shows how $T_{surface}$ and $T_{ambient}$ affect the increment of heat inflow when 1000 kcal/m^2/h of heat is irradiated onto a wet surface (Table 2). The value $\Delta Q1$ increased as the surface temperature decreased, and the ambient air temperature increased. The difference between radiated and non-radiated ($\Delta Q2$) was negatively correlated with $T_{surface}$, and $T_{ambient}$. These results suggest that the transfer of radiant heat to the human body is negatively regulated by the skin surface temperature.

Representative data for conducting this experiment on humans are shown in Supplement 5. Two heat flow meters covered with dry tissue paper were attached to human skin, and the output of the heat flow meters was stabilized while irradiating heat with a lamp (value A'). After that, water was sprayed on one of the meters, and approximately 3 min later, the output became stable (value B'). The output of the heat flow meter temporarily decreased immediately after the water was applied; however, it rapidly increased to reach a new equilibrium. No change in output was observed on the 'dry' heat flow meter during this period. An increment in heat flow due to sprayed water ($\Delta\mathbf{Q}_{hs}$) is the residue from B’ minus A’. The average skin temperature (S1) during “dry” heat irradiation (A') and the average skin temperature (S2) during “wet” heat irradiation (B’) were determined to be S because no significant change was observed. The values of S, A', B', $\Delta\mathbf{Q}$, and a regression equation of $\Delta\mathbf{Q}_{hs}$ by lamp radiation and sprayed water showed a linear function with skin temperature (S) in Table 3.

Table 3 insert near here.

The visible light transmittances for dry and wet tissue paper were 70% and 85%, respectively. The reflectance of the surfaces of dry and wet tissue papers were 28% and 13%, respectively. That is, surface water on tissue paper affected both the transmission of visible light through the paper and the reflection of visible light off the paper.

The absolute value of κ_{dry} at SHED surface temperatures of 30 °C and 35 °C in a room (25 °C, 80% RH, and <0.2 m/s air velocity) was approximately 10 kcal/m^2/h/°C, which is similar to that of a thermal mannequin (Mochida, 1982; Kurazumi, et al., 2008). The κ_{wet} measured by the same method was approximately thrice the value of κ_{dry}. It was expected to be equivalent to the sum of κ_{dry} and evaporative cooling rates (Nishi and Gagge, 1970). However, there were some recommendations on the evaporative cooling rate (7.86 kcal/m^2/h/°C) of a standing subject in a specific condition (30 °C, 60% RH, airflow 0.2 m/s) (Nag, 1984); 10 kcal/m^2/h/°C was obtained by applying the regression equation (Colin and Haudas, 1967), and it was similar to the measured κ_{wet}. However, in our calibration using a Leslie cube, the heat exchange of the water-covered 35 °C SHED surface had a mean κ_{wet} of 29.8 kcal/m^2/h/°C, which was compatible with the previous measurements (28.0–44.5 kcal/m^2/h/°C) in a room with an artificial climate (Table 1). Because κ_{dry} was close to ***hc*** in the absence of wind, it is reasonable that κ_{wet} is thrice the value of κ_{dry} based on the Lewis relation (Gagge and Nishi, 1977).

κ_{dry} is the sum of the convective heat transfer coefficient ***hc*** and radiant heat transfer coefficient ***hr*** on a dry vertical surface. When a vertical plane receives radiant heat, the temperature of the surface increases, which affects convection and conduction. Thus, a new thermal balance of the entire sensor is established. However, in the SHED, heat recovery or release is performed in a separate circuit, and the surface temperature is constantly buffered so that the output depends only on the prevailing environmental conditions. In the SHED calibration that used a Leslie cube as the radiant heat source, the **R** and **C** derived from **Q** minus **R** were positively correlated to

Q. The value of **Q** minus **R** fluctuates greatly when the surface is wet, so convective heat exchange is considered to account for most of the fluctuation. The surface of human skin is rich in blood vessels and acts as a buffer against heat invasion from the external environment. Skin temperature during exercise is even more strongly buffered by increased blood flow and sweating. Therefore, because the SHED output maintains a constant surface temperature, it closely represents the amount of heat exchanged between the human skin surface and the external environment.

The following important points were obtained by analyzing the amount of heat exchange ($\mathbf{Q}_{\text{dry}}$ or $\mathbf{Q}_{\text{wet}}$) in Experiment 1 conducted at 25 °C. [1] $\mathbf{Q}_{\text{dry}}$ cannot dissipate heat when T_{surface} is $\leq$40 °C, and $\mathbf{Q}_{\text{wet}}$ can dissipate heat when T_{surface} is <28 °C. [2] The $\mathbf{Q}_{\text{dry}}$ and $\mathbf{Q}_{\text{wet}}$ attained equivalence when T_{surface} was <22 °C, and our theoretical estimation of **C'** (sum of evaporation and convection caused by the temperature difference between the SHED surface and ambient air) cannot exceed **C** which was obtained from Experiment 1 (dashed line in Panel 3B). That is, at ambient temperature of 25 °C, $\mathbf{Q}_{\text{dry}}$ and $\mathbf{Q}_{\text{wet}}$ with a surface temperature of 13.5 °C or less always match regardless of the dry / wet state of the surface. It is presumed that one of the causes of [2] is that the value, Q minus R, increases owing to the aggregation of water vapor on the SHED. In the case of this experiment, it was shown that $\mathbf{Q}_{\text{wet}}$ does not promote cooling but instead promotes heat absorption. Moreover, it works remarkably when T_{surface} is between 20 °C and 30 °C. Geoscientific studies have already shown that moist soil absorbs 10% more sunlight than dry soil (Budyko, 2008), and the results of our experiment support this. We believe that this is evidence of a similar phenomenon that occurs in relation to sweating human skin. During cold days, runners and outdoor workers absorb more solar heat than previously predicted when their skin surface is wet. The authors referred to this phenomenon as the hidden heat inflow (HHI), whereby greater heat flows into wet skin surfaces than dry ones when radiant heat is applied.

