九州大学学術情報リポジトリ
Kyushu University Institutional Repository

Indoor thermal environment of Mongolian traditional mobile housing used as urban habitat in winter

Purev, Uelun-Ujin
Interdisciplinary Graduate School of Engineering Science, Kyushu University

Hagishima, Aya
Interdisciplinary Graduate School of Engineering Science, Kyushu University

Buyan, Munkhbayar
School of Civil Engineering and Architecture, Mongolian University of Science and Technology

https://hdl.handle.net/2324/4763167

出版情報：Journal of Building Engineering. 48, 2022-05-01. Elsevier
バージョン：
権利関係：CC BY-NC-ND

KYUSHU UNIVERSITY

Indoor thermal environment of Mongolian traditional mobile housing used as urban habitat in winter

Uelun-Ujin Purev[1*], Aya Hagishima[1], Munkhbayar Buyan[2]

[1]Interdisciplinary Graduate School of Engineering Science, Kyushu University, Japan

[2]School of Civil Engineering and Architecture, Mongolian University of Science and Technology, Mongolia

*E-mail: ujin@kyudai.jp

Telephone: +81 080 8703 7512

Abstract: *Gers*, which are traditional mobile tents used by nomadic society of Mongolia, are currently used for urban habitats, and pollutants emitted from coal stoves used in urban *gers* are one of the major causes of air pollution in Ulaanbaatar in winter. Replacing coal stoves with low-emission heating devices in *ger* housing is, therefore, a pressing issue. Nevertheless, fuel stoves have been used in *gers* for generation since the nomadic period, and a previous study reported that urban *ger* residents were generally satisfied with the indoor environment heated by a coal stove. Against this background, the present study aimed—based on field measurements—to characterize the spatial and temporal characteristic of the thermal environment within gers heated by coal stoves, to provide insights for smoothly shifting the current stoves to electric heating. The measurement results showed diverse daily fluctuations of indoor temperature among days and households dominated by the unstable heating power of stoves, which is influenced by the occupants' style of coal input. The indoor air temperature occasionally resulted in outliers beyond the comfort temperature range. By contrast, the operative temperature was above the lower limit of the ASHRAE comfort range for over 70% of the time owing to the direct radiation of stoves, highlighting that the current design of *gers* and the use of fuel stove are reasonable to achieve a comfortable indoor environment in winter under the conditions of nomadic mobile dwellings, which necessitates a lightweight envelope with poor insulation performance.

Keywords: Indoor thermal environment; traditional housing; field measurement; cold climate; solid fuel stoves

1. *Introduction*

In Mongolia, located in the northern part of East Asia, space heating is indispensable because of the cold winters with temperature reaching below −40 °C [1]. Space heating consumes over one-third of the energy used in households and the commercial sector in this country [2,3]. Furthermore, 58% of the heating energy of households relies on coal, causing severe air pollution in the capital city, Ulaanbaatar, in winter [4]. In fact, Soluyanov et al. [5] reported that 80% of the air pollution is caused by coal stoves used in houses in urban areas. Otgonbayar et al. [6] conducted a cost–benefit analysis of three air-pollution countermeasures, including introducing improved low-emission coal stoves, replacing coal stoves with electric heaters, and relocation from detached houses to suitably insulated apartments. They pointed out that replacing coal stoves with electric heaters in detached houses will significantly reduce the pollutant emission, although, this would require the considerable investment in the construction of a new power plant based on the cost-benefit analysis. These facts suggest that energy saving and emission reduction of the heating in houses are pressing issues. However, it is not easy for Mongolia to implement standard approaches which have been taken in developed countries, such as improvement of building insulation performance and introduction of energy-efficient and low-emission heating devices, because of factors specific to developing countries. One of the factors is related to many detached houses located in *ger* districts, which are unplanned residential districts with insufficient urban infrastructure for water services, sewage treatment, and heating. Note that a *ger* refers to a traditional portable tent; it was originally a home for nomadic people but is currently used as an urban habitat [7]. In Ulaanbaatar, 58% of the total households lived in *ger* districts [4], and 52.4% of the households in *ger* districts lived in *gers* in 2016 [4]. Furthermore, most of dwellings in *ger* districts rely on coal stoves for space heating.

With such background, Purev and Hagishima [8] surveyed residents of 47 *gers* located in Ulaanbaatar to grasp the current situation of *ger* envelopes, heating devices, and fuel consumption and the perceptions of living conditions. Their survey highlighted the excellent affordability of *gers* for low-income households and excess coal consumption owing to the low insulation envelope. In this survey, more than 90 % of respondents stated that indoor thermal conditions were occasionally either too hot or too cold because of the frequent inflow of cold air when occupants open a door to go to a toilet or other places. Even though urban *gers* are intended as temporary housing during the transition from nomadic migration culture to settlement culture [9,10], considering the fact that *gers* are home to ~114,000 urban households [11], suitable actions to reduce pollutant emissions without worsening the indoor thermal environment are urgently required in the short term. To do this, switching from coal stoves to electric heating in *ger* housing is a possible scenario. In fact, the Mongolian government started a project that used excess electricity for heating during the night in *ger* districts to encourage the use of electric heaters instead of coal stoves in 2017 to counter air pollution [12]. Pillarisetti et al. [13] performed a long-term measurement of the performance of electric heat pumps tailored to cold climates in self-built detached houses and *gers* and reported acceptably moderate performance of the heat pumps. Note that 90% of the electricity in Mongolia was generated by coal-fired thermal power plants, and the contribution of renewable energy was only 8% in 2018 [14]. On the other hand, Bayandelger et al. [15] conducted a field experiment to assess the feasibility of electric thermal storage utilizing photovoltaics (PV) in a *ger* with additional insulation. They pointed out that 31% of the energy demand of an electric thermal storage heater could be supplied by a PV system.

Nevertheless, the use of fuel stoves in *gers* has been practised for a long time during and since the nomadic period, and about 80% of people who lived in *gers* stated that they were satisfied with the current indoor thermal environment of their *gers* heated by a coal stove according to the survey of Purev and Hagishima [8]. Therefore, for smoothly shifting the current stoves to electric heating, it is vital to understand the characteristics of the current indoor thermal environment of *gers* heated by fuel stoves to which many people have been exposed. Very few studies have reported on the indoor thermal environment of *gers* heated by a stove. Ishikawa et al. [16] measured the indoor temperature of six *gers* in Ulaanbaatar in winter and reported a large vertical temperature difference owing to the low insulation performance. Buyantogtokh and Zhang [17] measured indoor temperatures and relative humidity as well as CO and CO_2 concentrations for 10 *gers* for a total of 14 days in winter, and estimated the ventilation rates. They presented box plots of the indoor air temperature and relative humidity at 1.2 m height and revealed a wide range of indoor air temperatures from 8 °C to 41 °C. Furthermore, they plotted the measured data on psychrometric charts and concluded that low and high indoor temperatures and low relative humidity were outside the ISO7730 standard thermal comfort range. Tsovoodavaa and Kistelegdi [18] estimated the heating and cooling energy for nine types of *gers*, including a current Mongolian *ger*, as well as similar traditional temporary housing used in other countries based on the building energy simulation approach.

In spite of such attempts, the detailed indoor thermal features of current *gers* heated by a coal stove have not been well documented in either English or Mongolian. One of the knowledge gaps is the temporal and spatial behaviour of indoor thermal conditions. It may be assumed that *gers* experience frequent room-temperature drops during the winter months due to the door being opened for use of the outdoor toilets. In fact, the survey by Purev and Hagishima [8] indicated that 80% of *ger* residents considered the room temperature in their ger to be occasionally too hot or too cold. However, the detailed temporal variation of room temperature has not been clarified by actual measurements. The spatial distribution of the indoor temperature, including both surface and air, has been insufficiently examined, even though strong heterogeneity of the temperature field is expected due to the low insulation performance of *ger* envelopes compared to standard modern buildings. Furthermore, little attention has been directed toward the influence of direct radiant heating from primitive coal stoves on the indoor thermal environment, which is extremely rare in modern air-conditioned buildings.

Under these circumstances, the objective of this study is to elucidate the features of temporal and spatial variation of the indoor thermal environment of typical urban *gers* and to improve understanding of the thermal influence of radiant heating from primitive coal stoves in winter. To do this, we conducted *in situ* measurements of indoor air temperature at multiple positions in two typical urban *gers* for 12 days. To understand the heating characteristics of coal stoves, the stove of one *ger* was replaced by an electric convection-type heaters during the last two days of the period. Section 2 describes the details of the methodology used in the field measurements. Section 3 reports the observed spatiotemporal distribution of air temperature and the analysis of space heating power. The characteristics of the indoor thermal environment for occupants are also discussed in relation to the current *gers*' design. Section 4 summarises the findings of this study.

2. Methodology

2.1 Location and period of field measurement

The two *gers*, named as *Ger* A and *Ger* B, located in the Songinokhairkhan district (47 °58′ N 106 °49′ E), which is in the northwest outskirt of Ulaanbaatar with a distance of 11 km from the city centre, were selected for the measurement of the indoor thermal condition. The locations of the surveyed *gers* are shown in Fig. 1. The two surveyed *gers* were located in the same plot. As the *gers* have no toilet, the occupants of these *gers* share an outhouse, which includes a pit latrine in the same plot.

Table 1 shows the measurement period, which was basically classified into two, namely Term CS of 10 days as baseline condition of coal stove heating for *Ger* A and *Ger* B, and Term EH of extra 2 days for *Ger* B with electric heating. Throughout the entire measurement period, the occupants of the two *gers* continued their usual routines; hence, residents of the *gers* occasionally travelled out of the house and left the *gers* unoccupied. During two days of Term CS and one day of Term EH, however, there was always at least one occupant present in the *gers*. These periods are named Term CS-fo and Term EH-fo. In the following sections, the data of Terms CS-fo and EH-fo are mainly used for analysing the detailed time patterns of indoor thermal variables as the result of occupants' heating control to satisfy their thermal sensation. On the other hand, the data of the entire period are used mainly to understand the general thermal behaviours of the *gers*.

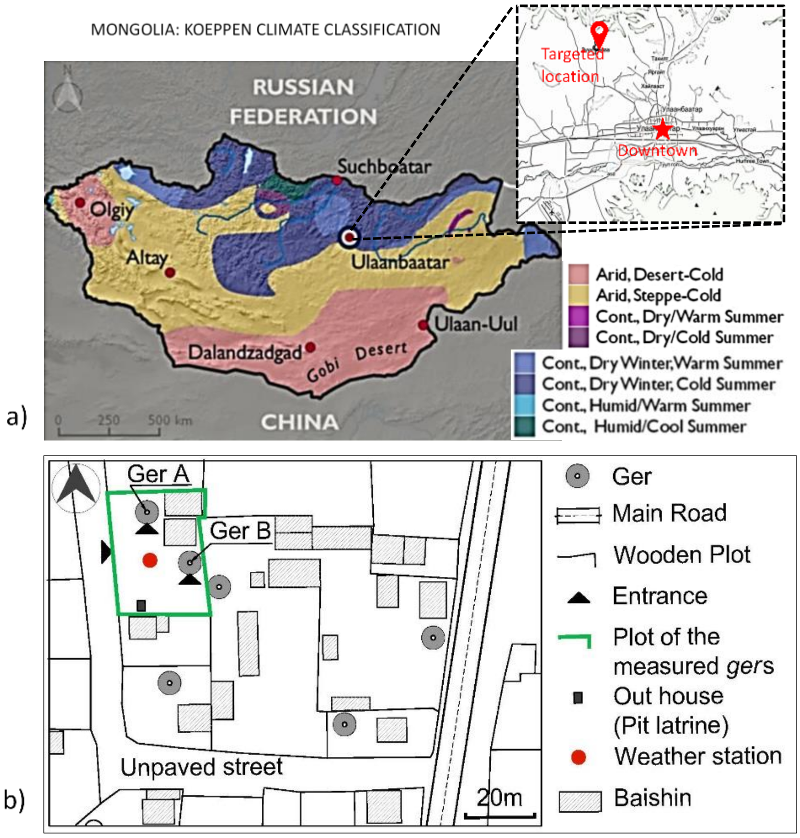

Fig. 1 (a) Measurement location on the map of Köppen climate classification [19,20] (b) Site plan of the plot in which the surveyed *gers* are located.

Table 1. Measurement period

	Measurement period	*Remark*
Term CS	January 18 – January 27, 2020 (10 days)	Measurement of *Ger* A and *Ger* B with the coal stove heating
Term EH	January 28 – January 29,2020 (2 days)	Measurement of *Ger* B with electric heaters
Term CS-fo	January 18 and 26, 2020	Both the *gers* were always occupied by at least one resident.
Term EH-fo	January 29, 2020	Ger B was always occupied by at least one resident.

2.2 Details of the surveyed gers

The two *gers* were selected because of their typical features, which mostly follow the national standard [21]. Table 2 lists the specifications of the *gers* and occupants. Fig. 2 shows photographs of the exterior and interior of the two *gers*. Fig. 3 illustrates the section and layout of the *gers*. Both the *gers* having almost same size are categorised as '5-wall', which is the most popular size according to previous survey [8]. The envelope of the *gers* comprises a thin white cotton sheet for the outermost cover, a tarpaulin sheet, and two layers of wool-felt sheet, known as *Esgii*, for insulation. The major components of *Ger* A have been used for 40 years, and they moved to the current location 7 years ago. *Ger* B has been used for 2 years at the same location. It is noteworthy that the thermal properties of the envelope of these two gers, which we could not measure in this study, are probably different because of their different durations of use; this difference is similar to the difference between various insulation materials.

Table 2. Characteristics of the surveyed *gers*

	Ger A	*Ger* B
Number of occupants	2	4
Adult	2	1
Children	0	3
Ger volume [m³]	50.02	47.01
Envelope surface [m²]	82.33	79.06
Floor Area [m²]	27.5	25.8

Fig. 2 (a) Exterior of *Ger* A, (b) exterior of *Ger* B, (c) interior of *Ger* A, (d) interior of *Ger* B (e) *Ulzii* stove used at *Ger* A, (f) *Khas* stove used at *Ger* B, and (g) electric heaters used at *Ger* B during Term EH

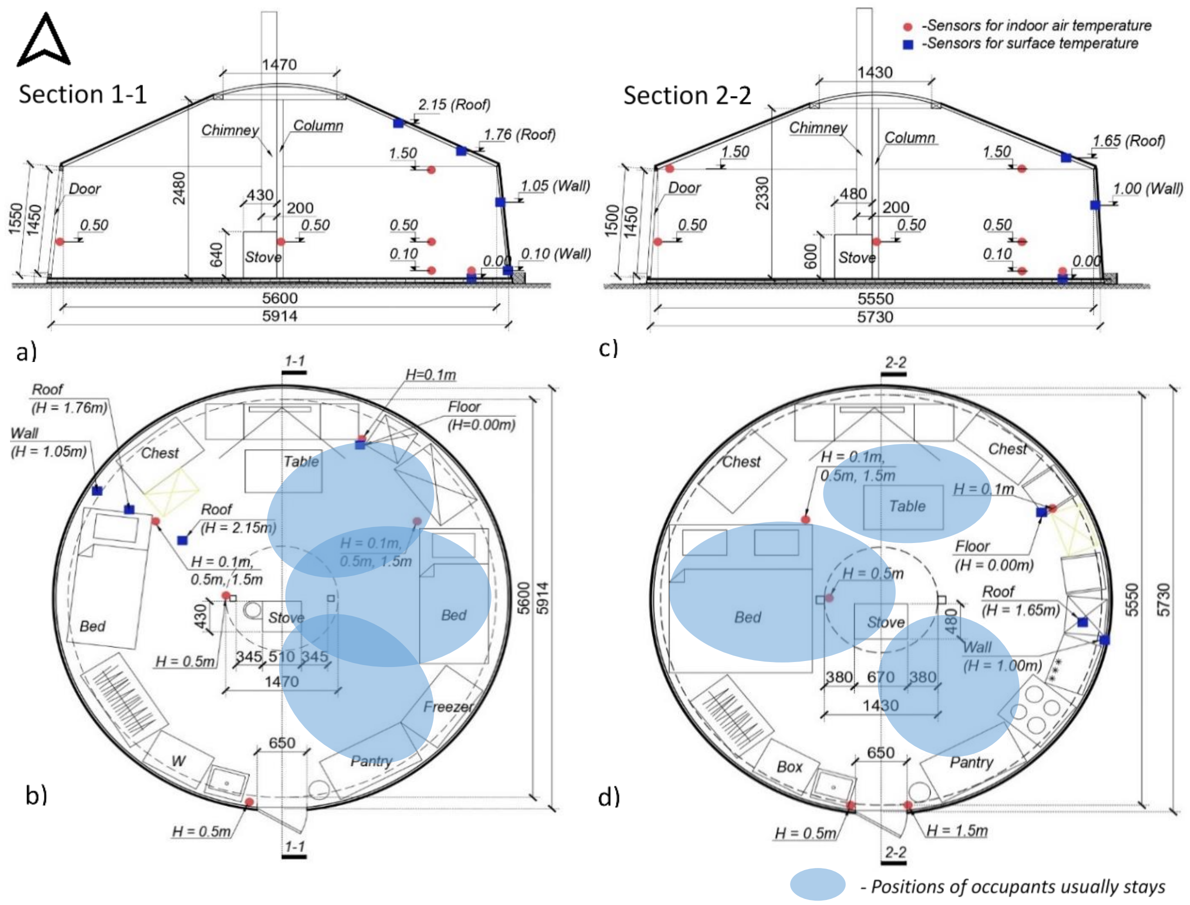

Fig. 3 (a) Section of *Ger* A, **(b)** layout of *Ger* A, **(c)** section of *Ger* B, and **(d)** layout of *Ger* B

The specifications of the heating devices used in the *gers* are listed in Table 3. The family of these two *gers* used coal stoves with top-lit-updraft design, which are commonly called as "improved stoves" in Mongolia [22]. In both the *gers*, smokeless coal was used owing to the "smokeless fuel" project which banned the use of raw coal in the city[23]. During Term EH, we replaced a coal stove with two electric ceramic fan heaters in *Ger* B. To avoid accidental fires caused by the electrical leakage of aging distribution systems, thermostats were attached to the electric heaters, set to 25 °C based on the range of acceptable operating temperature suggested by ASHRAE 55 [24].

Table 3. Specifications of heating devices used in the *gers*.

