Doctor Dissertation (Engineering)

Indoor Thermal Environment and Energy Consumption of Dwellings in Ulaanbaatar, Mongolia

モンゴル国ウランバートル市における住宅の温熱環境とエネルギー消費

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ABSTRACT

The energy consumption in Mongolia has increased, which contributes to severe air pollution and energy shortages in recent years. So, energy conservation of residences is an urgent issue to deal with.

The purposes of this study are to make clear the energy consumption and the indoor environment of residences including residential buildings, Gers and to give suggestions about energy saving measures based on surveying, measurement and simulations. To fulfill those purposes several consecutive studies were conducted.

Firstly, as a necessary tool of building simulations, the Typical Meteorological Year (TMY) for Ulaanbaatar, Mongolia containing hourly data of main weather elements such as dry bulb temperature, relative humidity, humidity ratio, global solar radiation on horizontal surface, direct normal solar radiation, diffuse radiation, wind direction, wind speed, total cloud cover and atmospheric pressure was developed.

Next, the indoor environment of residential buildings in Ulaanbaatar, Mongolia was clarified by questionnaire and measurement. According to the measurement results, the indoor environment of the residential buildings is typically hot and dry while indoor CO_2 concentration is within the national standard level. The heat loss coefficient is between 0.74W/(m^2K) to 1.53 W/(m^2K). It is high for Type A (non-insulated precast ceramsite) and Type B (non-insulated brick structures), which implies high potential of energy savings by insulation renovation comparing to other three structure types such as Types C (insulated brick), D (insulated lightweight block) and E (insulated concrete).

Then, the indoor environment of the traditional dwellings as Gers in Ulaanbaatar, was clarified. The indoor environment of the Gers is uncomfortable due to the wide range of temperature change and low relative humidity. The heat loss coefficient of the Gers is between 1.31 W/(m^2K) and 3.96 W/(m^2K) based on the coal consumption of the Gers.

Finally, the potential of energy saving was identified for existing residential buildings. Parametric analyses were carried out for the typical floor model of residential buildings which was developed based on the survey results and using the TMY developed in Chapter 2. The order of impacts on the heating load is: insulation thickness, air change rate, indoor air temperature, window type and building orientation. The potential of energy saving is 60% for Type A, 35% for Type D, 21% for Type E, respectively by the proposed energy saving model which combines all the effctive measures.

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CHAPTER 1
Introduction

1.1 Background

Mongolia is a landlocked country located in north-central Asia with the population of 3.17 million. Due to its continental climate, high elevation and latitude Ulaanbaatar is the coldest capital city in the world. Because the heating season is long lasting from September to May, and Mongolia is rich in coal, the main source for space heating is coal for a long time.

The economy has started growing since 2000 related to the effective mining production and increasing demand of export except a drop in 2009. Figure 1.1 shows the growth rate of GDP for 2000 to 2017 [1]. The average GDP growth rate is 6.95% throughout the this period.