The results of Experiment 2 were significant. They showed a significant difference between the wet and dry surfaces of the heat inflow (Figure 4). In this experiment, fluctuations in airflow, room temperature, and humidity were minimized, so the surface temperature was the only factor invoking the heat inflow or HHI. It was confirmed that vaporization cooling was restored when the surface temperature of the SHED was 25 °C or higher, and below that, the HHI was expressed. The experiment also showed that Δ**Q**, the difference between $\mathbf{Q}_{\text{wet}}$ and $\mathbf{Q}_{\text{dry}}$, decreased with increasing T_{ambient} (Table 2). The bulb used as the heat source in this study is a high-temperature and point-radiant source; **Q** is not calibrated by Stefan–Boltzmann's equation, but the fluctuation of **Q** can be read.

The results of the three experiments are summarized in Figure 5. This shows that Δ**Q** is inversely proportional to the T_{surface}, or skin temperature. It also shows that when the surface temperature of the SHED is below 25 °C, the surface must be lost its water evaporation, or occurring condensation of water vapor in the ambient air. This phenomenon is also expected to occur on the skin running in cold air (Maron, Wagner, and Horvath, 1977). These results explain the cause of the EHS that occurred during the marathon race held on a cold day and suggests that Roberts' case report is by no means a misdiagnosis (Roberts, 2000).

Figure 5 insert near here.

Wind direction is another important factor. The winds in the Northern Hemisphere have different velocities, but their directions are mostly westerly. The running courses in which EHS cases have been reported often include long straight ways heading east-northeast. The Hakone Ekiden in Japan is no exception. The body temperature balance of runners running under such environmental conditions tends to be negative, increasing the risk of EHS. An 18-year epidemiological analysis of a seven-mile (11 km) road race in a summer resort (outside temperature, 23 ± 2.5 °C; 70 ± 19% RH) showed a high rate of EHS (2.13 ± 1.62/1000 runners) (DeMartini et al., 2014). The course is designed to run east-northeast, and we hope that it will be re-analyzed from the perspective of wind direction and radiant heat.

We believe that minimizing the HHI will protect runners from the EHS and help improve marathon running records. Runners should wear light-colored clothing, and caps to block solar radiant heat as personal protection against hyperthermia. However, it should be noted that radiant heat protection with clothing is not an efficient HHI countermeasure for runners, considering their sparse running attire, and regular running caps are prone to heat accumulation because of their poor ventilation. Our goal is to protect runners from solar radiation, HHI, and EHS by recommending the running course designs based on local wind history, and by promoting the best materials for solar protection.

Maintaining high athletic performance during competitive endurance sports is desirable for athletes as well as their coaches and spectators. However, the reduction in air-cooling capacity due to tailwinds is a major environmental EHS risk factor for long-distance runners. In this study, a new direct heat exchange estimator for the body surface was developed and thermally characterized. When this device is exposed to a cold and thermally radiated environment, water placed on its surface accelerates heat flow into the surface. Contrary to the well-known phenomenon of heat dissipation due to sweating on the body surface, a wet and low-temperature surface receives more heat than a dry surface when thermally radiated (Clark, Mullan, and Pugh, 1977; Tanda, 2016). A water-induced lowered thermal conductivity (Chen, Fan and Zhang, 2003) and diminished sweat evaporation by the lowered skin temperature, are causative factors for this phenomenon. Thus, cooled skin surfaces add an unknown heat source for runners in cold air, causing an occasional EHS and decreased endurance. Further studies are necessary to find ways to protect outdoor athletes from radiant heat and to enable them to maintain their level of performance.

Acknowledgments

Authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Our results of the present study do not constitute an endorsement by ACSM. Scientific support for heat transmission was given by Dr. Y. Kuwasawa, Director, National Institute for Land and Infrastructure Management (Tsukuba, Ibaraki 305-0802). Technical support with tissue paper staining with water-insoluble black ink was provided by Nakamura-Giken (President: Saichi Nakamura, Ashikaga, Tochigi Prefecture). The operation of the environmental chamber was performed with the assistance of Dr. T. Nishiyasu and Dr. Y. Honda. Statistical analysis was performed by Dr. N. Nishijima. Finally, we would like to thank Editage for English language editing.

Conflicts of Interest and Source of Funding

This study was supported financially by the University of Tsukuba Research Project 2013–2015. The research fund was given to K T (2013) by the Obayashi Road Corporation, Technical Research Institute, Kamikiyoto 4-640, Kiyose, Tokyo 204-0011, and the Nissin-Sangyo scholarship grant for thermal radiation research on athletes' health was given to K T. No other financial aid was received for this study. There are no conflicts of interest from these sources of funding.

References

Blazejczyk K, Nilsson H, Holmer I (1993) Solar heat load on man. Review of different methods of estimation. Int J Biometeorol. 37:125-32. https://doi.org/10.1007/BF01212621

Budyko MI (2008) Heat Balance of the Earth's Surface, 1st Russian ed. Uchijima Z, translator, Seizando-Publishing, Tokyo, pp. 39-43.

Chen YS, Fan J, Zhang W (2003) Clothing thermal insulation during sweating. Tex Res J. 73:152-7. https://doi.org/10.1177/004051750307300210

Clark RP, Mullan BJ, Pugh L.G (1977) Skin temperature during running – A study using infrared colour thermography. J Physiol. 267:53-62. https://physoc.onlinelibrary.wiley.com/doi/pdf/10.1113/jphysiol.1977.sp011800

Colin J, Haudas Y (1967) Experimental determination of coefficient of heat exchanges by convection of human body. J Appl Physiol 22: 31-8. https://doi.org/10.1152/jappl.1967.22.1.31

Costill DL (1972) Physiology of marathon running. JAMA. 221: 1024-9. https://doi.org/10.1001/jama.1972.03200220058013

de Freitas CR, Ryken MG (1989) Climate and physiological heat strain during exercise. Int J Biometeorol. 33:157-64. https://doi.org/10.1007/BF01084600