	***Ger* A**	***Ger* B**	***Ger* B**
Period	Term CS	Term CS	Term EH
Type of heating device	Improved coal stove	Improved coal stove	2 ceramic fan heaters with thermostats (set to 25 °C)
Model of heating device (Manufacture)	Ulzii (Royal ocean LLC)	Khas (Selenge construction LLC)	MDN-RD114 (Mei Ling Ltd.)
Heating Power	6.5 kW	7.5 kW	2 level (1.6 kW, 3.2 kW) for each heater

2.3 Instrumentation

The measurement instruments used in this survey were selected for its appropriate accuracy and low susceptibility to noise in the field, and similar to those widely employed for indoor thermal measurement in buildings [25]. The measuring instruments are listed in Table 4. Outdoor temperature (T_{out}), relative humidity (RH), and solar radiation were measured at a height of 2 m inside the plot as reference weather conditions. Temperature of the indoor air, floor surface, and internal surfaces of *ger* envelopes were measured at multiple positions at each *ger*. The measurement positions inside the *gers* are shown in Fig. 3. The electricity consumption of the ceramic fan heaters of *Ger* B was also monitored during Term EH. All the aforementioned measurement items were recorded every 1 min. In addition to the environmental variables, the authors questioned the average daily coal consumption of the occupants.

Table 4. Measuring instruments and accuracy of sensors.

Measurement items	**Sensors and loggers**	**Range and accuracy**
Outdoor air temperature, relative humidity	HOBO U30 Weather Station Data logger & Sensor S-THB-M002	−40 °C to 75 °C ±0.21 °C-over 0 °C to 50 °C
Solar radiation	S-LIB-M003 Silicon Pyranometer	±10 W/m^2
Indoor air temperature (9 positions at ***Ger*** A, 7 positions ad ***Ger*** B)	T-type Thermocouple (ϕ = 0.1 mm), HIOKI logger LR8432 Z2015-01	−40 to 125 °C ±0.5 °C
Surface temperature (5 positions at *Ger* A, 3 positions ad ***Ger* B)**	T-type Thermocouple (ϕ = 0.1mm) + HIOKI logger LR8432 & Z2015-01	−40 to 125 °C ±0.5 °C
Electricity consumption of heaters (Term EH, ***Ger*** B)	Electricity monitor (OWL+USB)	NA

3. Results and discussion

3.1 Climate conditions

Fig. 4 shows the outdoor weather conditions for the entire measurement period. The data of the spatial averages of the indoor air temperature of the *gers* are also included for reference. As can be seen from the figures, the outdoor temperature shows a periodic diurnal cycle, ranging between −2 and −27 °C, with an average of −17 °C. The daily maximum and minimum values for each day slightly differed, and the latter 5 days showed relatively high daily maximum temperatures. The outdoor relative humidity showed an opposite trend of air temperature as expected, ranging from 43% to 85%. Unfortunately, solar radiation data were not available for half of the measurement period owing to technical issues. The data of the remaining 6 days indicated symmetric daily variation, suggesting clear sky conditions.

Regarding the indoor air temperature, the values of the two *gers* were always higher than the outdoor temperature owing to space heating, and the difference between the indoor and outdoor temperatures ranges from 15 to 47 °C. The minimum indoor air temperatures of *Gers* A and B were 2 and 5 °C, respectively, and the maximum temperatures were 32 and 30 °C, respectively, during the measurement.

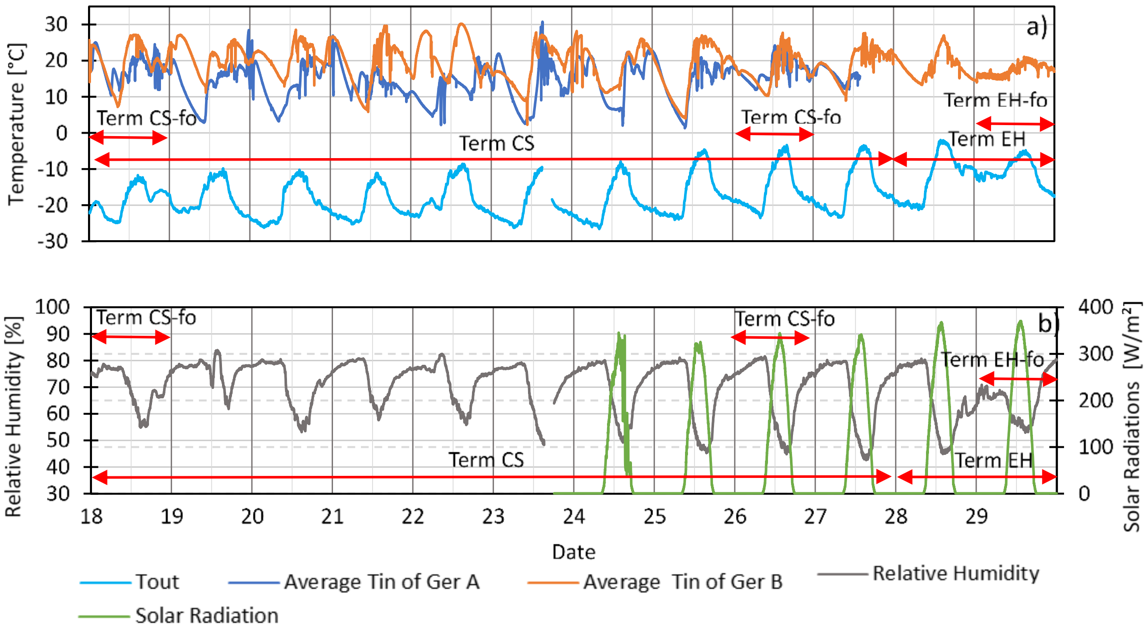

Fig. 4 Time variations of (a) Outdoor air temperature (Tout) and spatial average of the indoor air temperature (Tin) of *Gers* A and B, (b) relative humidity of outdoor air environment and global solar radiation for the entire period.

3.2 Detailed time patterns of indoor temperature during Term CS-fo and EH-fo

Figs. 5 show the temperatures of the indoor air and surfaces observed at multiple positions every 1 min during Term CS-fo and EH-fo, in which the *gers* were occupied by residents all day. The estimated radiation energy of stoves (*See* Appendix) and the electricity consumption of ceramic fan heaters are also included in Fig. 5.

First, for *Gers* A and B during Term CS-fo, the measured indoor air and surface temperatures exhibited similar fluctuation patterns with the same time cycle of 3–9 h. In addition, the time of peak occurrence and the magnitude of fluctuation differed between the two *groups* for two days. Furthermore, such fluctuation patterns with multiple peaks in a day were different from the diurnal cycles of both the outside air temperature and solar radiation with a single peak. Such diverse daily patterns of indoor air temperature with multiple peaks are supposed to be related to the occupants' behaviours to add fuel to burning stove in various timings. In other words, the aforementioned time cycle of 3–9h roughly matches the frequency with which occupants add coal in the stove. In fact, occupants of *Ger* B with longer time scale of the fluctuation patterns explained to the authors that they tended to add large amount of fuel at one time and not add fuel until the fuel is fully burned out.

In *Ger* A, the position 1.5 m and 0.5 m laterally from the stove exhibited the largest indoor air temperature fluctuation of 13 and 40 °C while the level at 0.1 m exhibited the smallest temperature variation of 5 and 19 °C. Such a large vertical temperature difference is consistent with previous observations [16] and is believed to be due to the radiant heating of coal stoves and to heat loss through the *ger* envelopes. The temperature near the door exhibited sudden drops, which are mainly caused by door opening when someone enters or exits the *ger*. On the other hand, on 26 January, occupants frequently opened doors in the afternoon around an hour to ventilate and decrease the indoor air temperature to avoid overheating. Such behaviour was observed on other days when the indoor air temperature was too high. The wall and roof surface temperatures were similar to the indoor air temperature, which was caused by the strong radiation emitted from the stove. Similar tendencies were observed in *Ger* B when a coal-burning stove was used.

During Term EH with electric heaters, the thermostat was set at 25 °C therefore, the heaters were repeatedly and automatically switched on and off at intervals of 15–20 min during the day. As a result, the indoor temperature at 1.5 m exhibited oscillation at ~3 °C when there was fluctuation in the electricity consumption.

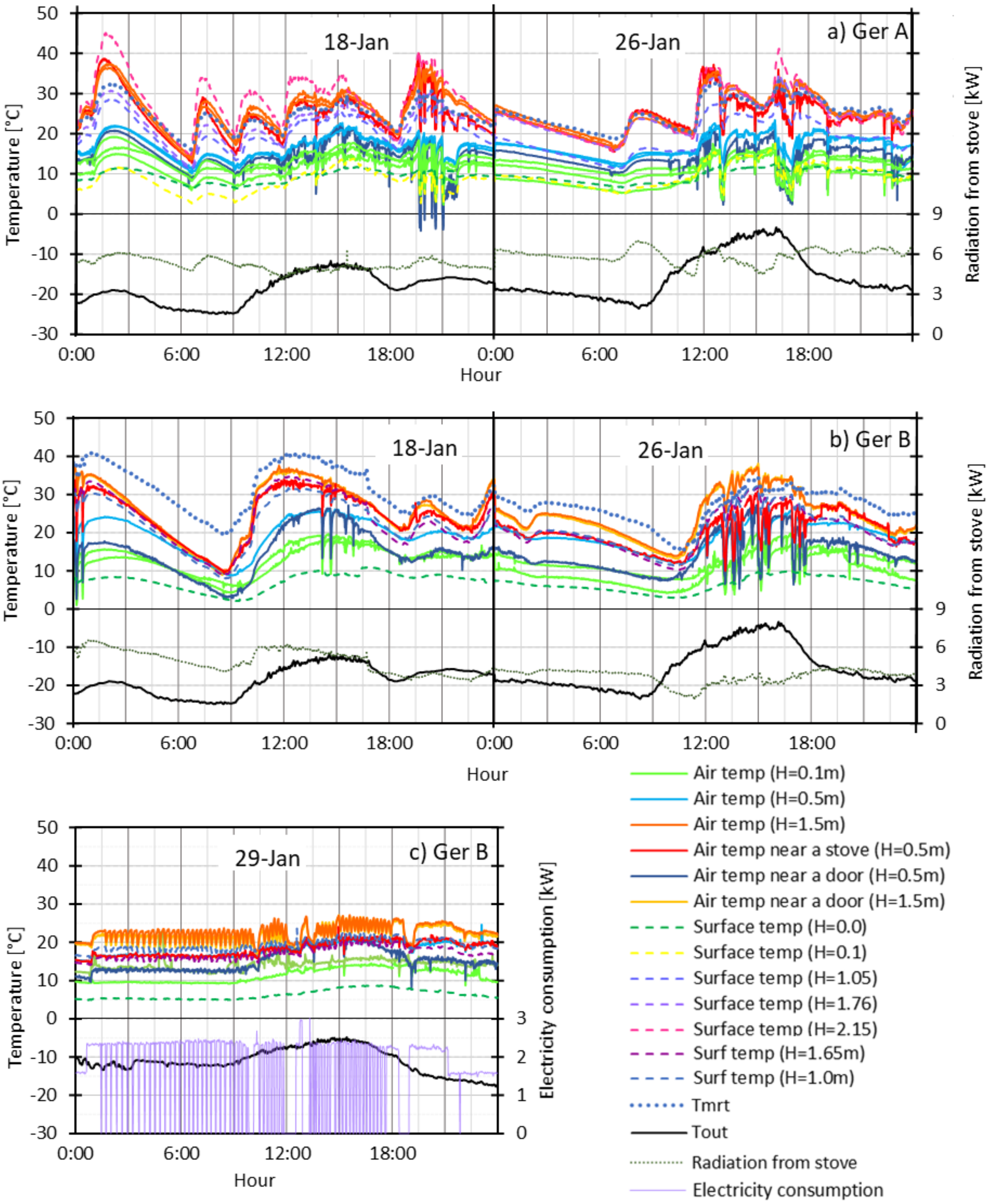

Fig. 5 Air and surface temperatures at various positions inside (a) Ger A heated using a coal stove (Term CS-fo), (b) Ger B heated using a coal stove (Term CS-fo), and (c) Ger B heated using electric heaters (Term EH-fo).

3.3 Range of indoor temperature under the different outdoor air temperature

Fig. 6 shows the range of spatially averaged indoor air temperature against various outdoor air temperature T_{out} and sol-air temperature T_{sol}, respectively, based on the data of 10-minute average. T_{sol} is a simplified index with a temperature unit for considering the influence of both outdoor air temperature and heat gain of the solar radiation, expressed as Eq. (1).

$$T_{sol} = T_{out} + \frac{a \cdot SR}{h} \qquad (1),$$

where *a* is solar absorptivity of the ger envelope assumed to be 0.52 [26]; *SR* is global solar radiation [Wm^{-2}]; *h* is convection heat transfer coefficient of external surfaces of the *gers*, assumed to be 10 W $m^{-2}K^{-1}$ [27].

As can be seen from the figures, the indoor temperature was maintained in the range of 5 to 30 °C by heating while the outdoor temperature was in the range of –25 to –5 °C. As already shown in Fig.5, the time variation of the indoor temperature in both Term CS and EH was strongly influenced by the heating and showed very different tendencies from the daily variation of the outdoor temperature, therefore it is reasonable that there is little correlation between the T_{in} and T_{out} for both the *gers*. Similarly, there is little correlation between T_{in} and T_{sol}. Nevertheless, under conditions where T_{out} is above –10 °C and T_{sol} is above 10 °C, the indoor temperature was maintained at a relatively high level. However, considering that the times of day when the outdoor temperature is high or the solar radiation is high are generally coincident with the times of day when the occupants were active and preferred to keep the indoor temperature high, the effect of the heating devices is supposed to be also significant rather than outdoor conditions.

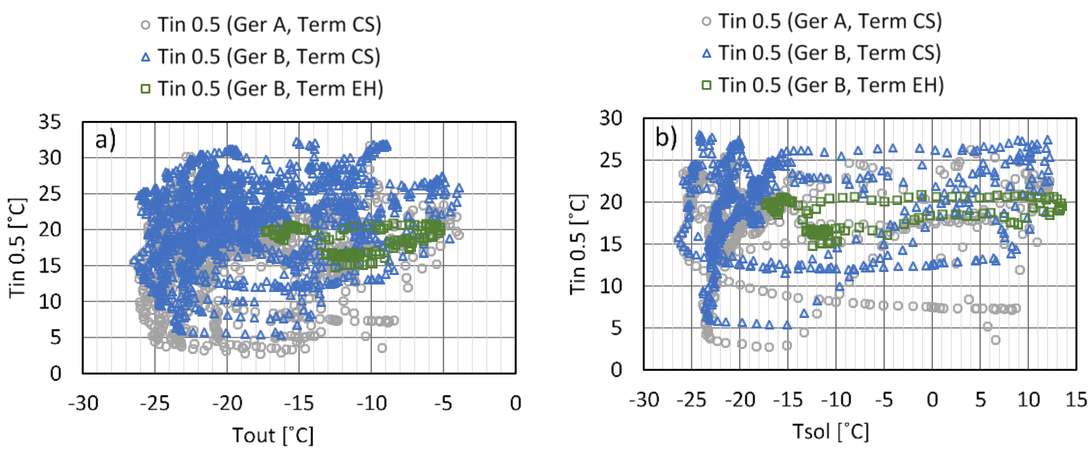

Fig. 6 (a) Scatter plot between outdoor air temperature (T_{out}) and indoor air temperature height of 0.5 m (T_{in} 0.5) (b) Scatter plot between Sol-air temperature (T_{sol}) and indoor air temperature height of 0.5m (T_{in} 0.5)

3.4 Heating energy consumption

The initial time when the estimated radiation heat of the stoves and indoor air temperature starts to increase is assumed to coincide with the timing of the fire ignition as mentioned before. Thus, the number of multiple local negative peaks of radiation energy can be recognised as the number of fire ignitions accompanied by fuel addition. With this assumption, we estimated the number of fire ignitions per day (Table 5). Although both the *gers* used stoves categorised as "improved stoves" having similar heating power, the result indicated the clear difference in usage style of the occupants.

Table 5. Daily number of fire ignitions of coal stoves

	***Ger* A**	***Ger* B**
Average	4.0	2.5
Standard deviation	1.2	0.8

Fig. 7 shows the daily average electricity consumption of the electric heaters of Term EH and the daily average of the estimated radiation energy of the stoves of Term CS. Moreover, the heating degree hours (HDH)—assuming a reference set point of 18 °C, the lower limit of indoor air temperature according to the Mongolian Standard [28]—was included for comparison. The occupants of the *gers* explained that they used coal of 25 kg on a daily basis, which is equivalent to 5.78 kW considering a calorific value of 20 MJ/kg. In contrast, the average estimated radiation heat of the stoves for the entire period was 5.08 and 4.23 kW for *Gers* A and B, respectively. Meanwhile, assuming that the stove surface and indoor air temperatures were 200 [29] and 20 ºC, respectively, we can estimate convection heat between the stove and indoor air to be 1.49 and 1.83 kW for these two *gers*, considering a convection heat transfer coefficient of 6.9 W/m^2K, which is determined by the relation between the Nusselt number, Grashof number, and Prandtl number for the natural convection of a flat plate [30]. It indicates that the averaged total heating power was 6.57 and 6.06 kW for *Gers* A and B, respectively, and the contribution of radiation to the total heating power of the stoves was around 77% and 70%, respectively. Although these values should be treated as approximations, the order is similar to both the calculated values based on the weight of coal used daily and the specifications of the manufacturers of the stoves (A: 6.5 kW and B: 7.5 kW).

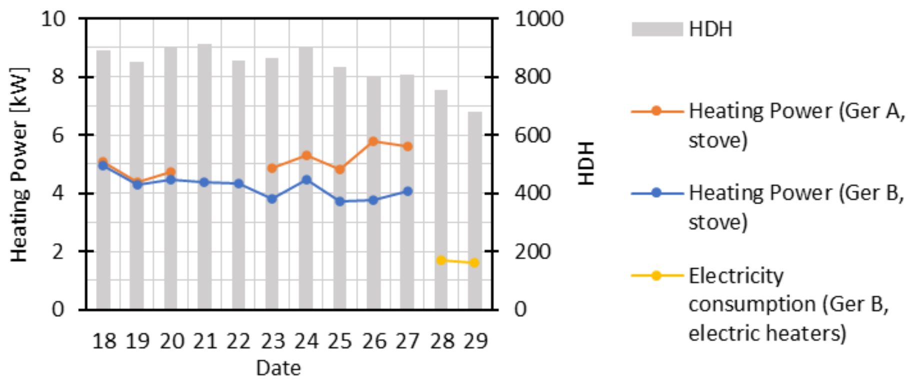

Fig. 7 Daily HDH, estimated radiation heating power of stoves, and electricity consumption of heaters

On the other hand, the electricity consumption of Term EH was about 1.65 kW, which was less than half of the estimated radiation heat, less than one-third of the heating power calculated from coal use, and the values mentioned in the specifications of the manufacturers. In contrast, HDH ranged from 800 to 950 during Term CS, and it decreased by ~17% for Term EH. This implies that the coal stoves consumed an excess amount of energy compared to the electric heaters.