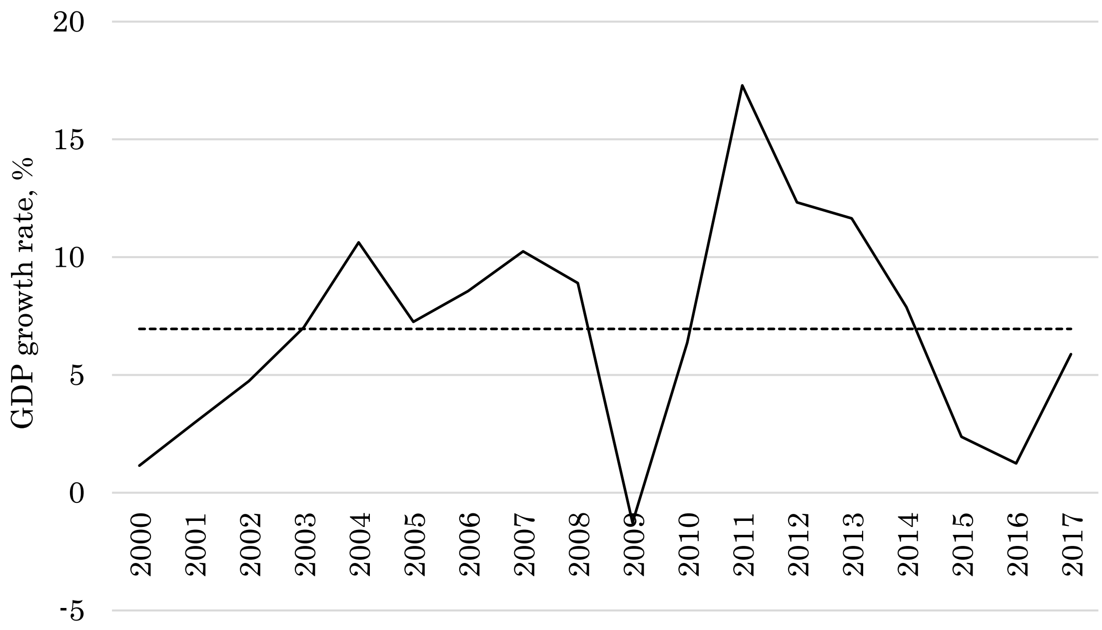


Fig.1.1 GDP growth rate (2000-2017)

Along with the economic development, people's living standard has been improving, and the living space of the residents gets larger for the new buildings. According to the statistics of 2015, the percentage of apartments with floor areas of 21-40 m^2 and over 41m^2 have risen by 41% and 3%, respectively, while that below 20m^2 has decreased by 3.9% in 5 years [2].

The capital city Ulaanbaatar is located at north-central part of the country surrounding by four mountains. A population movement to Ulaanbaatar has been rising related to the economic development and a tendency of centralization. The population in 2000 was 773.6 thousand and increased to 1,380.8 thousand in 2016 [3]. According to the statistics, 3,400 Gers, 5,300 detached houses and 6,500 apartments are constructed on average each year [4].

With the increase of population and housing the energy demands by the residents and related serivces grow rapidly. There are three co-generation power plants and one heat-only plant to distribute thermal energy which is used for space heating and hot water supply system of the buildings. All these plants have reached their utmost capacity and energy shortages is expected to occur [5].

As a result of natural conditions of Ulaanbaatar, improvement of people's living standard, growth of population, coal consumption increases sharply which contributes to severe air pollution in recent years. As estimated by Sarath Guttikunda the power plants emit 34% of PM10 which is most significant portion among other sources [6].

Energy savings of dwellings becomes an urgent issue in order to create sustainable environment.

1.2 Purposes of the study

The primary purposes of the study are to give suggestions about energy saving measures for existing and prospective dwellings in Ulaanbaatar, Mongolia. The main highlights of the purposes are as follows:

- To develop the Typical Meteorological Year, the typical weather data for building simulations;
- To clarify indoor thermal environment and energy consumption of existing apartments and Gers;
- To clarify effects of each parameter on the heating load;
- To give suggestions about energy savings for the existing as well as newly constructed buildings based on the surveying, measurement, and simulations.

1.3 Literature review

The term energy savings or energy efficiency was introduced to Mongolia in late 1990's. Accordingly, the building code was updated to comply with energy efficiency concept in 1997 [7]. According to this legislative, the exterior envelope of the new buildings should meet with the minimum value of the thermal resistance. From this time insulation technology of the exterior surface was adopted to new buildings. Even though new buildings became insulated, the large number of old buildings with non-insulated structures are still existing. Recently the national program for energy savings was approved as legislative in 2017 [8]. The main highlights of the program from 2017 to 2022 are:

- To determine the energy consumption of buildings and certify them according to the energy consumption levels;
- To develop a standard methodology to clarify actual energy consumption;
- To establish the acceptable limit for the heat loss coefficient regarding to weather condition;
- To conduct energy auditing for existing buildings;
- To develop requirements for energy-efficient or passive buildings in Mongolian context;
- To improve the legislative and building codes related to the energy efficiency to reach the international level;
- To adopt energy efficient design for the perspective buildings;
- To retrofit non-insulated old buildings to reduce heat loss by 20% at least.

There are very few studies conducted about weather data for building simulations, energy consumption, and the indoor environment for dwellings in Mongolia.

The hourly weather data is necessary for dynamic simulations. The Typical Meteorological Year that represents typical months of historical year was developed for five locations of Mongolia by Zhang et al [9]. In their study, the global horizontal solar radiation was estimated with the model developed for Beijing, China but it is needed to be verified by the observational data in Ulaanbaatar.