DeMartini JK, Casa DJ, Belval LN, et al (2014) Environmental conditions and the occurrence of exertional heat illnesses and exertional heat stroke at the Falmouth road race. J Athletic Training 49: 478-485. https://doi.org/10.4085/1062-6050-49.3.26

Gagge AP, Nishi Y (1977) Heat exchange between human skin surface and thermal environment. In: Pollock, DM, editor. Handbook of Physiology, Reactions to environmental agents. Wiley Online Library, https://doi.org/10.1002/cphy.cp090105

Hardy JD (1934) The radiation of heat from the human body. I. An instrument for measuring the radiation and surface temperature of the skin. J Clin Invest. 13:593-604. https://dx.doi.org/10.1172%2FJCI100607

Jones BH, Rock PB, Smith LS, et al (1985) Medical complaints after a marathon run in cool weather. Physician and Sportsmedicine 13: 103-110. https://doi.org/10.1080/00913847.1985.11708904

Kerslake DM, Waddell JL (1958) The heat exchanges of wet skin. J Physiol. 141:156-163. https://physoc.onlinelibrary.wiley.com/doi/pdf/10.1113/jphysiol.1958.sp005962

Krys SA, Brown RD (1990) Radiation absorbed by a vertical cylinder in complex outdoor environments under clear sky conditions. Int. J. Biometeorol. 34: 69-75. https://doi.org/10.1007/BF01093450

Kurazumi Y, Tsuchikawa T, Ishii J, et al (2008) Radiative and convective heat transfer coefficients of the human body in natural convection. Building and Environment 43: 2142-2153. Radiative and convective heat transfer coefficients of the human body in natural convection - ScienceDirect

Kyröläinen H, Pullinen T, Candau R, et al (2000) Effects of marathon running on running economy and kinematics. Eur J Appl Physiol. 82:297-304. https://doi.org/10.1007/s004210000219

Laitano O, Leon LR, Roberts WO, et al (2019) Controversies in exertional heat stroke diagnosis, prevention, and treatment. J Appl Physiol 127: 1338–1348. https://doi:10.1152/japplphysiol.00452.2019.

Maron MB, Wagner JA, Horvath SM (1977) Thermoregulatory responses during competitive marathon running. J Appl Physiol: Respirat Environ Exercise Physiol 42: 909-914. https://doi.org/10.1152/jappl.1977.42.6.909

Mochida T (1982) Mean convective heat transfer coefficient for the human body. The Japanese Journal of Ergonomics 18: 261-267. (In Japanese with English abstract) https://doi.org/10.5100/jje.18.261

Nag PK (1984) Convective and Evaporative heat transfer coefficients of the persons in different activities. J. Human Ergol. 13: 43-49. https://doi.org/10.11183/jhe1972.13.43

Nielsen B. (1990) Solar heat load: heat balance during exercise in clothed subjects. Eur J Appl Physiol. 60:452-6. https://doi.org/10.1007/BF01212621

Nielsen B (1996) Olympics in Atlanta: a fight against physics. Med Sci Sports Exerc. 28:665–8. https://www.ncbi.nlm.nih.gov/pubmed/8784753

Nishi Y (1981) Thermal heat exchange between human and environment. In: Nakayama A, editor. Thermophysiology. Rikogaku-sya; 1981. p. 33-43, Japanese.

Nishi Y, Gagge AP (1970) Direct evaluation of convective heat transfer coefficient by naphthalene sublimation, J Appl Physiol. 29: 830-8. https://doi.org/10.1152/jappl.1970.29.6.830

Roberts WO (2000) A 12-yr profile of medical injury and illness for the Twin Cities Marathon. Med Sci Sports Exerc. 32:1549-55. https://doi.org/10.1097/00005768-200009000-00004

Roberts WO (2006) Exertional heat stroke during a cool weather marathon: a case study. Med Sci Sports Exerc. 38:1197-203. https://doi.org/10.1080/23328940.2017.1316352

Tagami K (2011) Japan Pat. No. 4608653, Human thermal exchange detector, 2011. http://jstore.jst.go.jp/PDFView.html?type=nationalPatent&id=11966&property=entryPdf (in Japanese). Accessed 21 Oct. 2020.

Tanda, G (2016) Skin temperature measurements by infrared thermography during running exercise. Experimental Thermal and fluid Science. 71: 103-113. http://dx.doi.org/10.1016/j.expthermflusci.2015.10.006

Young KC (1979) The influence of environmental parameters on heat stress during exercise. J Appl Meteorol. 18:886-97. https://doi.org/10.1175/1520-0450(1979)018<0886:TIOEPO>2.0.CO;2

Supplemental Digital Content

Supplement 1. Exp. 2, Ambient temperature = 17 °C.

Supplement 2. Exp. 2, Ambient temperature = 21 °C.

Supplement 3. Exp. 2, Ambient temperature = 27 °C.

Supplement 4. Exp. 2, Ambient temperature = 30 °C.

Supplement 5. Representative data of human lamp radiation experiment.

Legends for Tables and Figures

Table 1. SHED specific κ and Δ**Q** measurements at 25 °C.

Table 2. Results of Experiment 2. The differences in heat flow (Δ**Q** kcal/m^2/h) of lamp-radiated dry surface (**Q**$_{\text{dry}}$) and wet surface (**Q**$_{\text{wet}}$). When ΔQ is negative, it indicates more lamp-radiated heat flow into the wet SHED surface, but when Δ**Q** is positive it indicates heat flow out from the wet SHED surface.

Table 3. Absolute differences between heat flow (Δ’flow) of lamp-irradiated dry skin (A’) and wet skin (B’) of ten human subjects. Positive Δ’flow indicates higher lamp-irradiated heat inflow, and negative values indicate less heat flow into human skin by water addition. Two trials in a warmer room or colder room were performed on the same day.

Figure 1. **Panel 1A:** A schematic diagram of a surface heat exchange detector (SHED). **Panel 1B:** SHED calibrator (Leslie cube). This Leslie cube consisted of a stainless-steel water bath, attaching a circular cone with 200 mm long, and 75mm diameter opening, and painted the inside in matte black. The size of the cone hole-opening matched the SHED detector.