Such excess energy consumption is partly caused by the primitive function of the stoves to module the intensity of the coal combustion according to the indoor thermal conditions. The behaviour of the occupants to intentionally open doors to avoid overheating, shown in Fig. 5a, can also be recognised as a limitation. In contrast, ceramic fan heaters connected with a thermostat showed reasonable performance in realising a stable indoor air temperature during Term EH-fo, as shown in Fig. 5c. This feature suggests that considering energy saving and emission reduction of the current coal stoves based on the change in the behaviour of the occupants is challenging.

3.5 Spatial heterogeneity of indoor air temperature

Fig. 8 shows the relationship between the spatially averaged indoor air temperature at a height of 0.5 m (hereafter, $T_{in-0.5}$) and the standard deviation of the indoor air temperature of all the measurement positions for Terms CS and EH. In addition, Fig. 9 shows the comparison of the spatially averaged indoor air temperature at a height of 0.5 m with other two levels (0.5 and 1.5 m). To reduce the influence of the transient temperature drops owing to the short-term door openings, 10-minute averaged values were used for these graphs.

As shown in Fig. 8, during Term CS with coal stoves, the spatial nonuniformity of the indoor air temperature increases with $T_{in-0.5}$. In contrast, the standard deviation decreases with the decrease in $T_{in-0.5}$ caused by the fire extinction of the stoves. The linear relations illustrated in Fig. 9 indicate that the stratified temperature profiles owing to the buoyancy force are intensified with an increase in $T_{in-0.5}$ caused by heating. Fig. 9 indicates that the temperature differences between the levels of 0.1 and 1.5 m were ~12 and 18 °C under the conditions of $T_{in-0.5}$ = 20 and 30 °C, respectively. On the other hand, ASHRAE 55-2017[24] indicated that the vertical air temperature difference between the head and ankle levels should not exceed 3 °C for seated occupants and 4 °C for standing occupants for the thermal comfort condition. Although recent studies, such as Mohlenkamp et al. [31], reported that the acceptable vertical temperature gradient for the thermal comfort of occupants might be much larger than this comfort standard, the strong thermal stratification of the indoor space of *gers* can be recognised as completely different from the fully air-conditioned environment of modern buildings with relatively uniform temperature distribution.

Comparing the data of Terms CS and EH, the spatial heterogeneity of the indoor air temperature during the usage of ceramic heaters tends to be small. In particular, the temperature difference between the levels of 0.5 and 0.1 m of Term EH is significantly smaller than that for Term CS with stove heating. A possible reason for this difference between the heating devices is the large infiltration rate of the interface between the floor and *ger* envelopes caused by the stack effect created by the stoves with much higher surface temperature, which is generated by the coal combustion, compared with the ceramic heaters. This implies that coal stoves may cause larger heat loss owing to the buoyancy-induced infiltration compared with convection-type electric heaters, although these heating devices can generate similar levels of mean indoor air temperature.

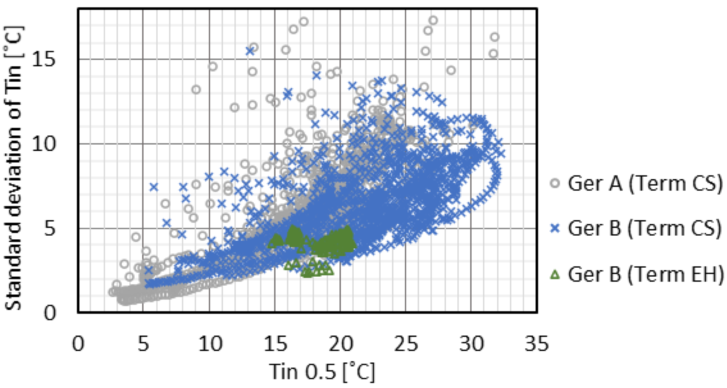

Fig. 8 Relation between the spatial average air temperature at a height of 0.5 m and the standard deviation of the indoor air temperature for all the measurement positions

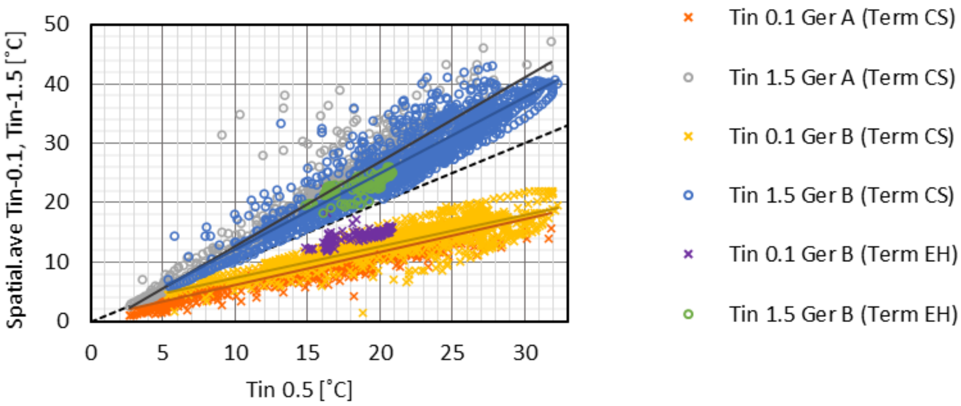

Fig. 9 Relation between the spatial average air temperature at a height of 0.5 m and different heights from the floor level (0.1 and 1.5 m)

3.6 Surface temperature of ger envelopes and floor

Fig. 10 shows relations between the indoor air temperature ($T_{in\text{-}0.5}$) and surface temperatures of various positions of *ger* envelopes and floor. The surface temperature at higher positions is higher compared with $T_{in\text{-}0.5}$ similar to the relation of air temperature at different heights shown in Fig. 9. Especially, the roof surface temperature of *Ger* A at a height of 2.15 m sometimes exceeds 50 °C. Considering the small thermal resistance of the envelopes and cold outdoor air temperature below -10 °C, this trend is assumed to be caused by hot updraft above the stove owing to natural convection and direct radiation energy emitted from the stove[1].

The temperature with regard to the floor and wall surface at 0.1 m reduced by ~25 °C. This low temperature is caused by the stratified indoor air temperature and cold inflow through the lower part of the *ger* envelopes owing to the stack effect. Note that the positions of the sensors to capture floor surface temperatures were placed relatively far from the stoves to minimise the disruption caused to the daily lives of the occupants; therefore, the sensors were not directly heated by the radiation generated from the stoves.

The floor surface temperature of *Ger* B differs between the two terms, and the values of the

---

[1] The interior surface temperature of the *ger* can be expressed by the following equation, assuming no radiant heating on the interior surface (*See* Appendix): $T_{s,in} = T_{in} - \frac{T_{in}-T_{out}}{\alpha_{in}\left(\frac{1}{\alpha_{in}}+\frac{\Delta x}{\lambda}+\frac{1}{\alpha_{out}}\right)}$. By substituting the thermal properties of the target site, $T_{s,in}$ can be estimated at around 5 °C for the situation of T_{in} = 20 °C and T_{out} = −20 °C. This estimation is much lower than the observed values, suggesting additional factors such as direct radiant heating and a local thermal plume above the stoves.

Term CS considering stove heating tended to be lower than that of the other term. This tendency is consistent with the indoor air temperature at a height of 0.1 m (Fig. 9), implying a higher infiltration owing to the stack effect created by the coal stove compared with the convection-type electric heaters, as mentioned before.

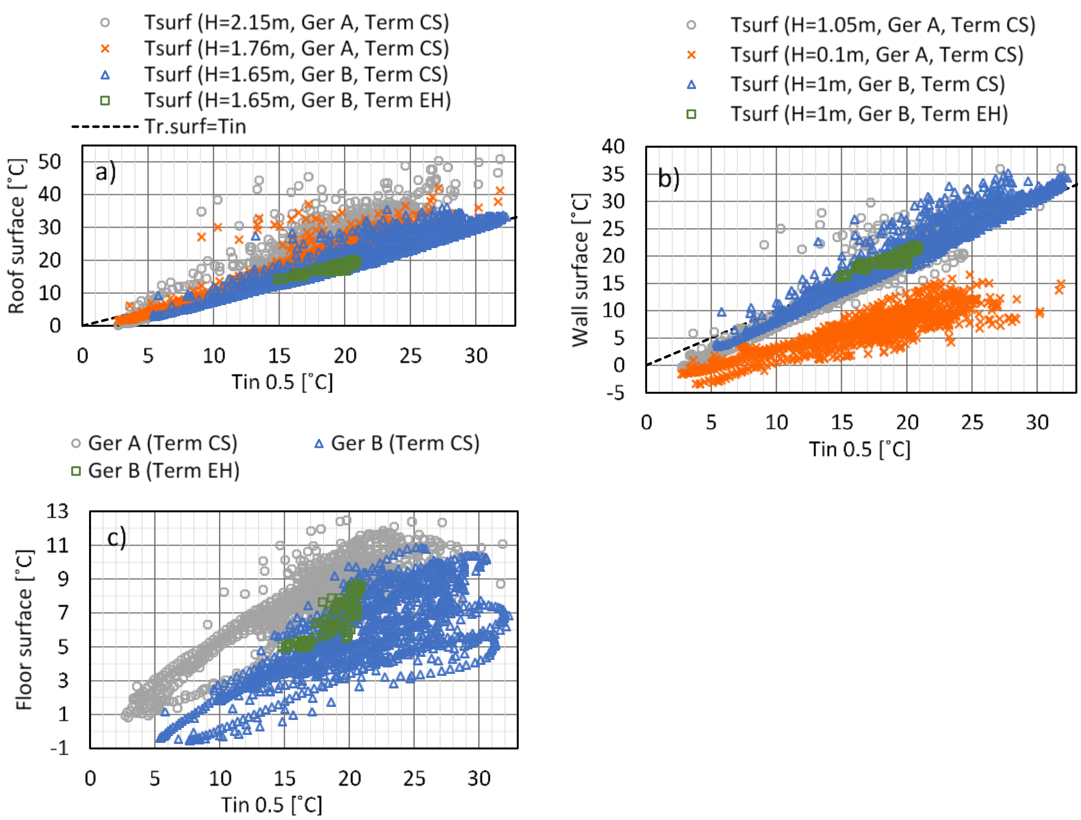

Fig. 10 (a) Relation between the spatial average air temperature at a height of 0.5 m and roof surface temperature. (b) Relation between the spatial average air temperature at a height of 0.5 m and wall surface temperature. (c) Relation between the spatial average air temperature at a height of 0.5 m and floor surface temperature

3.7 *Thermal exposure of the occupants*

The mean radiant temperature (MRT, T_r) was calculated to examine the thermal exposure of the occupants based on radiation using the measured surface temperature of *the ger* envelopes and estimated radiation energy of the stoves. In this calculation, the radiation generated by the stove to the body of the occupant was estimated assuming the omnidirectional emission from the stoves[2] and shape factors for a seated occupant provided by Dunkle [32]. The distance between an occupant and a stove was assumed to be 1.5 and 1.0 m for *Gers* A and B, respectively, considering the layout of the furniture and the lifestyle of the occupants. The emissivity of the *ger* envelope was assumed to be 1.0[3].

Fig. 11 shows the time variation of the estimated MRT during Term CS-fo, in which the occupants stayed in their *gers* throughout the day. Moreover, the spatially averaged air temperature at a height of 0.5 m ($T_{in\text{-}0.5}$) are included for reference. The MRT values exceeded the indoor air temperature by 5–15 ºC. The time patterns of MRT of the *gers* are similar to those of air temperature, except for the time period when the temperature decreased owing to door openings. MRT was always maintained at >20 ºC even though $T_{in\text{-}0.5}$ had gone below 10 ºC in the early morning just before the coal addition.

Regarding the evaluation of indoor thermal comfort, predicted mean vote (PMV)[24], which is derived based on the energy balance of a human body by using four environmental variables (air temperature, humidity, radiant temperature, and wind speed) and two occupants-related variables (metabolic rate and clothing insulation), has been widely used for decades especially for assessment in air-conditioned enclosed spaces. On the other hand, it has been reported that in naturally ventilated rooms and in environments where occupants have a high flexibility of thermal adaptation behaviours, PMV does not always correspond to people's thermal sensation[33]. The surveyed *gers* were heated by a stove, thus they cannot be classified as naturally ventilated rooms. However, the envelopes of the *gers* were not well insulated and airtight, besides, the occupants were exposed to the cold outdoor environment every time they went to the toilet and experienced sudden drops in room temperature. This situation is therefore substantially different from that of a modern air-conditioned room. In addition, the metabolic rate of the occupants varied according to various activities such as eating and sleeping, and they had a high flexibility of thermal adaptation behaviours. Considering such features, for estimating the current thermal conditions, we calculated operative temperature, T_{op} expressed in Eq. (2) rather than PMV for Term CS-fo, in which the *gers* were heated by a coal stove and occupied by residents all day.

[2] These stoves are made of cast iron and are rectangular in shape, with an opening at the top through which coal is fed into the stove. There are no windows on the sides through which the flame can be seen. Given the thermal conductivity of cast iron, it is a reasonable to regard the surface temperature of the stoves as approximately uniform and to treat the long-wave radiation from the stoves as omnidirectional.

[3] The surface area of a seated occupant is only about 1.5 % of the total surface area of the *gers*. Thus, the influence of reflected long-wave radiation upon the *ger* interior surface can be considered negligible.

$$T_{op} = (T_r + T_{in-0.5})/2. \quad (2)$$

Fig. 12 illustrates the probability density distributions (PDDs) and cumulative probability distributions (CPDs) of $T_{in-0.5}$ and operative temperature, T_{op} for Term CS-fo. $T_{in-0.5}$ of *Ger* A ranged from 6 to 29 ºC, being below 18 ºC over half the staying hours in spite of the large heating energy consumption shown in Fig. 7. In contrast, the air temperature of *Ger* B was slightly higher than that of *Ger* A. The value for a CPD of 50% was 22 ºC. Compared with the indoor air temperature, T_{op} of the *gers* ranged from 13 to 37 °C, suggesting effective radiative heating of the stove for occupants even though the indoor air temperature sometimes becomes lower than the modern building standard temperature. In BS-ISO 7730[34], winter comfort criterion in dwellings ranges from 20 to 24 °C [34], and the comfort range of ASHRAE 55-2017[24] is 19.5–24.5 °C. Compared with these standards, the CPDs in Fig. 12 (b) reveal that 74% and 85% of the day for *Ger*s A and B are above the lower limit of the comfort range, respectively. Furthermore, 50% of the time of *Ger* B and 20% of the time of *Ger* A had higher operative temperatures than the upper limit of the comfort range.

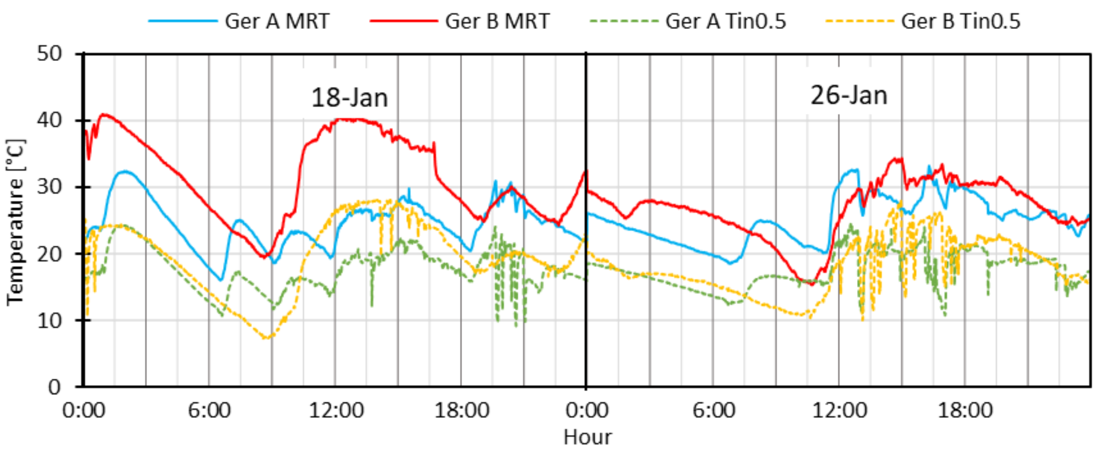

Fig. 11 Time variation of mean radiant and indoor air temperatures during Term CS-fo

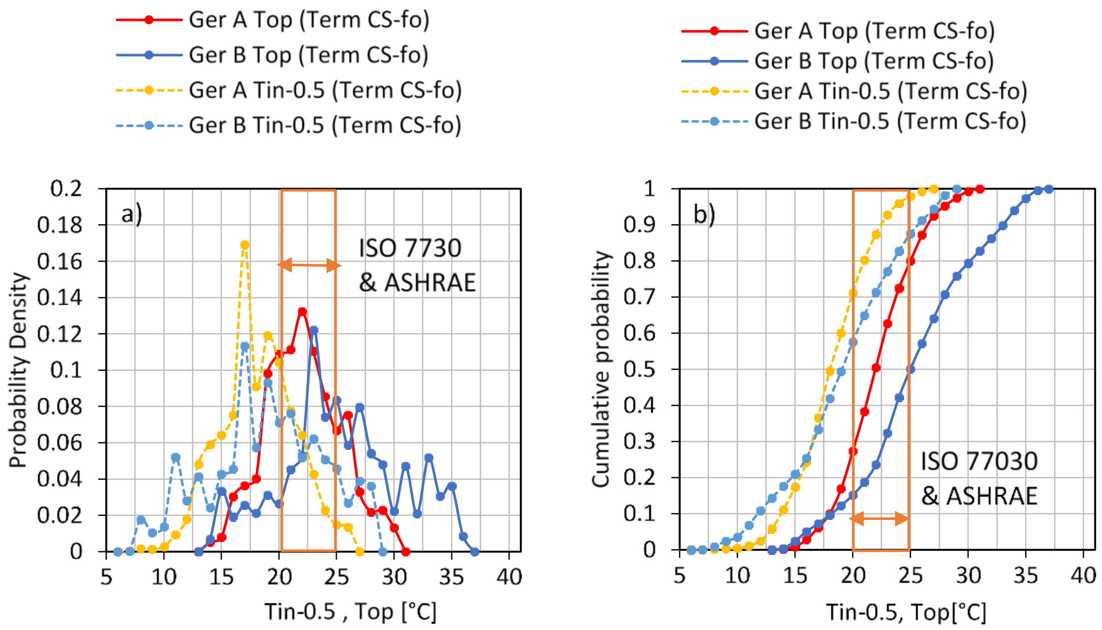

Fig. 12 (a) PDDs and (b) CPDs of the operative temperature (T_{op}) and spatially averaged air temperature at a height of 0.5 m ($T_{in\text{-}0.5}$)

3.8 Thermal characteristics and design of gers

A *ger* is a temporary housing originally tailored to nomadic pastoralism, in which people used to move several times a year from one place to another [7]. This one-room interior space is used for various purposes, i.e., sleeping, family gathering, cooking, and eating[8], but there are no toilets or bathrooms inside the *ger* that are physically connected to the local infrastructure services, such as water access and sewage management. Furthermore, owing to their mobile characteristic, *gers* are made of lightweight local materials that are easy to assemble and disassemble.