Most of the old buildings in Ulaanbaatar were built with Russian technology which means the thermal characteristics of these buildings are the same as buildings built after 1975 in Russia. Satu Paiho et al. estimated that the energy consumption for space heating of the precast ceramsite buildings in Moscow could be reduced by 37% when U-values were decreased by 65% for the exterior wall, 77% for the roof and 36% for the windows [10].

Endo et al. investigated the apartment with 10cm insulation on the wall and roof [11]. According to their estimation, heating energy consumption for each apartment is 48.28 GJ and it could be reduced to 21.16 GJ after additional 14 cm insulation on the wall and roof, 10 cm insulation on the ceiling of the basement floor and replacing the window with triple pane. The other study conducted by Ishikawa et al. considered the precast ceramiste buildings built with Russian technology [12]. They found that the indoor temperature is not stable for this type of apartments and some of them were overheated. None of those studies considered all types of structure and their thermal comfort in their studies.

Ishikawa et al. also studied the indoor environment and the energy consumption of the Gers in Ulaanbaatar [13]. They found that the Ger is not suitable dwelling for living from economic and indoor environment point of view.

Looking at the projects conducted up to date and new national legislative requirements, and the scarce information about thermal environment and energy consumption of residential buildings in Ulaanbaatar the author is intensively motivated by the subject of this study.

1.4 Outline of the study

This dissertation is organized with six chapters as follows:

Chapter 1 describes the background, purposes of the study, and reviews previous researches and related national legislations;

Chapter 2 deals with the development of the Typical Meteorological Year (TMY) for Ulaanbaatar. The TMY consists of 12 Typical Meteorological Months selected from the historical ten (2006-2015) years. In order to select each month of TMY from the historical years air elements such as solar radiation, dry bulb temperature, relative humidity, and wind speed are compared to the total average. Since obtained observational data does not contain solar radiation data, the model to estimate solar radiation was improved from the previous study;

Chapter 3 deals with the investigation of thermal environments and energy consumptions of the existing 5 types of apartment buildings in Ulaanbaatar. The investigation was carried out with a questionnaire survey of 374 households and field measurement of indoor air temperature, relative humidity, and CO_2 concentration for 18 apartments that are selected randomly from the surveyed ones. The ventilation rate of the apartments was estimated using the measured data of CO_2. The heat loss coefficient of each type of apartment buildings was estimated using the heat transfer coefficients of the corresponding structures and the ventilation rates;

Chapter 4 deals with the investigation of thermal environment and energy consumption of the Gers in Ulaanbaatar. The Ger is traditional type of dwelling usually used by the nomad people and are still used even in the city because of its mobility and affordable price. Due to its thermal characteristics, the indoor environment and energy consumption of the Gers is different from that of apartments. The questionnaire survey was conducted for 54 households and 10 of them were selected for measuring indoor air temperature, relative humidity, CO, CO_2 concentrations and coal consumption. The ventilation rate of the Gers was estimated using CO_2 concentration measured during 4:00-6:00am. The heat loss coefficient of the Gers was estimated with the coal consumption of each Ger;

In Chapter 5, the potential of energy savings for three types of apartment buildings (non-insulated precast ceramsite, insulated light weight concrete, insulated reinforced concrete) were examined using simulations. Parametric analyses were carried out with simulation program TRNSYS. The weather data developed in Chapter 2 was uploaded into the program. Based on the survey conducted, the typical floor model was developed for simulations. After carrying out dynamic simulations by changing parameters of orientation, insulation thickness, window type, indoor air temperature, and air change rates the effect of each parameter on the heat load of apartment buildings were clarified. An energy saving model which combines all the effective measures was proposed and the potential of energy saving was made clear;

Chapter 6 summarized the previous chapters and gave suggestions for energy retrofitting for the existing non-insulated buildings and thermal design for the prospective buildings as well.

Research procedure described above is summarized in the flow diagram shown in Fig.1.2.