Figure 2. A surface heat exchange detector (SHED) calibration. Radiation was estimated by the Stefan–Boltzmann equation with the cube water temperature (°C) and SHED surface temperature (°C). Others, subtracted radiation from SHED output (**Q**), consisted of the convective and conductive heat transfer into the surface of SHED.

Figure 3. Panel 3A: Results of Experiment 1. $\mathbf{Q}_{\mathrm{dry}}$, $\mathbf{Q}_{\mathrm{wet}}$, and $\mathbf{Q}_{\mathrm{wet}} - \mathbf{Q}_{\mathrm{dry}}$ are accordingly with SHED surface temperature; Panel 3B: $\mathbf{Q}_{\mathrm{wet}}$, $\mathbf{Q}_{\mathrm{wet}} - \mathrm{R}$, and theoretical estimation of Convection (CΔt, convection by the temperature difference of ambient air and SHED surface, plus Evaporation (CE)) are plotted. The values (Q wet – R) are not satisfied by the sum of predicted values of convection and evaporative (CΔt + CE) during this experiment.

Figure 4. A result of Experiment 2.

Figure 5. Regression lines of three experiments between absolute heat flows (wet minus dry) and their surface temperatures when thermally radiated with Leslie cube or an electric lamp.

Table 1

Table 1. SHED specific **κ** and Δ**Q** measurements at 25°C.

$T_{ambient}$ (°C), and RH%	$T_{surface}$ (°C)	$\mathbf{Q}_{dry}$ (kcal/m^2/h)	$\boldsymbol{\kappa}_{dry}$ (kcal/m^2/h/°C)	$\mathbf{Q}_{wet}$ (kcal/m^2/h)	$\boldsymbol{\kappa}_{wet}$ (kcal/m^2/h/°C)	$\Delta\mathbf{Q} = \mathbf{Q}_{wet} - \mathbf{Q}_{dry}$ (kcal/m^2/h)
25, 40	30	-48.5	-9.8	-225.9	-44.5	-177.4
	35	-134.7	-14.5	-391.9	-39.0	-257.2
25, 60	30	-47.4	-10.0	-185.2	-36.6	-137.8
	35	-120.1	-12.6	-307.2	-30.7	-187.1
25, 80	30	-53.4	-10.6	-147.4	-29.1	-94.0
	35	-101.1	-10.1	-280.4	-28.0	-179.3
Mean ± SD	30	-49.8±3.2	-10.1±0.4	-186.2±39.2	-36.7±7.7	-136.4±41.7
	35	-118.6±16.8	-12.4±2.2	-326.5±58.2	-32.6±5.7	-207.9±42.9
	All		-11.3±1.9		-34.6±6.5	-172.1±54.4

$\Delta Q = -17.527 \times T_{surface} + 412.61$ ($R^2 = 0.867$); $\Delta Q = 2.037 \times RH\% - 191.64$ ($R^2 = 0.100$)

Table 2

Table 2. Results of Experiment 2. The differences of Q induced by the surface water ($\Delta Q1$ (kcal/m^2/h) = Q_{wet} - Q_{dry}), and those induced by the radiation ($\Delta Q2$ (kcal/m^2/h) = $\Delta Q1\ L_{rad}$ - $\Delta Q1\ L_{n\text{-}rad}$) are listed in this table. When ΔQ is negative, it indicates more lamp-radiated heat flow into the wet SHED surface, but when ΔQ is positive it indicates heat flow out from the wet SHED surface. Multiple regression equations for ΔQ1 and ΔQ2 on $T_{surface}$ and $T_{ambient}$ are shown below this table.

Ambient temperature ($T_{ambient}$)	Measurement and treatment	Lamp non-radiated ($L_{n\text{-}rad}$) SHED surface temperature ($T_{surface}$)					Lamp radiated (L_{rad}) SHED surface temperature ($T_{surface}$)				
		15 °C	20 °C	25 °C	30 °C	35 °C	15 °C	20 °C	25 °C	30 °C	35 °C
12.2±1.4 °C	Q_{dry}	-7.4	-80.6	-118.3	-228.9	-312.0	946.7	939.1	773.9	739.1	674.1
	Q_{wet}	-80.6	-194.4	-368.2	-539.7	-699.8	1046.9	1001.9	629.6	408.3	314.7
	$\Delta Q1 = Q_{wet} - Q_{dry}$	**-73.2**	**-113.9**	**-249.9**	**-310.7**	**-387.7**	**100.2**	**62.9**	**-144.2**	**-330.8**	**-359.4**
	$\Delta Q2 = \Delta Q1L_{rad} - \Delta Q1L_{n\text{-}rad}$	—					**173.4**	**176.8**	**105.7**	**-20.1**	**28.3**
17.3±0.9 °C	Q_{dry}	—	-3.3	-52.5	-112.9	-184.3	—	1081.2	1032.5	992.2	935.9
	Q_{wet}	—	-89.4	-189.9	-301.8	-432.8	—	1167.9	1055.8	898.1	718.5
	$\Delta Q1$	—	**-86.1**	**-137.4**	**-189.0**	**-248.5**	—	**86.7**	**23.3**	**-94.1**	**-217.5**
	$\Delta Q2$	—					—	**172.8**	**160.4**	**94.9**	**31.0**
21.1±1.7 °C	Q_{dry}	—	-12.8	-69.3	-90.4	-146.5	—	1072.2	1052.5	1040.2	994.8
	Q_{wet}	—	-43.7	-125.4	-223.2	-346.4	—	1181.5	1043.8	900.0	740.6
	$\Delta Q1$	—	**-30.9**	**-56.1**	**-132.8**	**-199.9**	—	**109.2**	**-8.7**	**-140.2**	**-254.2**
	$\Delta Q2$	—					—	**139.9**	**47.4**	**-7.4**	**-54.3**
27.1±1.4 °C	Q_{dry}	—	73.8	28.0	-26.3	-82.5	—	1308.7	1247.0	1216.3	1170.5
	Q_{wet}	—	64.5	-48.4	-165.5	-278.8	—	1440.2	1307.2	1166.3	1013.0
	$\Delta Q1$	—	**-9.3**	**-74.6**	**-165.5**	**-278.8**	—	**131.6**	**60.2**	**-50.0**	**-157.4**
	$\Delta Q2$	—					—	**140.9**	**134.8**	**115.5**	**121.4**
30.6±1.7 °C	Q_{dry}	—	—	58.7	11.0	-53.2	—	—	1231.3	1225.7	1211.5
	Q_{wet}	—	—	19.1	-100.2	-243.1	—	—	1307.4	1194.1	1014.4
	$\Delta Q1$	—	—	**-39.6**	**-111.3**	**-189.9**	—	—	**76.1**	**-31.6**	**-197.1**
	$\Delta Q2$	—	—				—	—	**115.7**	**79.7**	**-7.2**