On the other hand, Fig. 12—derived from our measurement result—indicates the current *gers* enable to create a relatively comfortable indoor thermal environment in winter in spite of the low performance of thermal insulation and airtightness of the *ger* envelopes. As discussed in Section 3.2, the indoor temperature drops by more than 15 °C instantaneously owing to door opening, and the temperature near the floor is always low (5–18 °C) due to thermal stratification and cold air leakage, occasionally resulting in an out-of-comfort temperature range. To overcome this situation, radiant heating with a fairly high output has been a reasonable choice for occupants as Fig. 11 and 12 suggested.

Purev and Hagishima reported [8] that nowadays the dimensions and materials of each part of *a ger* are highly standardised [21], and people can purchase wooden frames, wool-felt sheets, tarpaulin, doors, and other related parts from different retailers based on their preferences, or they can receive used parts from their acquaintances. In addition, even in the case of large families, people do not modify *gers* to create large and complex indoor spaces but rather build multiple *gers* on a single site[7] . This is consistent with the fact that the current circular floor plan with a radius of ~2.5 m is suitable for securing a sufficient shape factor between a stove and a body of occupants, receiving necessary radiation heat gain, thus, maintaining a comfortable thermal environment for occupants as shown in section 3.7. In other words, the current design of *gers* is based on a high-powered radiation heater installed at the centre to achieve thermal comfort without being affected by low near-floor temperatures and frequent temperature drops caused by poor airtightness and the opening of entry doors. Therefore, replacing current coal stoves with convection-type electric heaters would possibly require the improvement of the insulation and airtightness of *the ger* envelopes to ensure the thermal comfort of occupants who have accustomed to the stoves.

4. Conclusions

To understand the thermal features of traditional housing *ger* heated by a fuel stove under the usual behaviours of occupants, a field measurement was conducted in Ulaanbaatar, Mongolia, in winter, focusing on two *gers* with typical sizes and materials. The findings of this survey are summarised below.

- Daily variations in indoor air temperatures of *gers* varied by household and day and were strongly affected by variations in heating power of stoves, which is influenced by the timing and amount of coal input to the stove by occupants.
- Under the conditions of intense stove heating, the vertical difference in indoor air temperature was large. The air temperature at a height of 1.5 m near the ceiling sometimes exceeded 40 °C, while the air temperature near the floor was always less than 20 °C. This stratified temperature field was more intense when a coal stove was used compared with the use of convection-type electric heaters.
- As a result, the operative temperature in the two *gers* was above the lower limit of the ASHRAE comfort range for 74% and 85% of the overall time. On the other hand, over-heating occasionally occurred, resulting in operative temperatures above the upper limit of the comfort range for 50% and 20% of the overall time owing to the limited function to modulate the heating power of the stoves. In addition, the behaviour of the occupants

to deliberately open the door to let in cold air from outside was observed as a countermeasure to overheating.

Overall, these findings — derived from field measurements — highlight the underlying processes of the unique indoor thermal environment of this traditional temporal housing, demonstrating clear academic contribution and scientific originality. To secure the mobility of a *ger*, thick, stiff, and well-insulated envelopes, like those installed in typical modern buildings in Northern Europe have never been adopted despite the cold climate in Mongolia. Instead, people in Mongolia have always preferred stoves with strong radiation heating devices placed at the centre of the circular plane in *gers* since the inception of nomadic society until today, where urban *ger* districts have developed. The results of the current field measurements unlock the mystery of how Mongolian nomads managed to create a comfortable thermal environment in extremely cold winters while maintaining their mobility. Although the *gers* examined in this paper are traditional houses indigenous to Mongolia, similar circular traditional mobile housing exists, or traditionally existed, in various countries including Hungary, Kazakhstan, Kyrgyzstan, and Afghanistan [18]. The results of this study also provide significant insights into the physical environmental factors behind the design of these other nomadic traditional settlements.

The effectiveness of direct radiant heating with primitive fuel stoves and the instability of their thermal output should also be emphasised. Fuel stoves are very rarely used in modern buildings, and for the building energy simulation (BES) to estimate the heating load—and to assess the indoor thermal comfort level—the room temperature is usually assumed to be maintained at a given temperature. Contrarily, the present results suggest that *gers* stoves—with their very limited degree of control over heat output—can lead to large temporal variations in room temperature, sometimes resulting in air temperatures below the comfort range. Nevertheless, even when the room air temperature is lower than the comfort range, direct radiant heating from a stove can maintain the thermal comfort of the occupants. These facts suggest that the BES—which does not take into account characteristics such as direct radiant heating, quite different from modern air-conditioned buildings—may not adequately reflect the actual situation. Considering that the World Health Organization reports 3 billion people worldwide currently using fuel stoves in their homes for heating and cooking [35], the findings of this study could also be valuable for exploring the indoor thermal environment of various buildings in a wide range of regions.

Finally, considering the future scenario of *gers* for urban settlers in Ulaanbaatar, it would be desirable to replace coal stoves with non-emission devices, such as electrically powered heaters, in order to reduce the severe air pollution and health risks associated with indoor air quality. Given that *gers* are designed around radiant heating, the replacement of coal stoves with electric heating should be combined with improvements in the insulation and airtightness of the *ger* envelopes, which will contribute not only to reducing the additional electricity consumed for heating but also to decreasing the non-uniformity of the room temperature.

Nomenclature

T_{out}	Outdoor temperature
T_{in}	Indoor temperature
$T_{in\text{-}0.5}$	Spatially averaged temperature at a height of 0.5 m
T_{surf}	Surface temperature
T_{op}	Operative temperature
T_r	Mean radiant temperature

Acknowledgements

This research was funded by the JSPS Grant-in-Aid for Scientific Research (C): 19K04730 and Sasakawa Scientific Research Grant of the Japan Science Society. We thank the occupants who collaborated to perform measurements in their *gers*. The research was conducted under the Kyushu University Research Ethical Guidance [36].

References

[1] National Climatic Data Center, Weather Data of Multiple Cities, (2017). www.ncdc.noaa.gov (accessed January 30, 2018).

[2] M. Energy Economic Institute, Mongolia's Energy Efficiency Indicators 2019, (2019).

[3] Energy Charter Secretariat, In-Depth Review of Energy Efficiency Policies and Programmes: MONGOLIA Energy Charter Secretariat 2011, 2011. www.encharter.org (accessed March 15, 2021).

[4] National Statistical Office of Mongolia, Population and housing by census of Mongolia-National report year of 2015, Ulaanbaatar, 2016.

https://1212.mn/BookLibraryDownload.ashx?url=hun_am_oron_suutsnii_2015_toollogo_eng.pdf&ln=Mn.

[5] A.A. Soluyanov, D. Gresch, M. Troyer, Air pollution in Mongolia: Policy brief, 2016.

[6] E. Otgonbayar, T. Matsumoto, G. Khaltai, Study on efficiency of air pollution control measures in ger area of Ulaanbaatar in Mongolia based on field survey, J. Japan Soc. Civ. Eng. Ser. G (Environmental Res. 69 (2013) 259–265. https://www.jstage.jst.go.jp/article/jscejer/69/5/69_I_259/_article/-char/en.

[7] U. Kawagishi, H. Sugimoto, K. Kitano, G. Ishjamts, N. Hirota, Living Environment of Nomads Residing on the Outskirts of Ulaanbaatar, Mongolia Part 2, J. Asian Archit. Build. Eng. 9 (2018) 139–146. https://doi.org/10.3130/jaabe.9.139.

[8] U. Purev, A. Hagishima, A field survey of traditional nomadic dwelling gers used as urban habitats in Ulaanbaatar, Mongolia, Evergreen. 7 (2020) 155–171. https://doi.org/10.5109/4055214.

[9] Japan International Cooperation Agency (JICA), C. and U. Ministry of Roads, Transportation, Development, Ulaanbaatar City Government, The Study on City Master Plan and Urban Development Program of Ulaanbaatar City (UBMPS), Ulaanbaatar, 2009.

[10] S. Ochirbat, Ger Area Redevelopment First Stage Location, Ulaanbaatar, 2013.

[11] 2020 Population and Housing Census of Mongolia /summary/ 2 CONTENTS, 2020.

[12] Ulaanbaatar Electricity Distribution Network, Night Time Electrical Subsidy| tog.mn, (n.d.). http://www.tog.mn/public/newsshow/id/514 (accessed May 27, 2019).

[13] A. Pillarisetti, M. Rongjiang, M. Buyan, N. Boldkhuu, A. Yuma, Y. Xudong, S.R. Kirk, Advanced household heat pumps for air pollution control: A pilot field study in Ulaanbaatar, the coldest capital city in the world, Environ. Res. (2019). https://doi.org/10.1016/J.ENVRES.2019.03.019.

[14] J. Jamsran, Energy sector of Mongolia, Country Report, 2018. https://eneken.ieej.or.jp/data/8044.pdf (accessed May 30, 2021).

[15] B.-E. Bayandelger, Y. Ueda, A. Adiyabat, Experimental Investigation and Energy Performance Simulation of Mongolian Ger with ETS Heater and Solar PV in Ulaanbaatar City, Energies. 13 (2020) 5840. https://doi.org/10.3390/en13215840.

[16] S. Ishikawa, H. Hayama, E. Purev-Erdene, M. Enai, K. Kikuta, A. Kato, Survey report

for indoor environment of settled down type ger in ger area, Ulaanbaatar, Mongolia, in: Summaries of Technical Papers of Annual Meeting, Hokkaido, 2007: pp. 53–54. https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/50691/1/GKKD-2_53-54.pdf (accessed June 17, 2019).

[17] B. Buyantogtokh, Q. Zhang, Investigation on indoor thermal environment of the GERS in Ulaanbaatar during winter: Studies on indoor environments and energy consumption of dwellings in Mongolia, Part 2, J. Environ. Eng. 84 (2019) 245–253. https://doi.org/10.3130/aije.84.245.

[18] G. Tsovoodavaa, I. Kistelegdi, Comparative analysis for traditional yurts using thermal dynamic simulations in Mongolian climate, Pollack Period. 14 (2019) 97–108. https://doi.org/10.1556/606.2019.14.2.9.

[19] World Maps of Köppen-Geiger climate classification, (n.d.). http://koeppen-geiger.vu-wien.ac.at/applications.htm (accessed January 13, 2021).

[20] USAID from the American People, Country Overview, 2017. https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID ATLAS_Climate Risk Profile - Mongolia.pdf (accessed January 13, 2021).

[21] Mongolian Agency for Standardization and Metrology, Mongolian national yurt MNS 0370:2003, (2003). http://www.estandard.gov.mn.

[22] Ulaanbaatar Services Improvement Project, Ulaanbaatar clean air project report, 2015.

[23] Mongolian State Professional Inspection Agency, Сайжруулсан түлш, (2018). http://home.inspection.gov.mn/news/248/single/1376 (accessed November 26, 2020).

[24] ASHRAE, Standard 55 Thermal environmental conditions for human occupancy, 2017. https://www.ashrae.org/about/news/2017/ashrae-publishes-2017-version-of-thermal-comfort-standard (accessed September 15, 2021).

[25] N.W. Tuck, S.A. Zaki, A. Hagishima, H.B. Rijal, F. Yakub, Affordable retrofitting methods to achieve thermal comfort for a terrace house in Malaysia with a hot–humid climate, Energy Build. 223 (2020) 110072. https://doi.org/10.1016/j.enbuild.2020.110072.

[26] Solar reflectivity (R) & solar reflectance index (SRI) by color – dean steel buildings, inc., (n.d.). https://www.deansteelbuildings.com/products/panels/sr-sri-by-color/ (accessed October 21, 2021).

[27] A. Hagishima, J. Tanimoto, Field measurements for estimating the convective heat transfer coefficient at building surfaces, Build. Environ. 38 (2003) 873–881. https://doi.org/10.1016/S0360-1323(03)00033-7.

[28] Mongolian agency for standardization and meteorology, Air quality general MNS 5825:2007, (2007).

[29] M. Gallagher, M. Beard, M.J. Clifford, M.C. Watson, An evaluation of a biomass stove safety protocol used for testing household cookstoves, in low and middle-income countries, Energy Sustain. Dev. 33 (2016) 14–25. https://doi.org/10.1016/j.esd.2016.03.008.

[30] P.F. Incropera, D. P.DeWitt, Fundamentals of Heat and Mass Transfer 5th edition, 2002.

[31] M. Möhlenkamp, M. Schmidt, M. Wesseling, A. Wick, I. Gores, D. Müller, Thermal comfort in environments with different vertical air temperature gradients, Indoor Air. 29 (2019) 101–111. https://doi.org/10.1111/ina.12512.

[32] R. V. Dunkle, Configuration factors for radiant heat-transfer calculations involving people, J. Heat Transfer. 85 (1963) 71–76. https://doi.org/10.1115/1.3686012.

[33] G.S. Brager, R.J. de Dear, Thermal Adaptation in the Built Environment: a Literature Review Publication Date, Energy Build. (1998) 86–96. https://doi.org/10.1016/S0378-7788(97)00053-4.

[34] BS EN ISO 7730 : 2005 Ergonomics of The Thermal Environment, British Standard Institution, 2005. https://infostore.saiglobal.com/en-us/Standards/BS-EN-ISO-7730-2005-303598_SAIG_BSI_BSI_702825/ (accessed January 18, 2021).

[35] WHO, Household fuel combustion WHO guidelines for indoor air quality, 2014.

[36] K.U, Responsible Conduct of Research, (n.d.). https://edu.aprin.or.jp (accessed February 14, 2021).

[37] Japan Society of Thermophysical Properties, Thermophysical Properties Handbook, Yokendo, (written in Japanese), 2008.

Credit authorship contribution statement

Uelun-Ujin Purev: Conceptualization, Collected and analysed data and Writing-original draft. **Aya Hagishima:** Conceptualization, Supervision and Writing-review and editing. **Munkhbayar Buyan:** Writing-review

APPENDIX

Although we did not directly measure the heating power of coal stoves, the thermal radiation emitted from a stove was estimated based on the measured temperatures of ceiling surface (H = 1.76 m for *Ger* A and H = 1.65 m for *Ger* B), indoor air temperature near the ceiling surface (H = 1.5 m) and outdoor air temperature based on the assumptions of one-dimensional thermal conduction of the *ger* envelopes and omnidirectional radiation emission from stoves, as described below.

Assuming one-dimensional heat transfer through the ger envelope, the energy balance can be expressed by the following equations:

$$q + R = \alpha_{out}(T_{surf,out} - T_{out}) \quad \text{(A1)}$$

$$q + R = \lambda(T_{surf,in} - T_{surf,out})/\Delta x \quad \text{(A2)}$$

$$q = \alpha_{in}(T_{in} - T_{surf,in}) \quad \text{(A3)}$$

where q is the conduction heat flux [W/m^2], *and* R is the radiation flux on the surface of *the ger* envelope delivered from a stove [W/m^2]. T_{in} and T_{out} are the indoor and outdoor air temperatures, respectively. $T_{s,in}$ and $T_{s,out}$ are the surface temperatures of the ger envelope for the indoor and outdoor sides, respectively. α_{in} and α_{out} are the convective heat transfer coefficients, λ is the thermal conductivity, and Δx is the depth of the ger envelope. By substituting measured values of T_{in}, $T_{surf,\ in}$ and T_{out}, assuming α_{in} = 5 W/(m^{2}K), α_{out} = 10 W/(m^{2}K), λ = 0.127 W/(m K) [37], Δx = 0.03 m [8], heat fluxes q and R can be estimated as below.

$$q = (T_{s,in} - T_{s,out})/(U^{-1} + U_{out}^{-1}) \quad \text{(A4)}$$

$$R = U_{out}(T_{s,in} - T_{s,out}) - q \quad \text{(A5)}$$

$$\text{where } U^{-1} = \frac{1}{\alpha_{in}} + \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{out}} \quad \text{(A6)}$$

$$U_{out}^{-1} = \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{out}} \quad \text{(A7)}$$

The estimated radiation flux reaching the internal surface of the *ger* envelope was exchanged with the radiation flux on the normal plane of the vector from a stove to the measurement point of a *ger* indoor surface using Eq. (A8).

$$R_{\circ} = Rcos\theta \quad \text{(A8)}$$

Assuming that the radiation from a stove is omnidirectional from a point source, the radiative heating power of a stove H_{stove} [W] was obtained by the surface integration of a hemisphere as follows:

$$H_{stove} = 2\pi L^2 R_{\circ} \quad \text{(A9)}$$

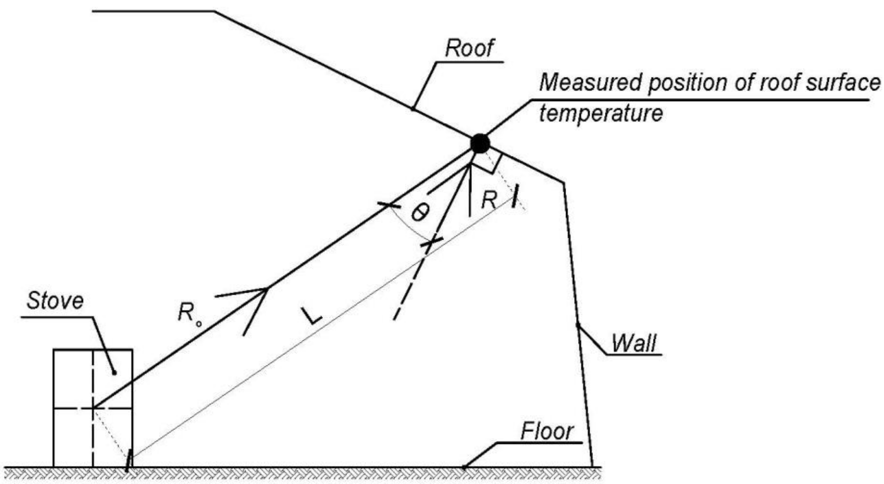

Fig. A.1 Schematic diagram for estimation of radiation heating power of a stove

Conflict of Interest (Please upload in Word format)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

None

Credit authorship contribution statement

Uelun-Ujin Purev: Conceptualization, Collected and analysed data and Writing-original draft. **Aya Hagishima:** Conceptualization, Supervision and Writing-review and editing. **Munkhbayar Buyan:** Writing-review

Click here to access/download
Supporting File
Supporting files .docx

Indoor thermal environment of Mongolian traditional mobile housing used as urban habitat in winter

Uelun-Ujin Purev[1*], Aya Hagishima[1], Munkhbayar Buyan[2]

[1]Interdisciplinary Graduate School of Engineering Science, Kyushu University, Japan

[2]School of Civil Engineering and Architecture, Mongolian University of Science and Technology, Mongolia

*E-mail: ujin@kyudai.jp

Telephone: +81 080 8703 7512

Abstract: *Gers*, which are traditional mobile tents used by nomadic society of Mongolia, are currently used for urban habitats, and pollutants emitted from coal stoves used in urban *gers* are one of the major causes of air pollution in Ulaanbaatar in winter. Replacing coal stoves with low-emission heating devices in *ger* housing is, therefore, a pressing issue. Nevertheless, fuel stoves have been used in *gers* for generation since the nomadic period, and a previous study reported that urban *ger* residents were generally satisfied with the indoor environment heated by a coal stove. Against this background, the present study aimed—based on field measurements—to characterize the spatial and temporal characteristic of the thermal environment within gers heated by coal stoves, to provide insights for smoothly shifting the current stoves to electric heating. The measurement results showed diverse daily fluctuations of indoor temperature among days and households dominated by the unstable heating power of stoves, which is influenced by the occupants' style of coal input. The indoor air temperature occasionally resulted in outliers beyond the comfort temperature range. By contrast, the operative temperature was above the lower limit of the ASHRAE comfort range for over 70% of the time owing to the direct radiation of stoves, highlighting that the current design of *gers* and the use of fuel stove are reasonable to achieve a comfortable indoor environment in winter under the conditions of nomadic mobile dwellings, which necessitates a lightweight envelope with poor insulation performance.