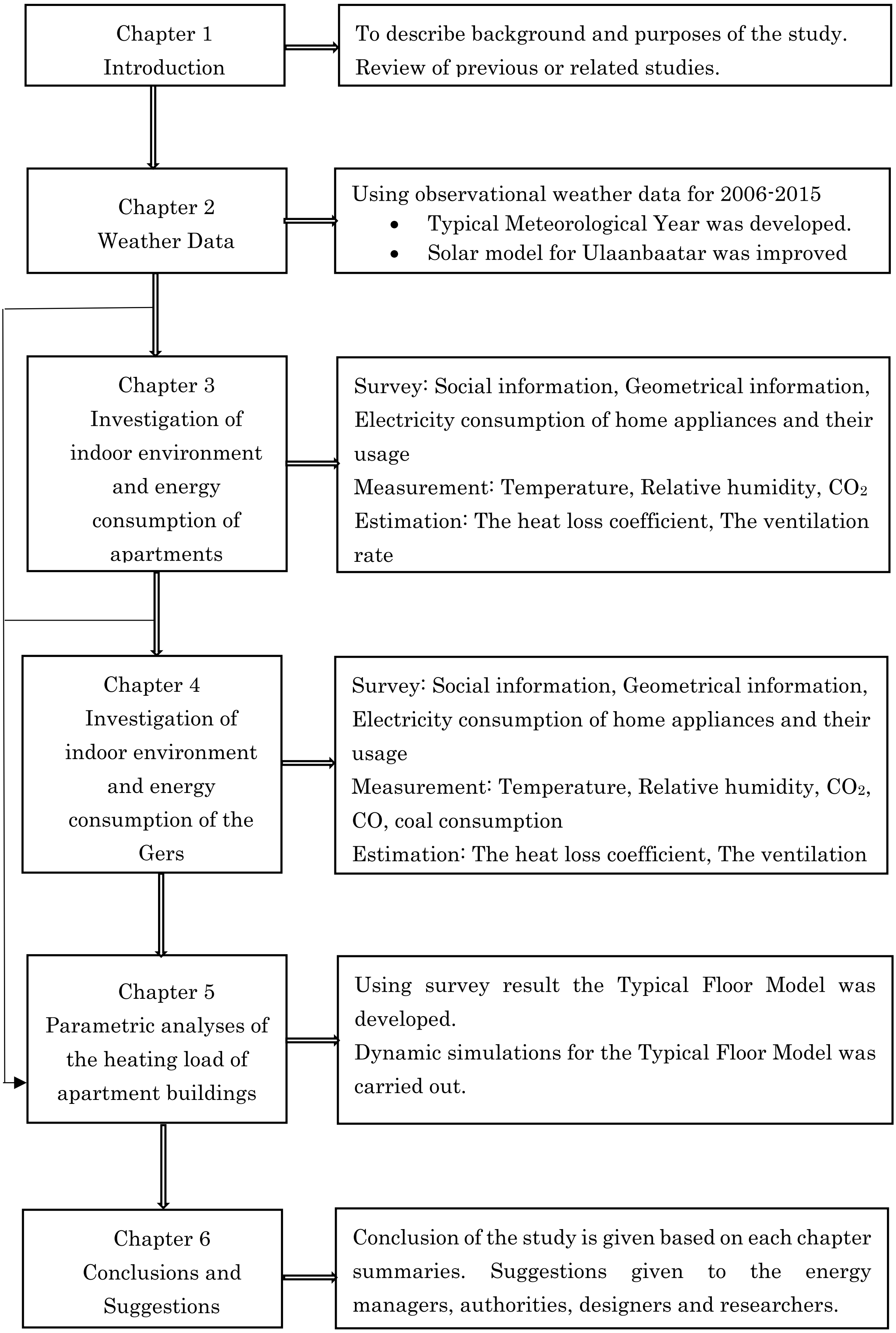


Fig.1.2 Research flow diagram

CHAPTER 2
Development of the Typical Meteorological Year for Ulaanbaatar

2.1 Introduction

The capital city Ulaanbaatar locates in the northern central part of the country at Latitude of 47.93 N, Longitude of 106.96 E, and 1,337 m above sea level. The climograph created with thirty historical years (1986-2015) data for Ulaanbaatar is shown in Fig.2.1.