ΔQ1 indicates the difference between Q_{wet} and Q_{dry} at each ambient temperature and surface temperature; ΔQ2 indicates the difference in ΔQ1 between the lamp is on and off, of each $T_{surface}$ condition; —: No data due to Q_{dry} cannot be distinguished from Q_{wet} in these experimental conditions; Multiple regression equations: $\Delta Q1 = -24.1 \times T_{surface} + 10.3 \times T_{ambient} + 378.7$ (R^2=0.905, F=0.000, P<0.001), and $\Delta Q2 = -10.1 \times T_{surface} + 0.1 \times T_{ambient} + 361.7$ ($R^2=0.611$, F=0.000, $P<0.001$).

Table 3

Table 3. Absolute differences between heat flow ($\Delta\mathbf{Q}_{hs}$) of lamp-irradiated dry skin (A’) and wet skin (B’) of ten human subjects. Positive values indicate higher lamp-irradiated heat inflow, and negative values indicate loss of heat from their skin surface. Two trials in a warmer room or colder room were performed on the same day. Supplement 5 is helpful how to analyze the individual data.

Subjects	Measurement & treatment	Trial 1	Trial 2		Subjects	Measurement & treatment	Trial 1	Trial 2
Sub. A	S1: Skin temp. pre-radiation (°C)	29.5	29.4		Sub. E	**S1**	28.5	27.7
	S: Skin temperature (°C)	38.2	40.6			S	39.0	37.1
	A’ (kcal/m^2/h)	530.3	466.8			A’	357.3	278.0
	B’ (kcal/m^2/h)	96.6	-55.3			B’	104.9	2.9
	$\Delta\mathbf{Q}_{hs}$ = B’ − A’ (kcal/m^2/h)	**-433.7**	**-522.2**			$\Delta\mathbf{Q}_{hs}$	**-252.4**	**-275.1**
Sub. B	S1	31.5	29.2		Sub. F	S1	30.0	29.1
	S	37.5	36.5			S	39.4	37.9
	A’	221.7	331.6			A’	400.1	342.9
	B’	-68.2	-128.8			B’	109.9	-30.3
	$\Delta\mathbf{Q}_{hs}$	**-289.9**	**-460.4**			$\Delta\mathbf{Q}_{hs}$	**-290.2**	**-312.6**
Sub. C	**S1**	29.3	30.7		Sub. G	S1	28.5	27.7
	S	38.5	37.5			S	38.4	37.6
	A’	507.4	330.1			A’	350.5	220.6
	B’	80.4	-33.6			B’	24.6	-72.8
	$\Delta\mathbf{Q}_{hs}$	**-427.0**	**-363.7**			$\Delta\mathbf{Q}_{hs}$	**-325.9**	**-293.4**
Sub. D	**S1**	30.7	29.3		Sub. H	S1	30.0	28.6
	S	41.4	39.7			S	39.6	37.8
	A’	653.4	637.1			A’	601.6	293.0
	B’	287.2	215.7			B’	221.4	80.5
	$\Delta\mathbf{Q}_{hs}$	**-366.2**	**-421.4**			$\Delta\mathbf{Q}_{hs}$	**-380.2**	**-212.5**

$\Delta\mathbf{Q}_{hs} = -27.864\ S + 710.85$ ($R^2 = 0.226$)

Figure 1

Figure 1. SHED Yuan et al.