Keywords: Indoor thermal environment; traditional housing; field measurement; cold climate; solid fuel stoves

1. Introduction

In Mongolia, located in the northern part of East Asia, space heating is indispensable because of the cold winters with temperature reaching below −40 °C [1]. Space heating consumes over one-third of the energy used in households and the commercial sector in this country [2,3]. Furthermore, 58% of the heating energy of households relies on coal, causing severe air pollution in the capital city, Ulaanbaatar, in winter [4]. In fact, Soluyanov et al. [5] reported that 80% of the air pollution is caused by coal stoves used in houses in urban areas. Otgonbayar et al. [6] conducted a cost–benefit analysis of three air-pollution countermeasures, including introducing improved low-emission coal stoves, replacing coal stoves with electric heaters, and relocation from detached houses to suitably insulated apartments. They pointed out that replacing coal stoves with electric heaters in detached houses will significantly reduce the pollutant emission, although, this would require the considerable investment in the construction of a new power plant based on the cost-benefit analysis. These facts suggest that energy saving and emission reduction of the heating in houses are pressing issues. However, it is not easy for Mongolia to implement standard approaches which have been taken in developed countries, such as improvement of building insulation performance and introduction of energy-efficient and low-emission heating devices, because of factors specific to developing countries. One of the factors is related to many detached houses located in *ger* districts, which are unplanned residential districts with insufficient urban infrastructure for water services, sewage treatment, and heating. Note that a *ger* refers to a traditional portable tent; it was originally a home for nomadic people but is currently used as an urban habitat [7]. In Ulaanbaatar, 58% of the total households lived in *ger* districts [4], and 52.4% of the households in *ger* districts lived in *gers* in 2016 [4]. Furthermore, most of dwellings in *ger* districts rely on coal stoves for space heating.

With such background, Purev and Hagishima [8] surveyed residents of 47 *gers* located in Ulaanbaatar to grasp the current situation of *ger* envelopes, heating devices, and fuel consumption and the perceptions of living conditions. Their survey highlighted the excellent affordability of *gers* for low-income households and excess coal consumption owing to the low insulation envelope. In this survey, more than 90 % of respondents stated that indoor thermal conditions were occasionally either too hot or too cold because of the frequent inflow of cold air when occupants open a door to go to a toilet or other places. Even though urban *gers* are intended as temporary housing during the transition from nomadic migration culture to settlement culture [9,10], considering the fact that *gers* are home to ~114,000 urban households [11], suitable actions to reduce pollutant emissions without worsening the indoor thermal environment are urgently required in the short term. To do this, switching from coal stoves to electric heating in *ger* housing is a possible scenario. In fact, the Mongolian government started a project that used excess electricity for heating during the night in *ger* districts to encourage the use of electric heaters instead of coal stoves in 2017 to counter air pollution [12]. Pillarisetti et al. [13] performed a long-term measurement of the performance of electric heat pumps tailored to cold climates in self-built detached houses and *gers* and reported acceptably moderate performance of the heat pumps. Note that 90% of the electricity in Mongolia was generated by coal-fired thermal power plants, and the contribution of renewable energy was only 8% in 2018 [14]. On the other hand, Bayandelger et al. [15] conducted a field experiment to assess the feasibility of electric thermal storage utilizing photovoltaics (PV) in a *ger* with additional insulation. They pointed out that 31% of the energy demand of an electric thermal storage heater could be supplied by a PV system.

Nevertheless, the use of fuel stoves in *gers* has been practised for a long time during and since the nomadic period, and about 80% of people who lived in *gers* stated that they were satisfied with the current indoor thermal environment of their *gers* heated by a coal stove according to the survey of Purev and Hagishima [8]. Therefore, for smoothly shifting the current stoves to electric heating, it is vital to understand the characteristics of the current indoor thermal environment of *gers* heated by fuel stoves to which many people have been exposed. Very few studies have reported on the indoor thermal environment of *gers* heated by a stove. Ishikawa et al. [16] measured the indoor temperature of six *gers* in Ulaanbaatar in winter and reported a large vertical temperature difference owing to the low insulation performance. Buyantogtokh and Zhang [17] measured indoor temperatures and relative humidity as well as CO and CO_2 concentrations for 10 *gers* for a total of 14 days in winter, and estimated the ventilation rates. They presented box plots of the indoor air temperature and relative humidity at 1.2 m height and revealed a wide range of indoor air temperatures from 8 °C to 41 °C. Furthermore, they plotted the measured data on psychrometric charts and concluded that low and high indoor temperatures and low relative humidity were outside the ISO7730 standard thermal comfort range. Tsovoodavaa and Kistelegdi [18] estimated the heating and cooling energy for nine types of *gers*, including a current Mongolian *ger*, as well as similar traditional temporary housing used in other countries based on the building energy simulation approach.

In spite of such attempts, the detailed indoor thermal features of current *gers* heated by a coal stove have not been well documented in either English or Mongolian. One of the knowledge gaps is the temporal and spatial behaviour of indoor thermal conditions. It may be assumed that *gers* experience frequent room-temperature drops during the winter months due to the door being opened for use of the outdoor toilets. In fact, the survey by Purev and Hagishima [8] indicated that 80% of *ger* residents considered the room temperature in their ger to be occasionally too hot or too cold. However, the detailed temporal variation of room temperature has not been clarified by actual measurements. The spatial distribution of the indoor temperature, including both surface and air, has been insufficiently examined, even though strong heterogeneity of the temperature field is expected due to the low insulation performance of *ger* envelopes compared to standard modern buildings. Furthermore, little attention has been directed toward the influence of direct radiant heating from primitive coal stoves on the indoor thermal environment, which is extremely rare in modern air-conditioned buildings.

Under these circumstances, the objective of this study is to elucidate the features of temporal and spatial variation of the indoor thermal environment of typical urban *gers* and to improve understanding of the thermal influence of radiant heating from primitive coal stoves in winter. To do this, we conducted *in situ* measurements of indoor air temperature at multiple positions in two typical urban *gers* for 12 days. To understand the heating characteristics of coal stoves, the stove of one *ger* was replaced by an electric convection-type heaters during the last two days of the period. Section 2 describes the details of the methodology used in the field measurements. Section 3 reports the observed spatiotemporal distribution of air temperature and the analysis of space heating power. The characteristics of the indoor thermal environment for occupants are also discussed in relation to the current *gers*' design. Section 4 summarises the findings of this study.

2. Methodology

2.1 Location and period of field measurement

The two *gers*, named as *Ger* A and *Ger* B, located in the Songinokhairkhan district (47 °58′ N 106 °49′ E), which is in the northwest outskirt of Ulaanbaatar with a distance of 11 km from the city centre, were selected for the measurement of the indoor thermal condition. The locations of the surveyed *gers* are shown in Fig. 1. The two surveyed *gers* were located in the same plot. As the *gers* have no toilet, the occupants of these *gers* share an outhouse, which includes a pit latrine in the same plot.

Table 1 shows the measurement period, which was basically classified into two, namely Term CS of 10 days as baseline condition of coal stove heating for *Ger* A and *Ger* B, and Term EH of extra 2 days for *Ger* B with electric heating. Throughout the entire measurement period, the occupants of the two *gers* continued their usual routines; hence, residents of the *gers* occasionally travelled out of the house and left the *gers* unoccupied. During two days of Term CS and one day of Term EH, however, there was always at least one occupant present in the *gers*. These periods are named Term CS-fo and Term EH-fo. In the following sections, the data of Terms CS-fo and EH-fo are mainly used for analysing the detailed time patterns of indoor thermal variables as the result of occupants' heating control to satisfy their thermal sensation. On the other hand, the data of the entire period are used mainly to understand the general thermal behaviours of the *gers*.

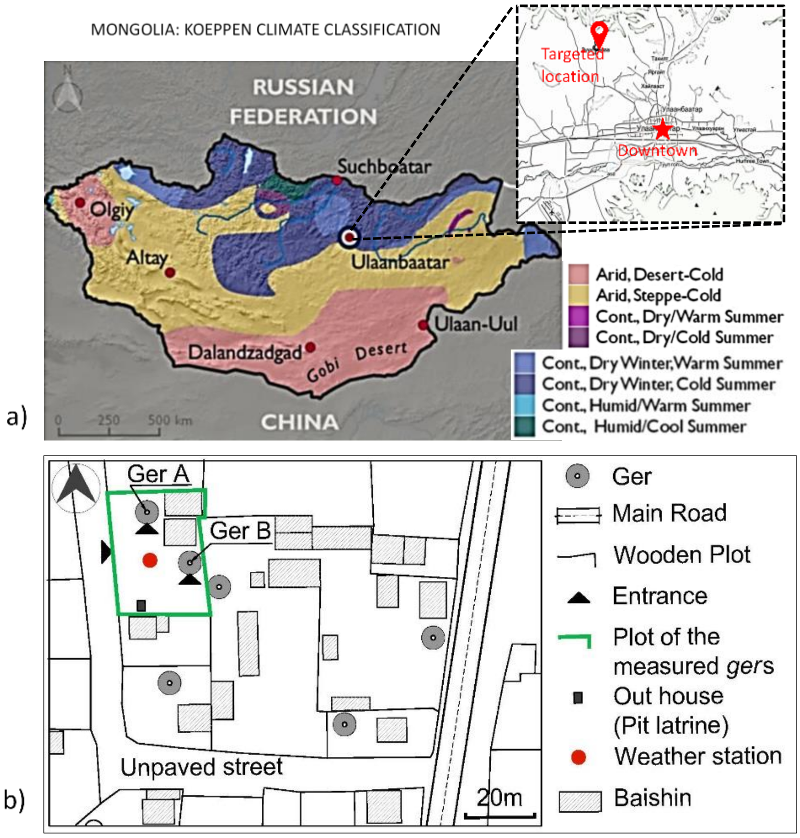

Fig. 1 (a) Measurement location on the map of Köppen climate classification [19,20] (b) Site plan of the plot in which the surveyed *gers* are located.

Table 1. Measurement period

	Measurement period	*Remark*
Term CS	January 18 – January 27, 2020 (10 days)	Measurement of *Ger* A and *Ger* B with the coal stove heating
Term EH	January 28 – January 29,2020 (2 days)	Measurement of *Ger* B with electric heaters
Term CS-fo	January 18 and 26, 2020	Both the *gers* were always occupied by at least one resident.
Term EH-fo	January 29, 2020	Ger B was always occupied by at least one resident.

2.2 Details of the surveyed gers

The two *gers* were selected because of their typical features, which mostly follow the national standard [21]. Table 2 lists the specifications of the *gers* and occupants. Fig. 2 shows photographs of the exterior and interior of the two *gers*. Fig. 3 illustrates the section and layout of the *gers.* Both the *gers* having almost same size are categorised as ‘5-wall’, which is the most popular size according to previous survey [8]. The envelope of the *gers* comprises a thin white cotton sheet for the outermost cover, a tarpaulin sheet, and two layers of wool-felt sheet, known as *Esgii*, for insulation. The major components of *Ger* A have been used for 40 years, and they moved to the current location 7 years ago. *Ger* B has been used for 2 years at the same location. It is noteworthy that the thermal properties of the envelope of these two gers, which we could not measure in this study, are probably different because of their different durations of use; this difference is similar to the difference between various insulation materials.

Table 2. Characteristics of the surveyed *gers*

	***Ger* A**	***Ger* B**
Number of occupants	2	4
Adult	2	1
Children	0	3
Ger volume [m^3]	50.02	47.01
Envelope surface [m^2]	82.33	79.06
Floor Area [m^2]	27.5	25.8

Fig. 2 (a) Exterior of *Ger* A, (b) exterior of *Ger* B, (c) interior of *Ger* A, (d) interior of *Ger* B (e) *Ulzii* stove used at *Ger* A, (f) *Khas* stove used at *Ger* B, and (g) electric heaters used at *Ger* B during Term EH

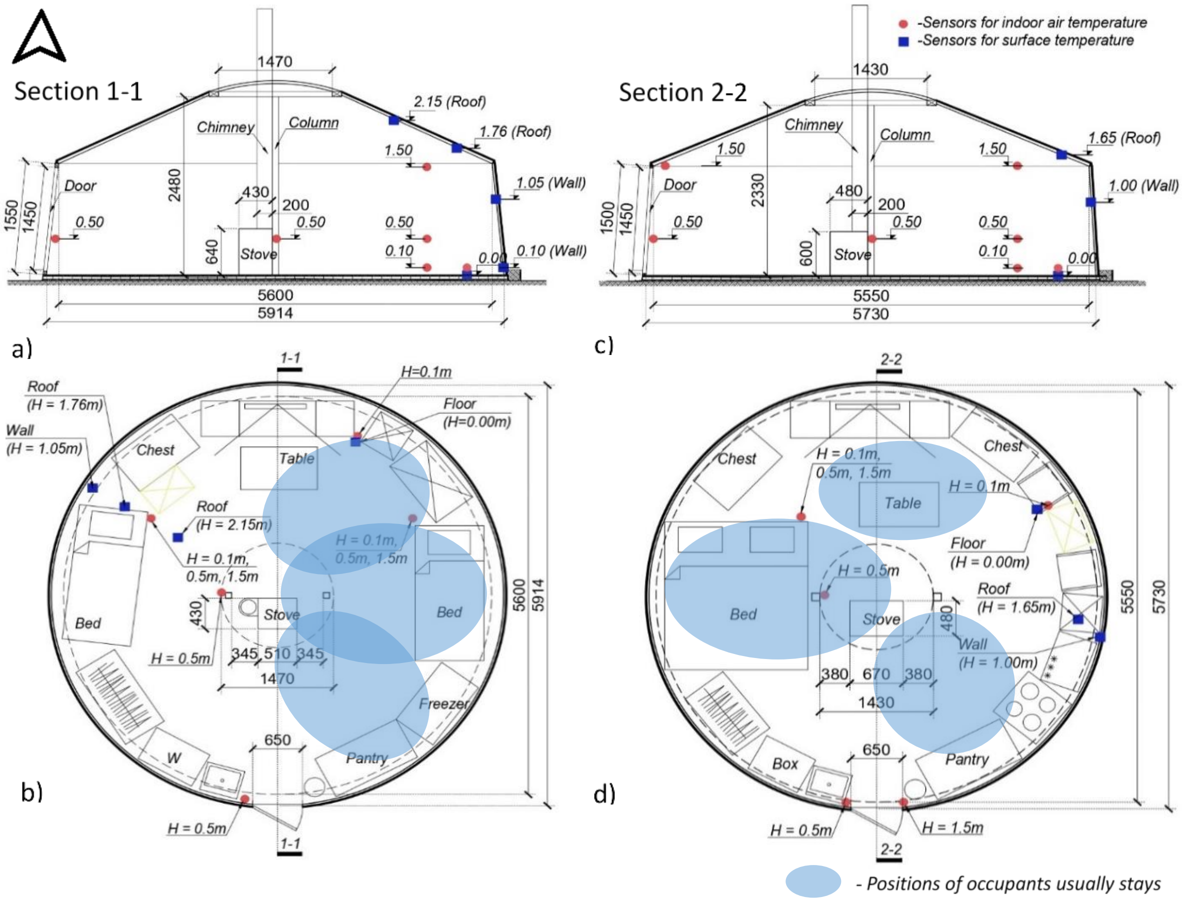

Fig. 3 (a) Section of *Ger* A, **(b)** layout of *Ger* A, **(c)** section of *Ger* B, and **(d)** layout of *Ger* B

The specifications of the heating devices used in the *gers* are listed in Table 3. The family of these two *gers* used coal stoves with top-lit-updraft design, which are commonly called as "improved stoves" in Mongolia [22]. In both the *gers*, smokeless coal was used owing to the "smokeless fuel" project which banned the use of raw coal in the city[23]. During Term EH, we replaced a coal stove with two electric ceramic fan heaters in *Ger* B. To avoid accidental fires caused by the electrical leakage of aging distribution systems, thermostats were attached to the electric heaters, set to 25 °C based on the range of acceptable operating temperature suggested by ASHRAE 55 [24].

Table 3. Specifications of heating devices used in the *gers*.

	***Ger* A**	***Ger* B**	***Ger* B**
Period	Term CS	Term CS	Term EH
Type of heating device	Improved coal stove	Improved coal stove	2 ceramic fan heaters with thermostats (set to 25 °C)
Model of heating device (Manufacture)	Ulzii (Royal ocean LLC)	Khas (Selenge construction LLC)	MDN-RD114 (Mei Ling Ltd.)
Heating Power	6.5 kW	7.5 kW	2 level (1.6 kW, 3.2 kW) for each heater

2.3 Instrumentation

The measurement instruments used in this survey were selected for its appropriate accuracy and low susceptibility to noise in the field, and similar to those widely employed for indoor thermal measurement in buildings [25]. The measuring instruments are listed in Table 4. Outdoor temperature (T_{out}), relative humidity (RH), and solar radiation were measured at a height of 2 m inside the plot as reference weather conditions. Temperature of the indoor air, floor surface, and internal surfaces of *ger* envelopes were measured at multiple positions at each *ger*. The measurement positions inside the *gers* are shown in Fig. 3. The electricity consumption of the ceramic fan heaters of *Ger* B was also monitored during Term EH. All the aforementioned measurement items were recorded every 1 min. In addition to the environmental variables, the authors questioned the average daily coal consumption of the occupants.

Table 4. Measuring instruments and accuracy of sensors.

Measurement items	**Sensors and loggers**	**Range and accuracy**
Outdoor air temperature, relative humidity	HOBO U30 Weather Station Data logger & Sensor S-THB-M002	−40 °C to 75 °C ±0.21 °C-over 0 °C to 50 °C
Solar radiation	S-LIB-M003 Silicon Pyranometer	±10 W/m^2
Indoor air temperature (9 positions at ***Ger*** A, 7 positions ad ***Ger*** B)	T-type Thermocouple (ϕ = 0.1 mm), HIOKI logger LR8432 Z2015-01	−40 to 125 °C ±0.5 °C
Surface temperature (5 positions at *Ger* A, 3 positions ad ***Ger* B)**	T-type Thermocouple (ϕ = 0.1mm) + HIOKI logger LR8432 & Z2015-01	−40 to 125 °C ±0.5 °C
Electricity consumption of heaters (Term EH, ***Ger*** B)	Electricity monitor (OWL+USB)	NA

3. Results and discussion

3.1 Climate conditions

Fig. 4 shows the outdoor weather conditions for the entire measurement period. The data of the spatial averages of the indoor air temperature of the *gers* are also included for reference. As can be seen from the figures, the outdoor temperature shows a periodic diurnal cycle, ranging between −2 and −27 °C, with an average of −17 °C. The daily maximum and minimum values for each day slightly differed, and the latter 5 days showed relatively high daily maximum temperatures. The outdoor relative humidity showed an opposite trend of air temperature as expected, ranging from 43% to 85%. Unfortunately, solar radiation data were not available for half of the measurement period owing to technical issues. The data of the remaining 6 days indicated symmetric daily variation, suggesting clear sky conditions.

Regarding the indoor air temperature, the values of the two *gers* were always higher than the outdoor temperature owing to space heating, and the difference between the indoor and outdoor temperatures ranges from 15 to 47 °C. The minimum indoor air temperatures of *Gers* A and B were 2 and 5 °C, respectively, and the maximum temperatures were 32 and 30 °C, respectively, during the measurement.

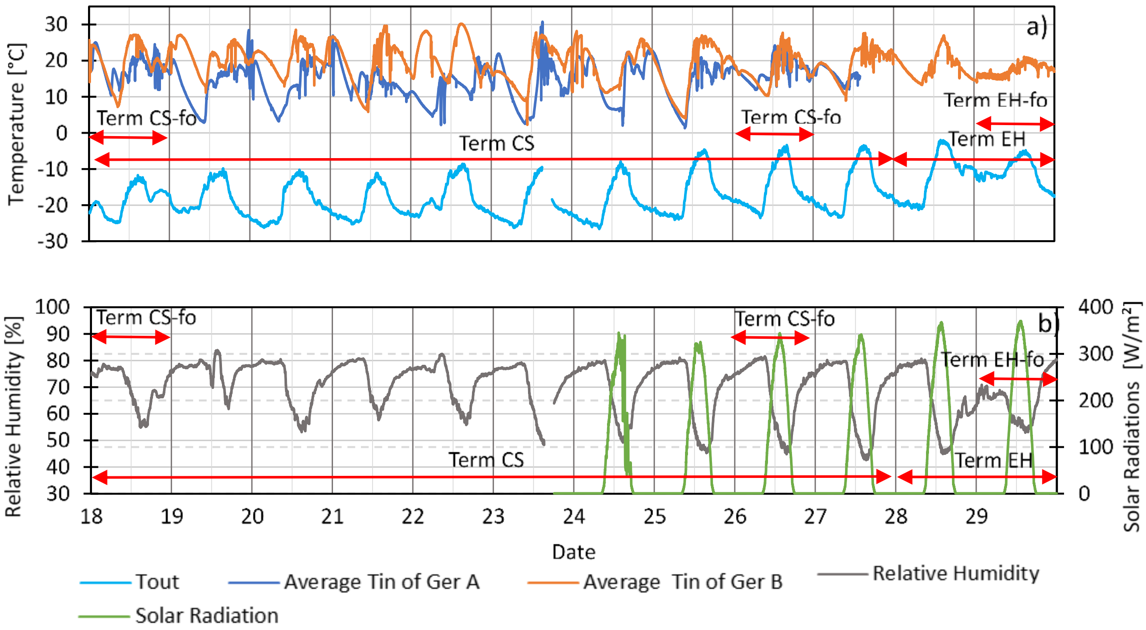

Fig. 4 Time variations of (a) Outdoor air temperature (Tout) and spatial average of the indoor air temperature (Tin) of *Gers* A and B, (b) relative humidity of outdoor air environment and global solar radiation for the entire period.

3.2 Detailed time patterns of indoor temperature during Term CS-fo and EH-fo

Figs. 5 show the temperatures of the indoor air and surfaces observed at multiple positions every 1 min during Term CS-fo and EH-fo, in which the *gers* were occupied by residents all day. The estimated radiation energy of stoves (*See* Appendix) and the electricity consumption of ceramic fan heaters are also included in Fig. 5.

First, for *Gers* A and B during Term CS-fo, the measured indoor air and surface temperatures exhibited similar fluctuation patterns with the same time cycle of 3–9 h. In addition, the time of peak occurrence and the magnitude of fluctuation differed between the two *groups* for two days. Furthermore, such fluctuation patterns with multiple peaks in a day were different from the diurnal cycles of both the outside air temperature and solar radiation with a single peak. Such diverse daily patterns of indoor air temperature with multiple peaks are supposed to be related to the occupants' behaviours to add fuel to burning stove in various timings. In other words, the aforementioned time cycle of 3–9h roughly matches the frequency with which occupants add coal in the stove. In fact, occupants of *Ger* B with longer time scale of the fluctuation patterns explained to the authors that they tended to add large amount of fuel at one time and not add fuel until the fuel is fully burned out.

In *Ger* A, the position 1.5 m and 0.5 m laterally from the stove exhibited the largest indoor air temperature fluctuation of 13 and 40 °C while the level at 0.1 m exhibited the smallest temperature variation of 5 and 19 °C. Such a large vertical temperature difference is consistent with previous observations [16] and is believed to be due to the radiant heating of coal stoves and to heat loss through the *ger* envelopes. The temperature near the door exhibited sudden drops, which are mainly caused by door opening when someone enters or exits the *ger*. On the other hand, on 26 January, occupants frequently opened doors in the afternoon around an hour to ventilate and decrease the indoor air temperature to avoid overheating. Such behaviour was observed on other days when the indoor air temperature was too high. The wall and roof surface temperatures were similar to the indoor air temperature, which was caused by the strong radiation emitted from the stove. Similar tendencies were observed in *Ger* B when a coal-burning stove was used.

During Term EH with electric heaters, the thermostat was set at 25 °C therefore, the heaters were repeatedly and automatically switched on and off at intervals of 15–20 min during the day. As a result, the indoor temperature at 1.5 m exhibited oscillation at ~3 °C when there was fluctuation in the electricity consumption.

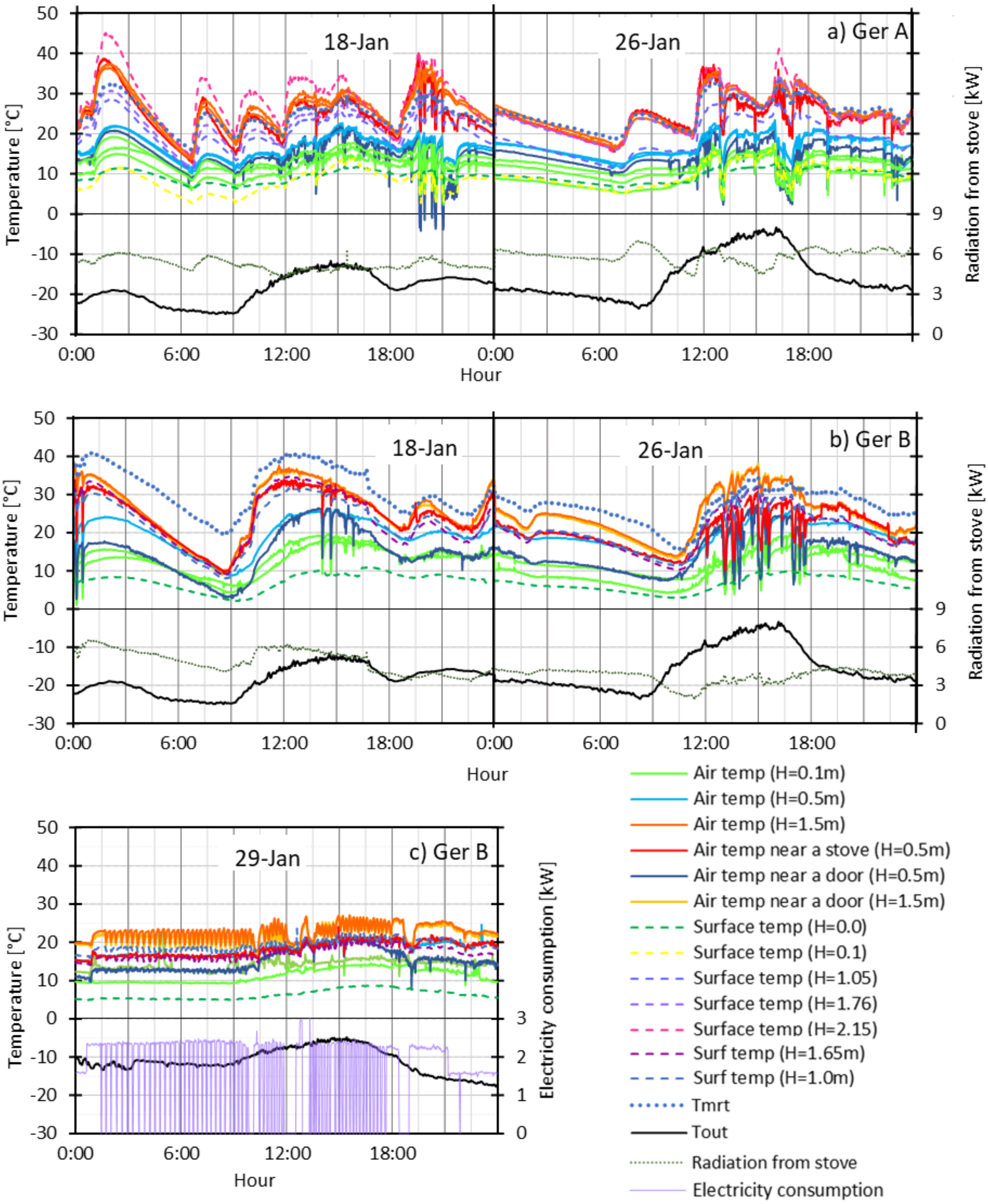

Fig. 5 Air and surface temperatures at various positions inside (a) Ger A heated using a coal stove (Term CS-fo), (b) Ger B heated using a coal stove (Term CS-fo), and (c) Ger B heated using electric heaters (Term EH-fo).

3.3 Range of indoor temperature under the different outdoor air temperature

Fig. 6 shows the range of spatially averaged indoor air temperature against various outdoor air temperature T_{out} and sol-air temperature T_{sol}, respectively, based on the data of 10-minute average. T_{sol} is a simplified index with a temperature unit for considering the influence of both outdoor air temperature and heat gain of the solar radiation, expressed as Eq. (1).

$$T_{sol} = T_{out} + \frac{a \cdot SR}{h} \qquad (1),$$

where *a* is solar absorptivity of the ger envelope assumed to be 0.52 [26]; *SR* is global solar radiation [Wm^{-2}]; *h* is convection heat transfer coefficient of external surfaces of the *gers*, assumed to be 10 W $m^{-2}K^{-1}$ [27].

As can be seen from the figures, the indoor temperature was maintained in the range of 5 to 30 °C by heating while the outdoor temperature was in the range of –25 to –5 °C. As already shown in Fig.5, the time variation of the indoor temperature in both Term CS and EH was strongly influenced by the heating and showed very different tendencies from the daily variation of the outdoor temperature, therefore it is reasonable that there is little correlation between the T_{in} and T_{out} for both the *gers*. Similarly, there is little correlation between T_{in} and T_{sol}. Nevertheless, under conditions where T_{out} is above –10 °C and T_{sol} is above 10 °C, the indoor temperature was maintained at a relatively high level. However, considering that the times of day when the outdoor temperature is high or the solar radiation is high are generally coincident with the times of day when the occupants were active and preferred to keep the indoor temperature high, the effect of the heating devices is supposed to be also significant rather than outdoor conditions.

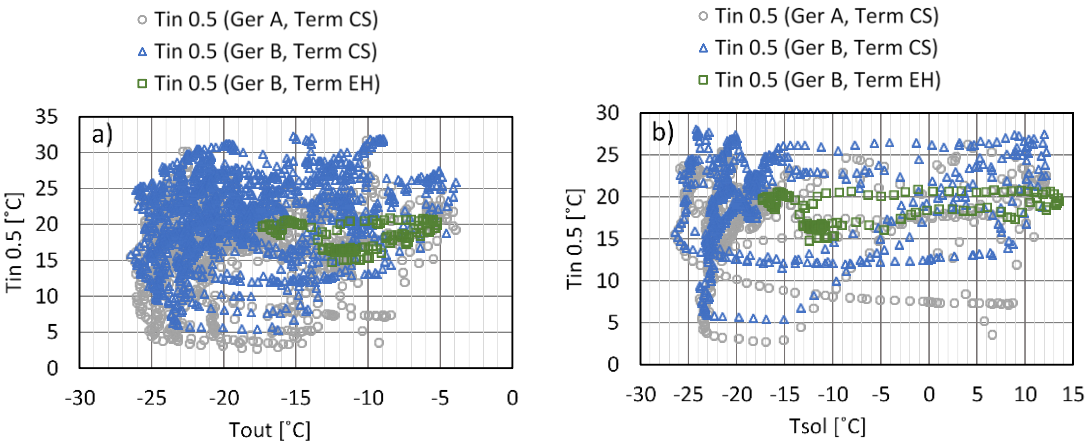

Fig. 6 (a) Scatter plot between outdoor air temperature (T_{out}) and indoor air temperature height of 0.5 m (T_{in} 0.5) (b) Scatter plot between Sol-air temperature (T_{sol}) and indoor air temperature height of 0.5m (T_{in} 0.5)

3.4 Heating energy consumption

The initial time when the estimated radiation heat of the stoves and indoor air temperature starts to increase is assumed to coincide with the timing of the fire ignition as mentioned before. Thus, the number of multiple local negative peaks of radiation energy can be recognised as the number of fire ignitions accompanied by fuel addition. With this assumption, we estimated the number of fire ignitions per day (Table 5). Although both the *gers* used stoves categorised as "improved stoves" having similar heating power, the result indicated the clear difference in usage style of the occupants.

Table 5. Daily number of fire ignitions of coal stoves

	***Ger* A**	***Ger* B**
Average	4.0	2.5
Standard deviation	1.2	0.8

Fig. 7 shows the daily average electricity consumption of the electric heaters of Term EH and the daily average of the estimated radiation energy of the stoves of Term CS. Moreover, the heating degree hours (HDH)—assuming a reference set point of 18 °C, the lower limit of indoor air temperature according to the Mongolian Standard [28]—was included for comparison. The occupants of the *gers* explained that they used coal of 25 kg on a daily basis, which is equivalent to 5.78 kW considering a calorific value of 20 MJ/kg. In contrast, the average estimated radiation heat of the stoves for the entire period was 5.08 and 4.23 kW for *Gers* A and B, respectively. Meanwhile, assuming that the stove surface and indoor air temperatures were 200 [29] and 20 ºC, respectively, we can estimate convection heat between the stove and indoor air to be 1.49 and 1.83 kW for these two *gers*, considering a convection heat transfer coefficient of 6.9 W/m^2K, which is determined by the relation between the Nusselt number, Grashof number, and Prandtl number for the natural convection of a flat plate [30]. It indicates that the averaged total heating power was 6.57 and 6.06 kW for *Gers* A and B, respectively, and the contribution of radiation to the total heating power of the stoves was around 77% and 70%, respectively. Although these values should be treated as approximations, the order is similar to both the calculated values based on the weight of coal used daily and the specifications of the manufacturers of the stoves (A: 6.5 kW and B: 7.5 kW).

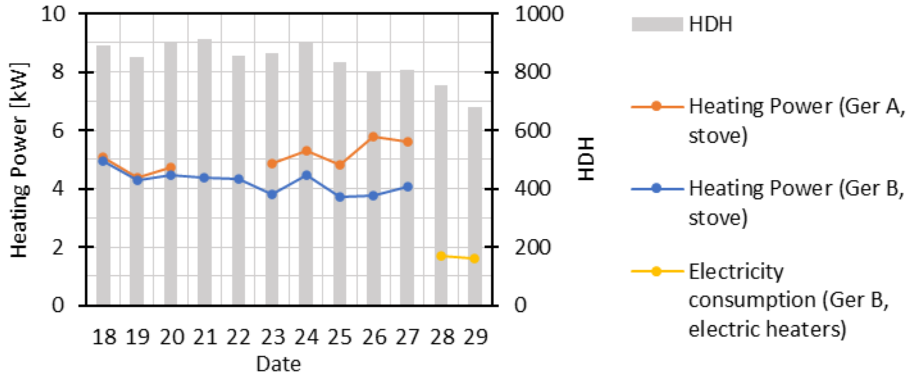

Fig. 7 Daily HDH, estimated radiation heating power of stoves, and electricity consumption of heaters

On the other hand, the electricity consumption of Term EH was about 1.65 kW, which was less than half of the estimated radiation heat, less than one-third of the heating power calculated from coal use, and the values mentioned in the specifications of the manufacturers. In contrast, HDH ranged from 800 to 950 during Term CS, and it decreased by ~17% for Term EH. This implies that the coal stoves consumed an excess amount of energy compared to the electric heaters.