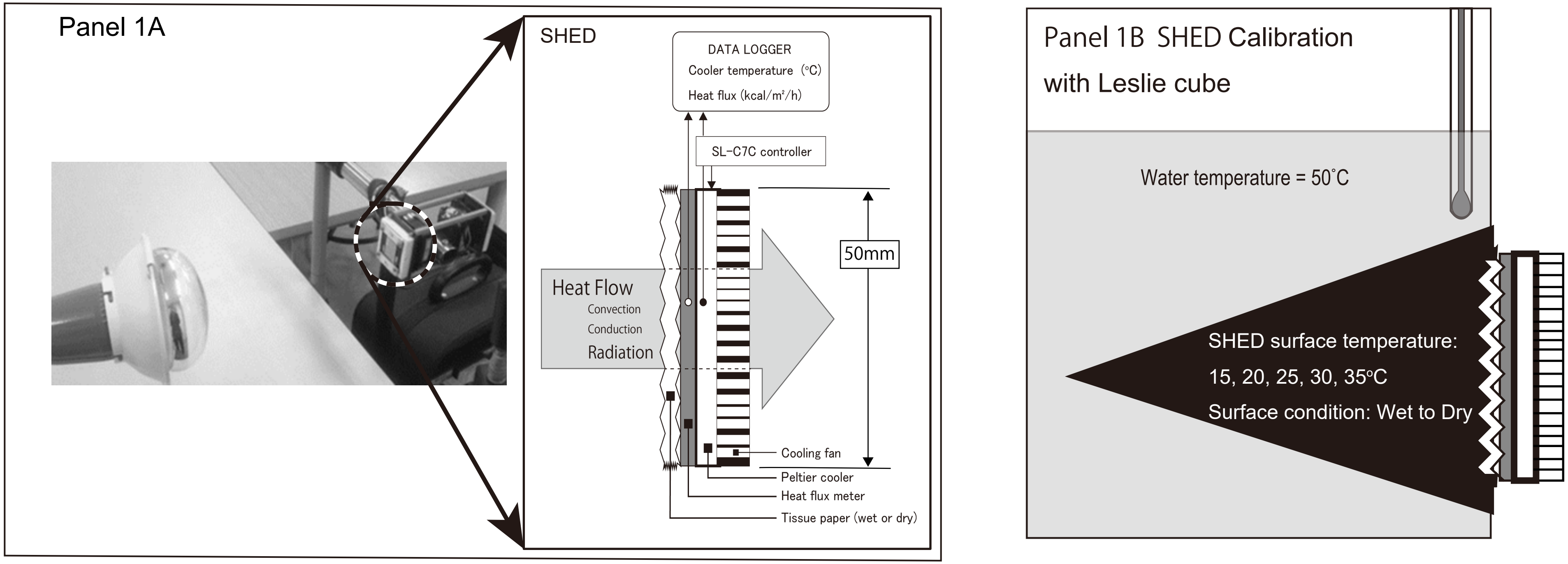


Figure 2. Yuan et al.

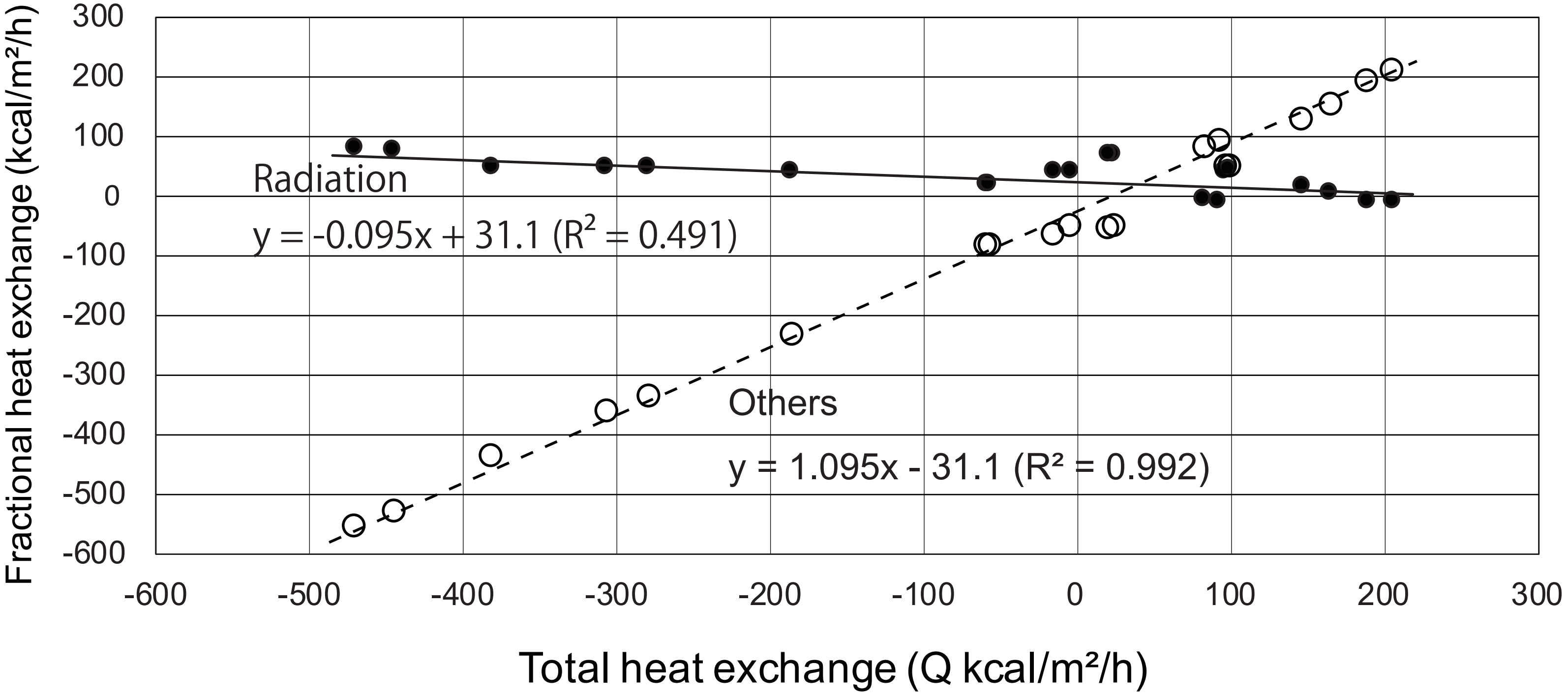


Figure 3

Figure 3. Yuan et al.