Such excess energy consumption is partly caused by the primitive function of the stoves to module the intensity of the coal combustion according to the indoor thermal conditions. The behaviour of the occupants to intentionally open doors to avoid overheating, shown in Fig. 5a, can also be recognised as a limitation. In contrast, ceramic fan heaters connected with a thermostat showed reasonable performance in realising a stable indoor air temperature during Term EH-fo, as shown in Fig. 5c. This feature suggests that considering energy saving and emission reduction of the current coal stoves based on the change in the behaviour of the occupants is challenging.

3.5 Spatial heterogeneity of indoor air temperature

Fig. 8 shows the relationship between the spatially averaged indoor air temperature at a height of 0.5 m (hereafter, $T_{in-0.5}$) and the standard deviation of the indoor air temperature of all the measurement positions for Terms CS and EH. In addition, Fig. 9 shows the comparison of the spatially averaged indoor air temperature at a height of 0.5 m with other two levels (0.5 and 1.5 m). To reduce the influence of the transient temperature drops owing to the short-term door openings, 10-minute averaged values were used for these graphs.

As shown in Fig. 8, during Term CS with coal stoves, the spatial nonuniformity of the indoor air temperature increases with $T_{in-0.5}$. In contrast, the standard deviation decreases with the decrease in $T_{in-0.5}$ caused by the fire extinction of the stoves. The linear relations illustrated in Fig. 9 indicate that the stratified temperature profiles owing to the buoyancy force are intensified with an increase in $T_{in-0.5}$ caused by heating. Fig. 9 indicates that the temperature differences between the levels of 0.1 and 1.5 m were ~12 and 18 °C under the conditions of $T_{in-0.5}$ = 20 and 30 °C, respectively. On the other hand, ASHRAE 55-2017[24] indicated that the vertical air temperature difference between the head and ankle levels should not exceed 3 °C for seated occupants and 4 °C for standing occupants for the thermal comfort condition. Although recent studies, such as Mohlenkamp et al. [31], reported that the acceptable vertical temperature gradient for the thermal comfort of occupants might be much larger than this comfort standard, the strong thermal stratification of the indoor space of *gers* can be recognised as completely different from the fully air-conditioned environment of modern buildings with relatively uniform temperature distribution.

Comparing the data of Terms CS and EH, the spatial heterogeneity of the indoor air temperature during the usage of ceramic heaters tends to be small. In particular, the temperature difference between the levels of 0.5 and 0.1 m of Term EH is significantly smaller than that for Term CS with stove heating. A possible reason for this difference between the heating devices is the large infiltration rate of the interface between the floor and *ger* envelopes caused by the stack effect created by the stoves with much higher surface temperature, which is generated by the coal combustion, compared with the ceramic heaters. This implies that coal stoves may cause larger heat loss owing to the buoyancy-induced infiltration compared with convection-type electric heaters, although these heating devices can generate similar levels of mean indoor air temperature.

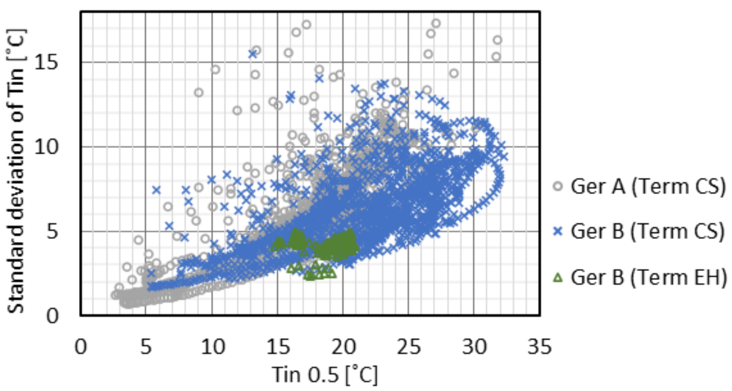

Fig. 8 Relation between the spatial average air temperature at a height of 0.5 m and the standard deviation of the indoor air temperature for all the measurement positions

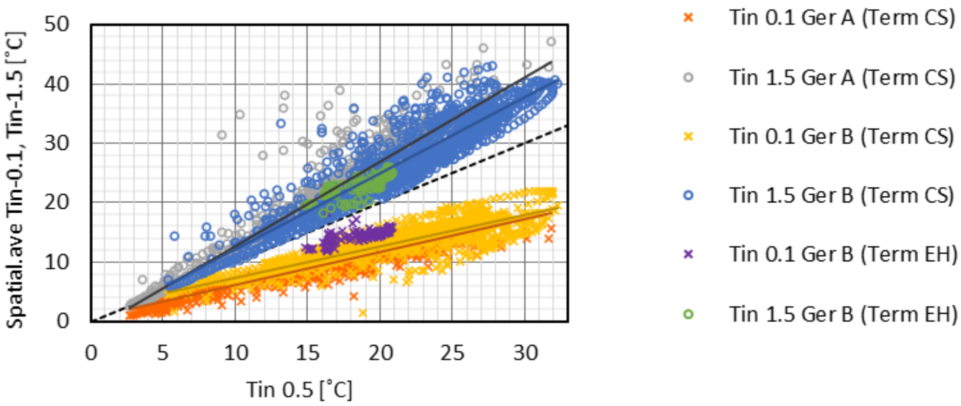

Fig. 9 Relation between the spatial average air temperature at a height of 0.5 m and different heights from the floor level (0.1 and 1.5 m)

3.6 *Surface temperature of ger envelopes and floor*

Fig. 10 shows relations between the indoor air temperature ($T_{\text{in-0.5}}$) and surface temperatures of various positions of *ger* envelopes and floor. The surface temperature at higher positions is higher compared with $T_{\text{in-0.5}}$ similar to the relation of air temperature at different heights shown in Fig. 9. Especially, the roof surface temperature of *Ger* A at a height of 2.15 m sometimes exceeds 50 °C. Considering the small thermal resistance of the envelopes and cold outdoor air temperature below -10 °C, this trend is assumed to be caused by hot updraft above the stove owing to natural convection and direct radiation energy emitted from the stove[1].

The temperature with regard to the floor and wall surface at 0.1 m reduced by ~25 °C. This low temperature is caused by the stratified indoor air temperature and cold inflow through the lower part of the *ger* envelopes owing to the stack effect. Note that the positions of the sensors to capture floor surface temperatures were placed relatively far from the stoves to minimise the disruption caused to the daily lives of the occupants; therefore, the sensors were not directly heated by the radiation generated from the stoves.

The floor surface temperature of *Ger* B differs between the two terms, and the values of the

---

[1] The interior surface temperature of the *ger* can be expressed by the following equation, assuming no radiant heating on the interior surface (*See* Appendix): $T_{s,in} = T_{in} - \frac{T_{in}-T_{out}}{\alpha_{in}\left(\frac{1}{\alpha_{in}}+\frac{\Delta x}{\lambda}+\frac{1}{\alpha_{out}}\right)}$. By substituting the thermal properties of the target site, $T_{s,in}$ can be estimated at around 5 °C for the situation of T_{in} = 20 °C and $T_{out} = -20$ °C. This estimation is much lower than the observed values, suggesting additional factors such as direct radiant heating and a local thermal plume above the stoves.

Term CS considering stove heating tended to be lower than that of the other term. This tendency is consistent with the indoor air temperature at a height of 0.1 m (Fig. 9), implying a higher infiltration owing to the stack effect created by the coal stove compared with the convection-type electric heaters, as mentioned before.

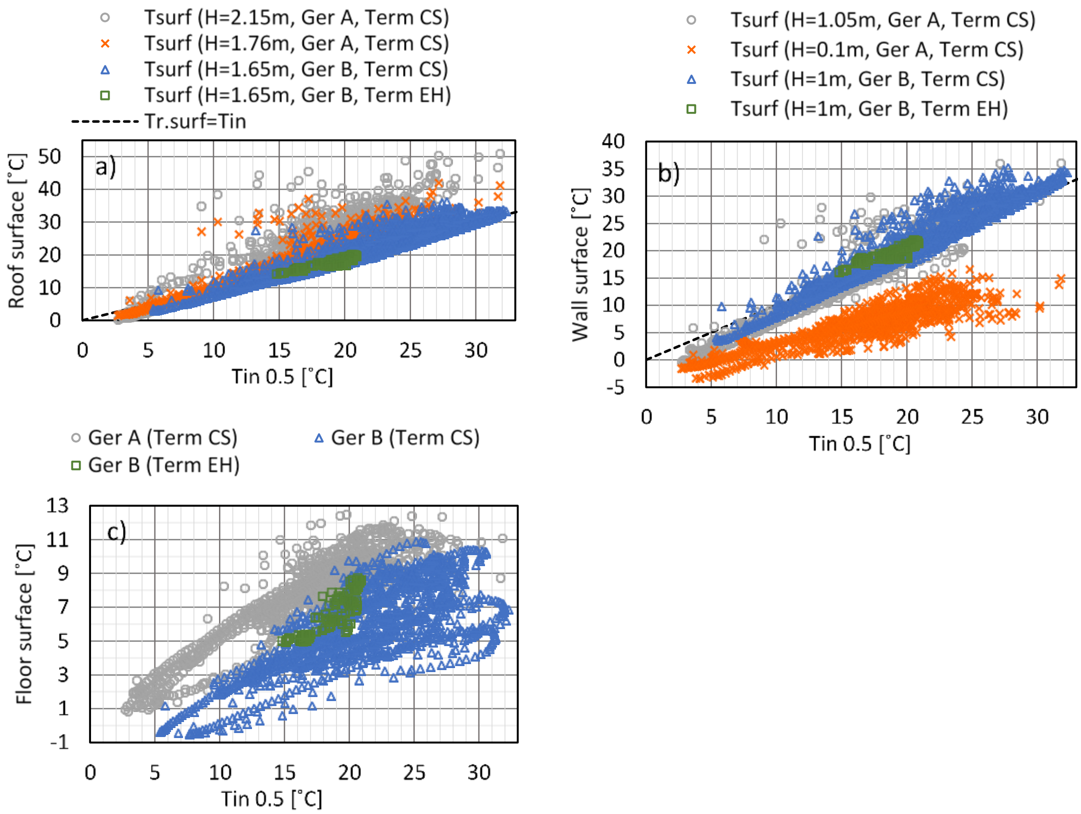

Fig. 10 (a) Relation between the spatial average air temperature at a height of 0.5 m and roof surface temperature. (b) Relation between the spatial average air temperature at a height of 0.5 m and wall surface temperature. (c) Relation between the spatial average air temperature at a height of 0.5 m and floor surface temperature

3.7 Thermal exposure of the occupants

The mean radiant temperature (MRT, T_r) was calculated to examine the thermal exposure of the occupants based on radiation using the measured surface temperature of *the ger* envelopes and estimated radiation energy of the stoves. In this calculation, the radiation generated by the stove to the body of the occupant was estimated assuming the omnidirectional emission from the stoves[2] and shape factors for a seated occupant provided by Dunkle [32]. The distance between an occupant and a stove was assumed to be 1.5 and 1.0 m for *Gers* A and B, respectively, considering the layout of the furniture and the lifestyle of the occupants. The emissivity of the *ger* envelope was assumed to be 1.0[3].

Fig. 11 shows the time variation of the estimated MRT during Term CS-fo, in which the occupants stayed in their *gers* throughout the day. Moreover, the spatially averaged air temperature at a height of 0.5 m ($T_{in\text{-}0.5}$) are included for reference. The MRT values exceeded the indoor air temperature by 5–15 ºC. The time patterns of MRT of the *gers* are similar to those of air temperature, except for the time period when the temperature decreased owing to door openings. MRT was always maintained at >20 ºC even though $T_{in\text{-}0.5}$ had gone below 10 ºC in the early morning just before the coal addition.

Regarding the evaluation of indoor thermal comfort, predicted mean vote (PMV)[24], which is derived based on the energy balance of a human body by using four environmental variables (air temperature, humidity, radiant temperature, and wind speed) and two occupants-related variables (metabolic rate and clothing insulation), has been widely used for decades especially for assessment in air-conditioned enclosed spaces. On the other hand, it has been reported that in naturally ventilated rooms and in environments where occupants have a high flexibility of thermal adaptation behaviours, PMV does not always correspond to people's thermal sensation[33]. The surveyed *gers* were heated by a stove, thus they cannot be classified as naturally ventilated rooms. However, the envelopes of the *gers* were not well insulated and airtight, besides, the occupants were exposed to the cold outdoor environment every time they went to the toilet and experienced sudden drops in room temperature. This situation is therefore substantially different from that of a modern air-conditioned room. In addition, the metabolic rate of the occupants varied according to various activities such as eating and sleeping, and they had a high flexibility of thermal adaptation behaviours. Considering such features, for estimating the current thermal conditions, we calculated operative temperature, T_{op} expressed in Eq. (2) rather than PMV for Term CS-fo, in which the *gers* were heated by a coal stove and occupied by residents all day.

---

[2] These stoves are made of cast iron and are rectangular in shape, with an opening at the top through which coal is fed into the stove. There are no windows on the sides through which the flame can be seen. Given the thermal conductivity of cast iron, it is a reasonable to regard the surface temperature of the stoves as approximately uniform and to treat the long-wave radiation from the stoves as omnidirectional.

[3] The surface area of a seated occupant is only about 1.5 % of the total surface area of the *gers*. Thus, the influence of reflected long-wave radiation upon the *ger* interior surface can be considered negligible.

$$T_{op} = (T_r + T_{in-0.5})/2. \quad (2)$$

Fig. 12 illustrates the probability density distributions (PDDs) and cumulative probability distributions (CPDs) of $T_{in-0.5}$ and operative temperature, T_{op} for Term CS-fo. $T_{in-0.5}$ of *Ger* A ranged from 6 to 29 ºC, being below 18 ºC over half the staying hours in spite of the large heating energy consumption shown in Fig. 7. In contrast, the air temperature of *Ger* B was slightly higher than that of *Ger* A. The value for a CPD of 50% was 22 ºC. Compared with the indoor air temperature, T_{op} of the *gers* ranged from 13 to 37 °C, suggesting effective radiative heating of the stove for occupants even though the indoor air temperature sometimes becomes lower than the modern building standard temperature. In BS-ISO 7730[34], winter comfort criterion in dwellings ranges from 20 to 24 °C [34], and the comfort range of ASHRAE 55-2017[24] is 19.5–24.5 °C. Compared with these standards, the CPDs in Fig. 12 (b) reveal that 74% and 85% of the day for *Ger*s A and B are above the lower limit of the comfort range, respectively. Furthermore, 50% of the time of *Ger* B and 20% of the time of *Ger* A had higher operative temperatures than the upper limit of the comfort range.

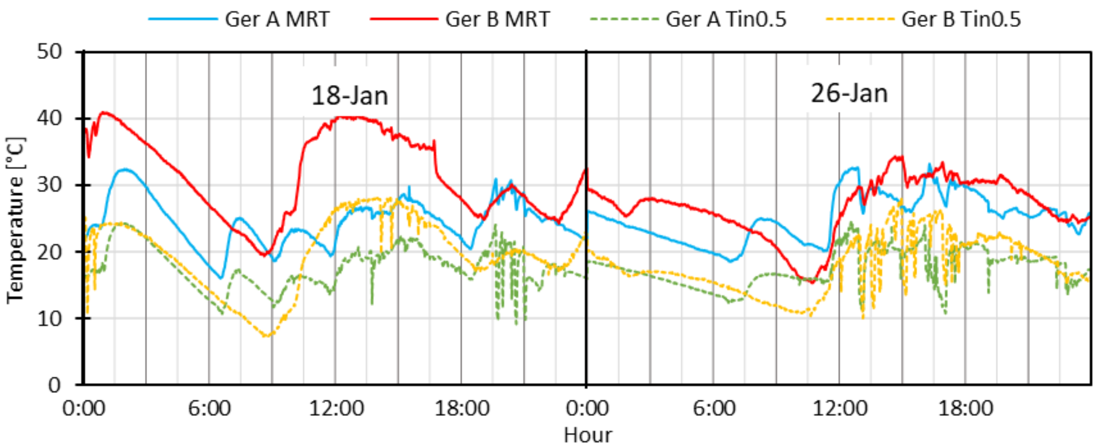

Fig. 11 Time variation of mean radiant and indoor air temperatures during Term CS-fo

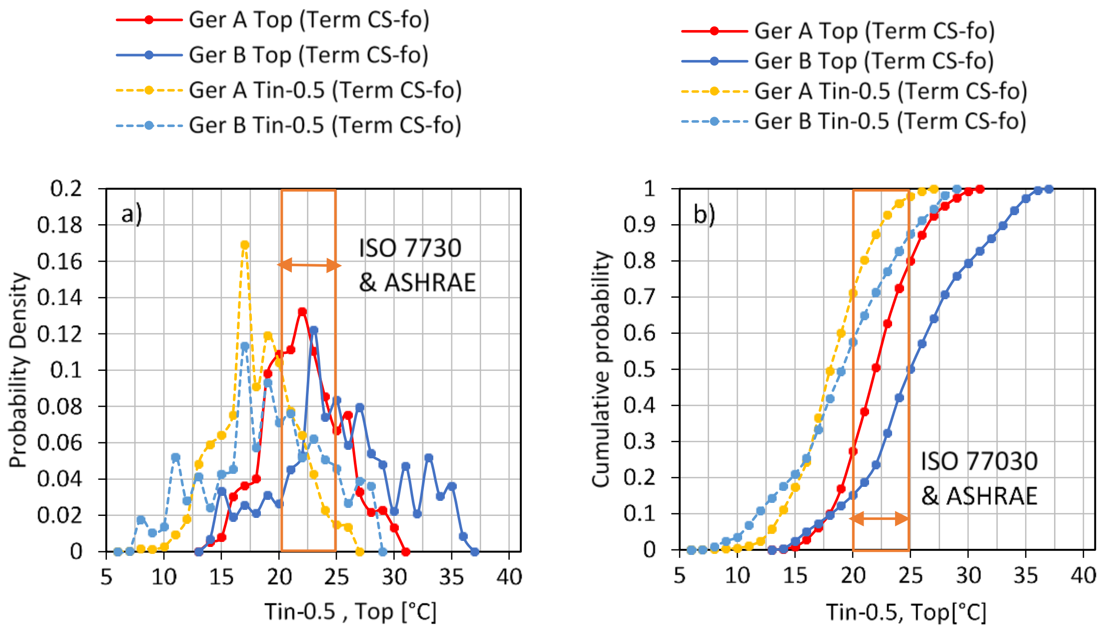

Fig. 12 (a) PDDs and (b) CPDs of the operative temperature (T_{op}) and spatially averaged air temperature at a height of 0.5 m ($T_{in-0.5}$)

3.8 Thermal characteristics and design of gers

A *ger* is a temporary housing originally tailored to nomadic pastoralism, in which people used to move several times a year from one place to another [7]. This one-room interior space is used for various purposes, i.e., sleeping, family gathering, cooking, and eating[8], but there are no toilets or bathrooms inside the *ger* that are physically connected to the local infrastructure services, such as water access and sewage management. Furthermore, owing to their mobile characteristic, *gers* are made of lightweight local materials that are easy to assemble and disassemble.