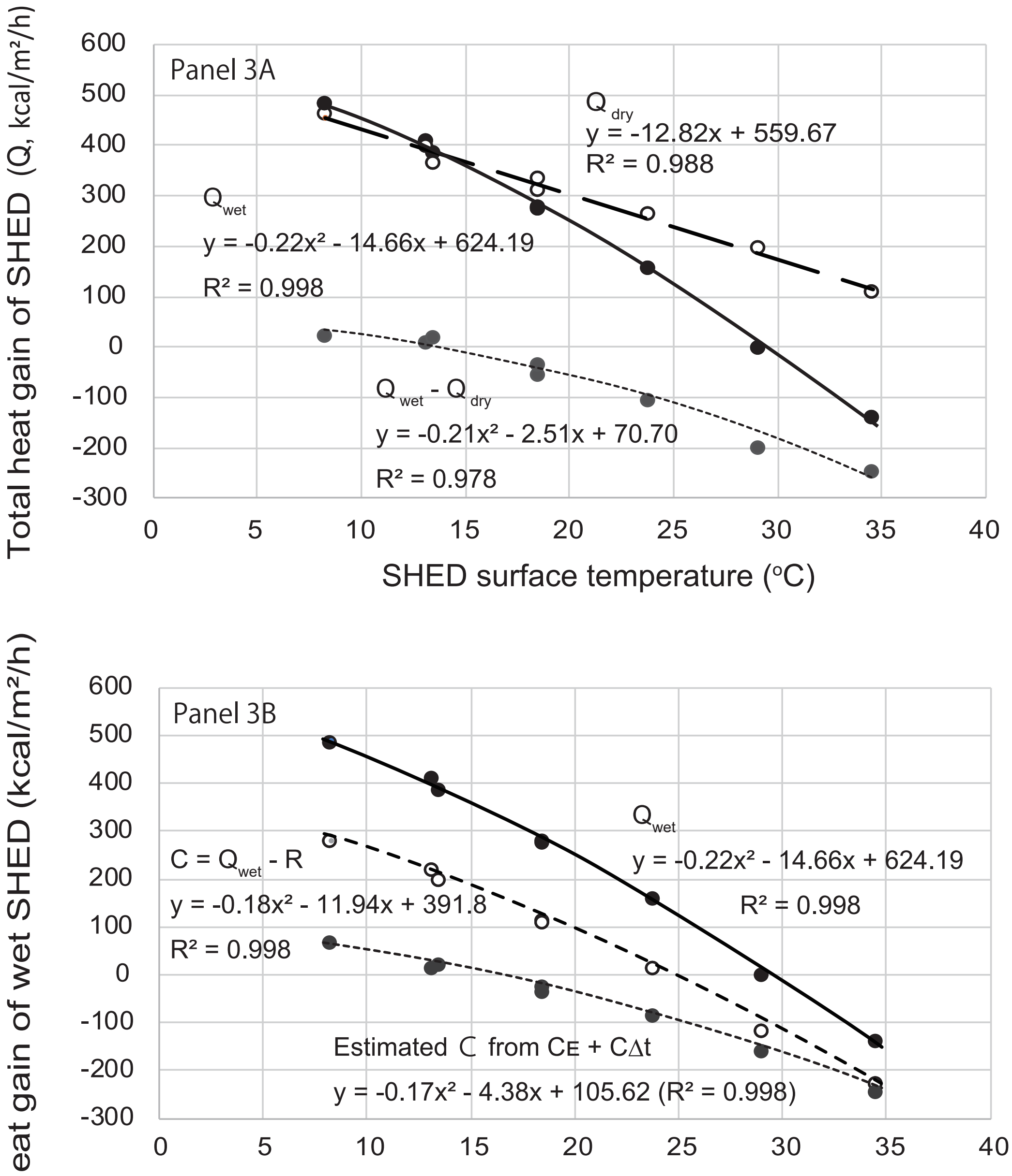
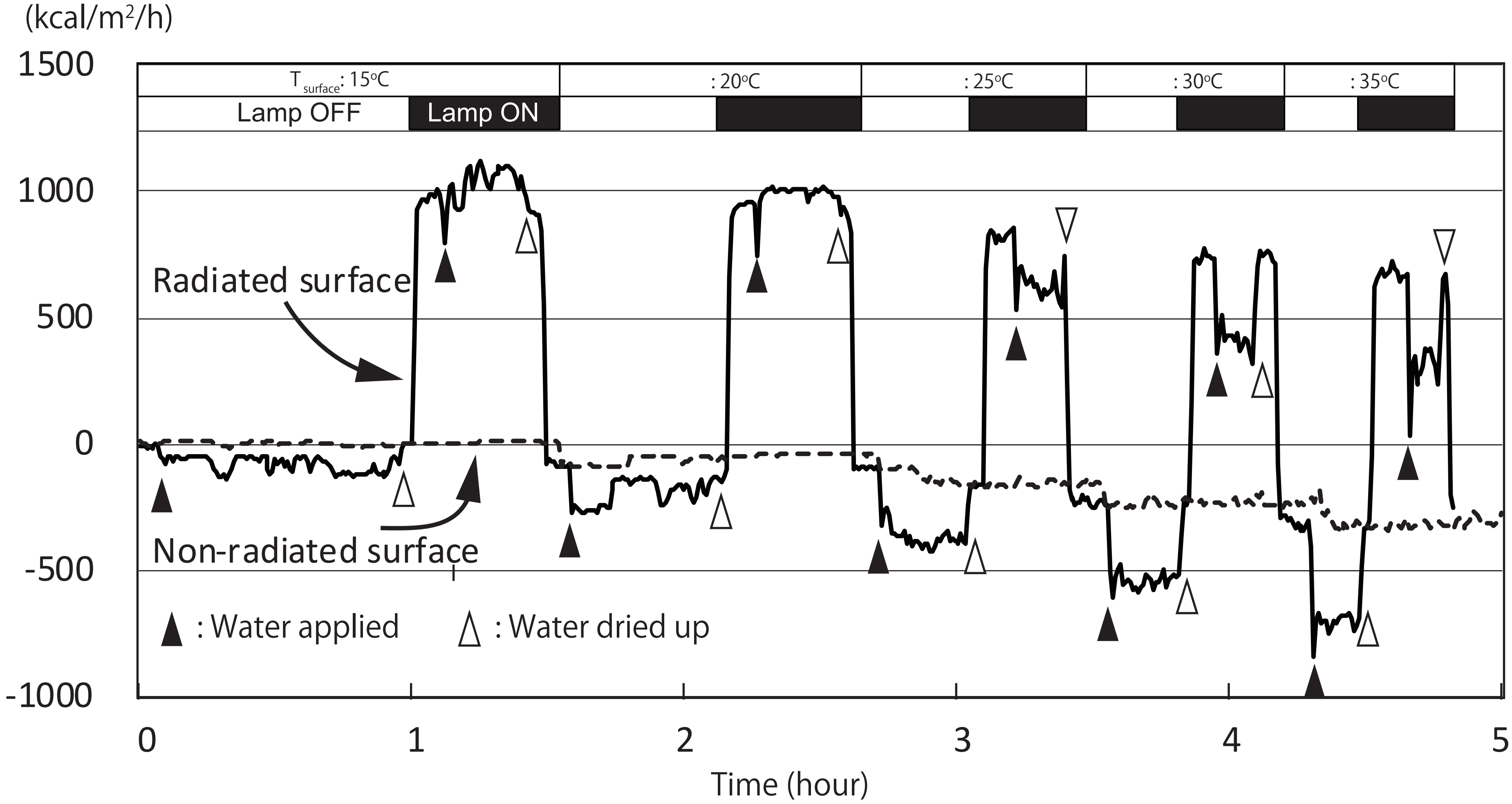


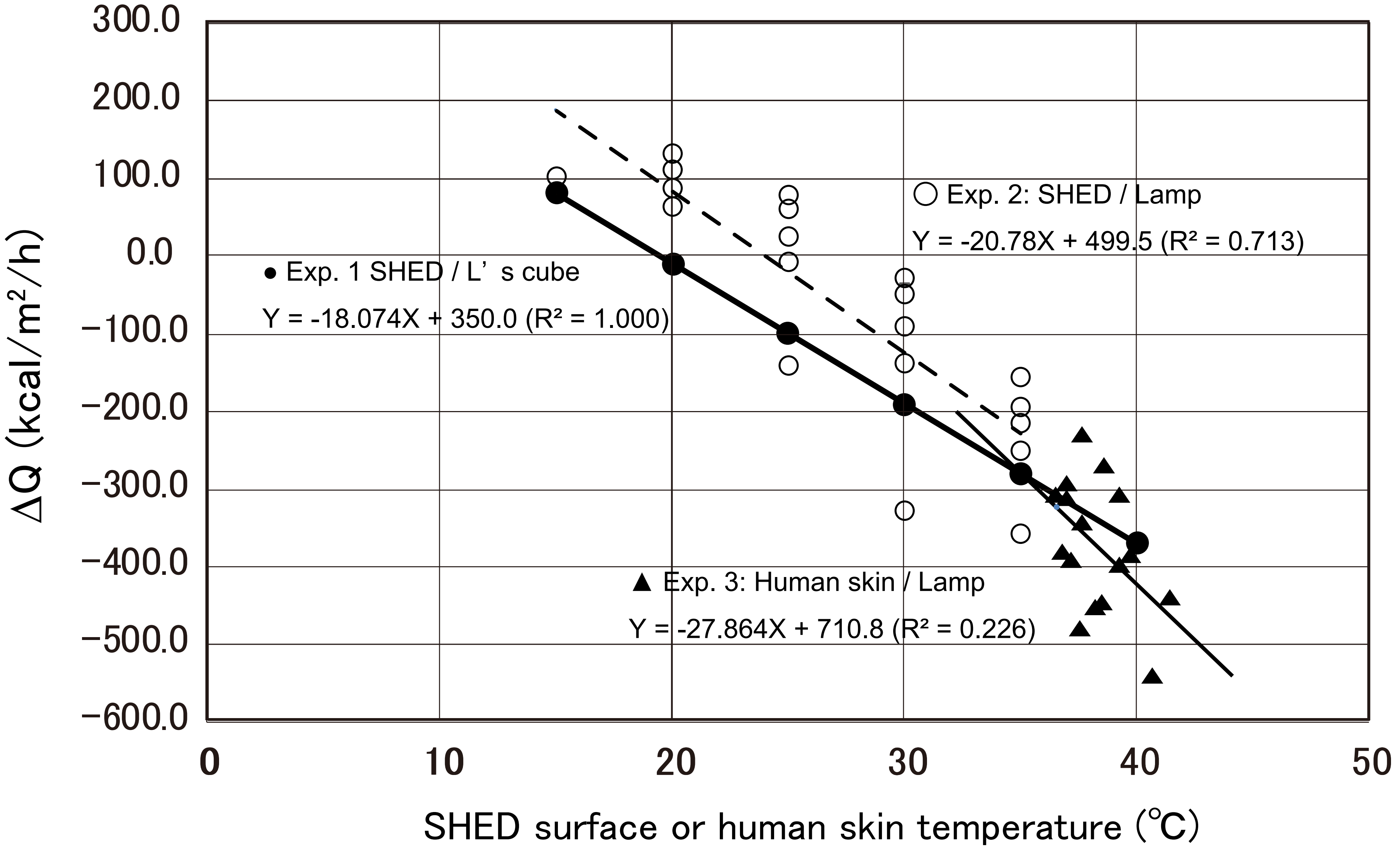
Figure 4



In a 12 °C room, water added (▲) on the 15 and 20°C SHED surface covered with tissue paper made more radiated heat flow into the surface while the water retained and until dried on the paper, and maintained the values until drying (Δ). This phenomenon was not visible while 25°C or more surface temperatures. The dashed line shows the output of the SHED when water was supplied without lamp irradiation. Heat transfer into the SHED surfaces with varying temperatures of 15–35 °C. The recordings are performed in rooms at 12, 17, 21, 27, and 31 °C. Black upward triangles indicate 100 µl of water supplied to the SHED surface. The dashed line shows untreated dry SHED output. A layer of tissue paper (3×3 cm) placed on the temperature regulated SHED surface was wetted with 100 µl of water (▲), and the surface temperature and heat flow were recorded in the absence of radiation until the surface dried up. The SHED was maximally irradiated by a lamp until a stable flow rate could be obtained, followed by the addition of 100 µl of water (△).
The values obtained were then recorded (bold line). The distance between the lamp and the SHED surface was determined at a 1,000-W/m² output and 27.1 °C ambient temperature, followed by other measurements. An additional SHED, positioned back to back, was recorded similarly, however, the device had no lamp radiation and no water application (dashed line). The other results of different ambient temperature conditions were shown in Supplement 1 to 4.

Figure 5

Figure 5. Yuan et al.



The bold line and dots are results from Experiment 1, dashed line and circles from Experiment 2, and fine line and triangles from Experiment 3. The regression quations are simple correlations. The conditions, when ΔQ are positive, are identified as HHI..

Electronic Supplementary Material 1