On the other hand, Fig. 12—derived from our measurement result—indicates the current *gers* enable to create a relatively comfortable indoor thermal environment in winter in spite of the low performance of thermal insulation and airtightness of the *ger* envelopes. As discussed in Section 3.2, the indoor temperature drops by more than 15 °C instantaneously owing to door opening, and the temperature near the floor is always low (5–18 °C) due to thermal stratification and cold air leakage, occasionally resulting in an out-of-comfort temperature range. To overcome this situation, radiant heating with a fairly high output has been a reasonable choice for occupants as Fig. 11 and 12 suggested.

Purev and Hagishima reported [8] that nowadays the dimensions and materials of each part of *a ger* are highly standardised [21], and people can purchase wooden frames, wool-felt sheets, tarpaulin, doors, and other related parts from different retailers based on their preferences, or they can receive used parts from their acquaintances. In addition, even in the case of large families, people do not modify *gers* to create large and complex indoor spaces but rather build multiple *gers* on a single site[7] . This is consistent with the fact that the current circular floor plan with a radius of ~2.5 m is suitable for securing a sufficient shape factor between a stove and a body of occupants, receiving necessary radiation heat gain, thus, maintaining a comfortable thermal environment for occupants as shown in section 3.7. In other words, the current design of *gers* is based on a high-powered radiation heater installed at the centre to achieve thermal comfort without being affected by low near-floor temperatures and frequent temperature drops caused by poor airtightness and the opening of entry doors. Therefore, replacing current coal stoves with convection-type electric heaters would possibly require the improvement of the insulation and airtightness of *the ger* envelopes to ensure the thermal comfort of occupants who have accustomed to the stoves.

4. Conclusions

To understand the thermal features of traditional housing *ger* heated by a fuel stove under the usual behaviours of occupants, a field measurement was conducted in Ulaanbaatar, Mongolia, in winter, focusing on two *gers* with typical sizes and materials. The findings of this survey are summarised below.

- Daily variations in indoor air temperatures of *gers* varied by household and day and were strongly affected by variations in heating power of stoves, which is influenced by the timing and amount of coal input to the stove by occupants.
- Under the conditions of intense stove heating, the vertical difference in indoor air temperature was large. The air temperature at a height of 1.5 m near the ceiling sometimes exceeded 40 °C, while the air temperature near the floor was always less than 20 °C. This stratified temperature field was more intense when a coal stove was used compared with the use of convection-type electric heaters.
- As a result, the operative temperature in the two *gers* was above the lower limit of the ASHRAE comfort range for 74% and 85% of the overall time. On the other hand, over-heating occasionally occurred, resulting in operative temperatures above the upper limit of the comfort range for 50% and 20% of the overall time owing to the limited function to modulate the heating power of the stoves. In addition, the behaviour of the occupants

to deliberately open the door to let in cold air from outside was observed as a countermeasure to overheating.

Overall, these findings — derived from field measurements — highlight the underlying processes of the unique indoor thermal environment of this traditional temporal housing, demonstrating clear academic contribution and scientific originality. To secure the mobility of a *ger*, thick, stiff, and well-insulated envelopes, like those installed in typical modern buildings in Northern Europe have never been adopted despite the cold climate in Mongolia. Instead, people in Mongolia have always preferred stoves with strong radiation heating devices placed at the centre of the circular plane in *gers* since the inception of nomadic society until today, where urban *ger* districts have developed. The results of the current field measurements unlock the mystery of how Mongolian nomads managed to create a comfortable thermal environment in extremely cold winters while maintaining their mobility. Although the *gers* examined in this paper are traditional houses indigenous to Mongolia, similar circular traditional mobile housing exists, or traditionally existed, in various countries including Hungary, Kazakhstan, Kyrgyzstan, and Afghanistan [18]. The results of this study also provide significant insights into the physical environmental factors behind the design of these other nomadic traditional settlements.

The effectiveness of direct radiant heating with primitive fuel stoves and the instability of their thermal output should also be emphasised. Fuel stoves are very rarely used in modern buildings, and for the building energy simulation (BES) to estimate the heating load—and to assess the indoor thermal comfort level—the room temperature is usually assumed to be maintained at a given temperature. Contrarily, the present results suggest that *gers* stoves—with their very limited degree of control over heat output—can lead to large temporal variations in room temperature, sometimes resulting in air temperatures below the comfort range. Nevertheless, even when the room air temperature is lower than the comfort range, direct radiant heating from a stove can maintain the thermal comfort of the occupants. These facts suggest that the BES—which does not take into account characteristics such as direct radiant heating, quite different from modern air-conditioned buildings—may not adequately reflect the actual situation. Considering that the World Health Organization reports 3 billion people worldwide currently using fuel stoves in their homes for heating and cooking [35], the findings of this study could also be valuable for exploring the indoor thermal environment of various buildings in a wide range of regions.

Finally, considering the future scenario of *gers* for urban settlers in Ulaanbaatar, it would be desirable to replace coal stoves with non-emission devices, such as electrically powered heaters, in order to reduce the severe air pollution and health risks associated with indoor air quality. Given that *gers* are designed around radiant heating, the replacement of coal stoves with electric heating should be combined with improvements in the insulation and airtightness of the *ger* envelopes, which will contribute not only to reducing the additional electricity consumed for heating but also to decreasing the non-uniformity of the room temperature.

Nomenclature

T_{out}	Outdoor temperature
T_{in}	Indoor temperature
$T_{in\text{-}0.5}$	Spatially averaged temperature at a height of 0.5 m
T_{surf}	Surface temperature
T_{op}	Operative temperature
T_r	Mean radiant temperature

Acknowledgements

This research was funded by the JSPS Grant-in-Aid for Scientific Research (C): 19K04730 and Sasakawa Scientific Research Grant of the Japan Science Society. We thank the occupants who collaborated to perform measurements in their *gers*. The research was conducted under the Kyushu University Research Ethical Guidance [36].

References

[1] National Climatic Data Center, Weather Data of Multiple Cities, (2017). www.ncdc.noaa.gov (accessed January 30, 2018).

[2] M. Energy Economic Institute, Mongolia’s Energy Efficiency Indicators 2019, (2019).

[3] Energy Charter Secretariat, In-Depth Review of Energy Efficiency Policies and Programmes: MONGOLIA Energy Charter Secretariat 2011, 2011. www.encharter.org (accessed March 15, 2021).

[4] National Statistical Office of Mongolia, Population and housing by census of Mongolia-National report year of 2015, Ulaanbaatar, 2016.

https://1212.mn/BookLibraryDownload.ashx?url=hun_am_oron_suutsnii_2015_toollogo_eng.pdf&ln=Mn.

[5] A.A. Soluyanov, D. Gresch, M. Troyer, Air pollution in Mongolia: Policy brief, 2016.

[6] E. Otgonbayar, T. Matsumoto, G. Khaltai, Study on efficiency of air pollution control measures in ger area of Ulaanbaatar in Mongolia based on field survey, J. Japan Soc. Civ. Eng. Ser. G (Environmental Res. 69 (2013) 259–265. https://www.jstage.jst.go.jp/article/jscejer/69/5/69_I_259/_article/-char/en.

[7] U. Kawagishi, H. Sugimoto, K. Kitano, G. Ishjamts, N. Hirota, Living Environment of Nomads Residing on the Outskirts of Ulaanbaatar, Mongolia Part 2, J. Asian Archit. Build. Eng. 9 (2018) 139–146. https://doi.org/10.3130/jaabe.9.139.

[8] U. Purev, A. Hagishima, A field survey of traditional nomadic dwelling gers used as urban habitats in Ulaanbaatar, Mongolia, Evergreen. 7 (2020) 155–171. https://doi.org/10.5109/4055214.

[9] Japan International Cooperation Agency (JICA), C. and U. Ministry of Roads, Transportation, Development, Ulaanbaatar City Government, The Study on City Master Plan and Urban Development Program of Ulaanbaatar City (UBMPS), Ulaanbaatar, 2009.

[10] S. Ochirbat, Ger Area Redevelopment First Stage Location, Ulaanbaatar, 2013.

[11] 2020 Population and Housing Census of Mongolia /summary/ 2 CONTENTS, 2020.

[12] Ulaanbaatar Electricity Distribution Network, Night Time Electrical Subsidy| tog.mn, (n.d.). http://www.tog.mn/public/newsshow/id/514 (accessed May 27, 2019).

[13] A. Pillarisetti, M. Rongjiang, M. Buyan, N. Boldkhuu, A. Yuma, Y. Xudong, S.R. Kirk, Advanced household heat pumps for air pollution control: A pilot field study in Ulaanbaatar, the coldest capital city in the world, Environ. Res. (2019). https://doi.org/10.1016/J.ENVRES.2019.03.019.

[14] J. Jamsran, Energy sector of Mongolia, Country Report, 2018. https://eneken.ieej.or.jp/data/8044.pdf (accessed May 30, 2021).

[15] B.-E. Bayandelger, Y. Ueda, A. Adiyabat, Experimental Investigation and Energy Performance Simulation of Mongolian Ger with ETS Heater and Solar PV in Ulaanbaatar City, Energies. 13 (2020) 5840. https://doi.org/10.3390/en13215840.

[16] S. Ishikawa, H. Hayama, E. Purev-Erdene, M. Enai, K. Kikuta, A. Kato, Survey report

for indoor environment of settled down type ger in ger area, Ulaanbaatar, Mongolia, in: Summaries of Technical Papers of Annual Meeting, Hokkaido, 2007: pp. 53–54. https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/50691/1/GKKD-2_53-54.pdf (accessed June 17, 2019).

[17] B. Buyantogtokh, Q. Zhang, Investigation on indoor thermal environment of the GERS in Ulaanbaatar during winter: Studies on indoor environments and energy consumption of dwellings in Mongolia, Part 2, J. Environ. Eng. 84 (2019) 245–253. https://doi.org/10.3130/aije.84.245.

[18] G. Tsovoodavaa, I. Kistelegdi, Comparative analysis for traditional yurts using thermal dynamic simulations in Mongolian climate, Pollack Period. 14 (2019) 97–108. https://doi.org/10.1556/606.2019.14.2.9.

[19] World Maps of Köppen-Geiger climate classification, (n.d.). http://koeppen-geiger.vu-wien.ac.at/applications.htm (accessed January 13, 2021).

[20] USAID from the American People, Country Overview, 2017. https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID ATLAS_Climate Risk Profile - Mongolia.pdf (accessed January 13, 2021).

[21] Mongolian Agency for Standardization and Metrology, Mongolian national yurt MNS 0370:2003, (2003). http://www.estandard.gov.mn.

[22] Ulaanbaatar Services Improvement Project, Ulaanbaatar clean air project report, 2015.

[23] Mongolian State Professional Inspection Agency, Сайжруулсан түлш, (2018). http://home.inspection.gov.mn/news/248/single/1376 (accessed November 26, 2020).

[24] ASHRAE, Standard 55 Thermal environmental conditions for human occupancy, 2017. https://www.ashrae.org/about/news/2017/ashrae-publishes-2017-version-of-thermal-comfort-standard (accessed September 15, 2021).

[25] N.W. Tuck, S.A. Zaki, A. Hagishima, H.B. Rijal, F. Yakub, Affordable retrofitting methods to achieve thermal comfort for a terrace house in Malaysia with a hot–humid climate, Energy Build. 223 (2020) 110072. https://doi.org/10.1016/j.enbuild.2020.110072.

[26] Solar reflectivity (R) & solar reflectance index (SRI) by color – dean steel buildings, inc., (n.d.). https://www.deansteelbuildings.com/products/panels/sr-sri-by-color/ (accessed October 21, 2021).

[27] A. Hagishima, J. Tanimoto, Field measurements for estimating the convective heat transfer coefficient at building surfaces, Build. Environ. 38 (2003) 873–881. https://doi.org/10.1016/S0360-1323(03)00033-7.

[28] Mongolian agency for standardization and meteorology, Air quality general MNS 5825:2007, (2007).

[29] M. Gallagher, M. Beard, M.J. Clifford, M.C. Watson, An evaluation of a biomass stove safety protocol used for testing household cookstoves, in low and middle-income countries, Energy Sustain. Dev. 33 (2016) 14–25. https://doi.org/10.1016/j.esd.2016.03.008.

[30] P.F. Incropera, D. P.DeWitt, Fundamentals of Heat and Mass Transfer 5th edition, 2002.

[31] M. Möhlenkamp, M. Schmidt, M. Wesseling, A. Wick, I. Gores, D. Müller, Thermal comfort in environments with different vertical air temperature gradients, Indoor Air. 29 (2019) 101–111. https://doi.org/10.1111/ina.12512.

[32] R. V. Dunkle, Configuration factors for radiant heat-transfer calculations involving people, J. Heat Transfer. 85 (1963) 71–76. https://doi.org/10.1115/1.3686012.

[33] G.S. Brager, R.J. de Dear, Thermal Adaptation in the Built Environment: a Literature Review Publication Date, Energy Build. (1998) 86–96. https://doi.org/10.1016/S0378-7788(97)00053-4.

[34] BS EN ISO 7730 : 2005 Ergonomics of The Thermal Environment, British Standard Institution, 2005. https://infostore.saiglobal.com/en-us/Standards/BS-EN-ISO-7730-2005-303598_SAIG_BSI_BSI_702825/ (accessed January 18, 2021).

[35] WHO, Household fuel combustion WHO guidelines for indoor air quality, 2014.

[36] K.U, Responsible Conduct of Research, (n.d.). https://edu.aprin.or.jp (accessed February 14, 2021).

[37] Japan Society of Thermophysical Properties, Thermophysical Properties Handbook, Yokendo, (written in Japanese), 2008.

Credit authorship contribution statement

Uelun-Ujin Purev: Conceptualization, Collected and analysed data and Writing-original draft.
Aya Hagishima: Conceptualization, Supervision and Writing-review and editing.
Munkhbayar Buyan: Writing-review

APPENDIX

Although we did not directly measure the heating power of coal stoves, the thermal radiation emitted from a stove was estimated based on the measured temperatures of ceiling surface (H = 1.76 m for *Ger* A and H = 1.65 m for *Ger* B), indoor air temperature near the ceiling surface (H = 1.5 m) and outdoor air temperature based on the assumptions of one-dimensional thermal conduction of the *ger* envelopes and omnidirectional radiation emission from stoves, as described below.

Assuming one-dimensional heat transfer through the ger envelope, the energy balance can be expressed by the following equations:

$$q + R = \alpha_{out}\left(T_{surf,out} - T_{out}\right) \qquad \text{(A1)}$$

$$q + R = \lambda\left(T_{surf,in} - T_{surf,out}\right)/\Delta x \qquad \text{(A2)}$$

$$q = \alpha_{in}\left(T_{in} - T_{surf,in}\right) \qquad \text{(A3)}$$

where q is the conduction heat flux [W/m^2], *and* R is the radiation flux on the surface of *the ger* envelope delivered from a stove [W/m^2]. T_{in} and T_{out} are the indoor and outdoor air temperatures, respectively. $T_{s,in}$ and $T_{s,out}$ are the surface temperatures of the ger envelope for the indoor and outdoor sides, respectively. α_{in} and α_{out} are the convective heat transfer coefficients, λ is the thermal conductivity, and Δx is the depth of the ger envelope. By substituting measured values of T_{in}, $T_{surf,\ in}$ and T_{out}, assuming α_{in} = 5 W/(m^{2}K), α_{out} = 10 W/(m^{2}K), λ = 0.127 W/(m K) [37], Δx = 0.03 m [8], heat fluxes q and R can be estimated as below.

$$q = \left(T_{s,in} - T_{s,out}\right)/(U^{-1} + U_{out}^{-1}) \qquad \text{(A4)}$$

$$R = U_{out}(T_{s,in} - T_{s,out}) - q \qquad \text{(A5)}$$

$$\text{where } U^{-1} = \frac{1}{\alpha_{in}} + \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{out}} \qquad \text{(A6)}$$

$$U_{out}^{-1} = \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{out}} \qquad \text{(A7)}$$

The estimated radiation flux reaching the internal surface of the *ger* envelope was exchanged with the radiation flux on the normal plane of the vector from a stove to the measurement point of a *ger* indoor surface using Eq. (A8).

$$R_{\circ} = Rcos\theta \qquad \text{(A8)}$$

Assuming that the radiation from a stove is omnidirectional from a point source, the radiative heating power of a stove H_{stove} [W] was obtained by the surface integration of a hemisphere as follows:

$$H_{stove} = 2\pi L^2 R_{\circ} \qquad \text{(A9)}$$

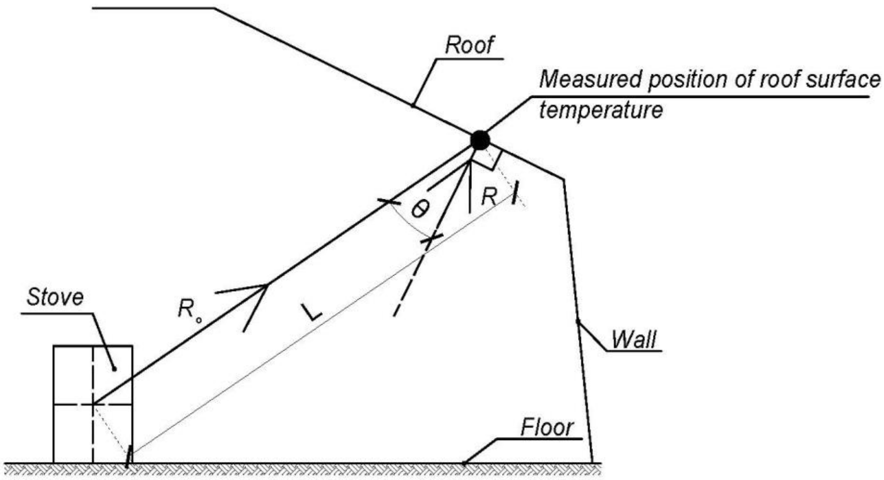

Fig. A.1 Schematic diagram for estimation of radiation heating power of a stove