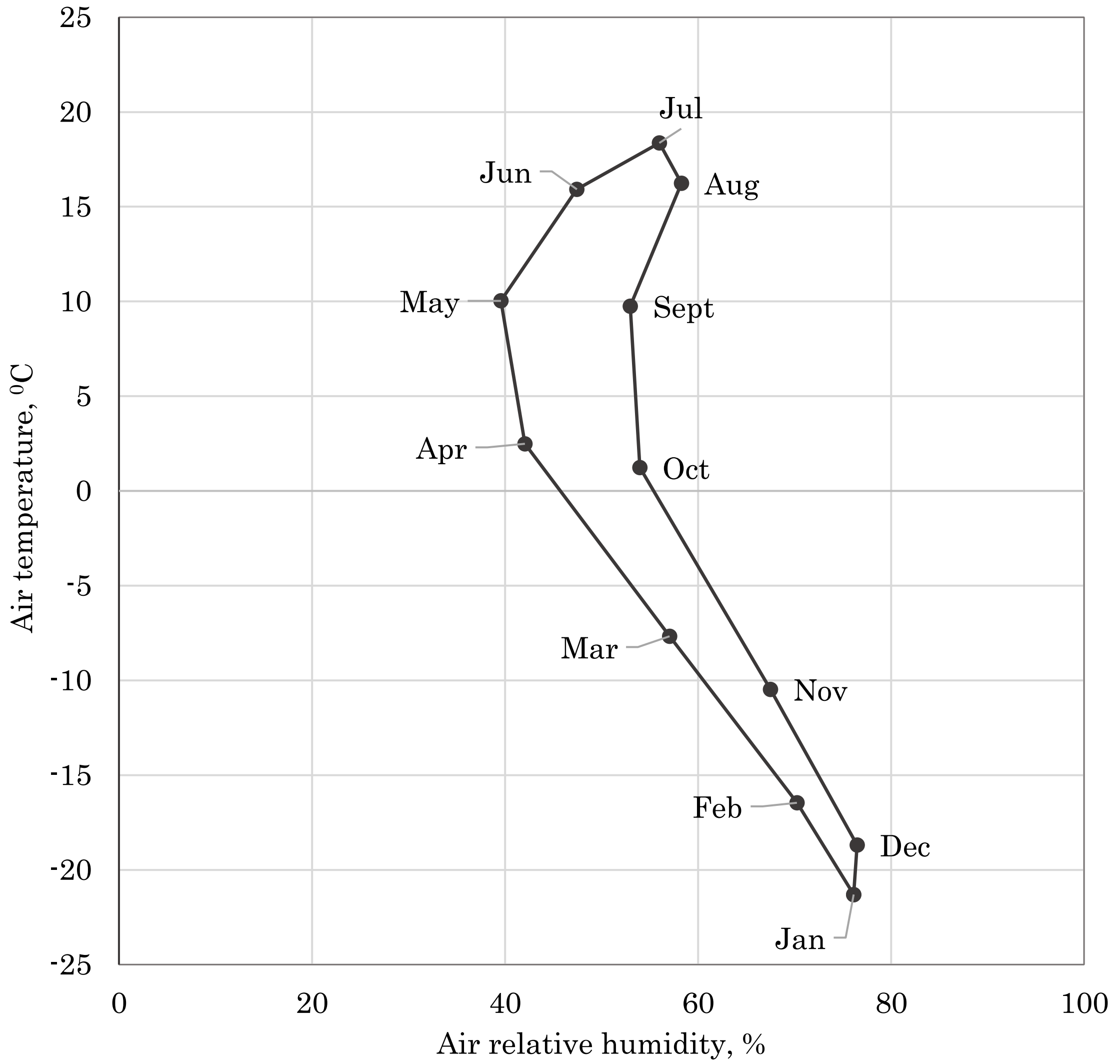


Fig.2.1 Climograph of Ulaanbaatar

Building simulation is one of the main tools for building energy and environmental analyses. Energy performance in buildings is simulated with computer programs which enable architects and engineers to make energy-conscious design while maintaining the comfortable indoor environments and energy managers to monitor energy efficiency in buildings. Weather data is an important input data for building simulation programs. Since most of the programs simulate building energy dynamically they require locally specific hourly weather data.

The Typical Meteorological Year (TMY) is one kind of weather data used for building simulations. Although TMY database was developed for Japan [14], USA [15], and China [16], but very few studies have been carried out for Mongolian locations mainly because: (1) energy simulation programs had not been introduced until recently; (2) purchase of weather data is prohibitively expensive for researchers; (3) weather data is not usually recorded hourly but in three-hour intervals. Zhang et al. developed a database of TMY for 50 locations in 20 Asian countries including five locations in Mongolia such as Ulaanbaatar, Ulaangom, Muren, Uliastai, and Dalanzadgad [9]. However, the solar radiation for all considered locations was estimated with the solar model developed for Beijing China.

Main purposes of this chapter are to develop a model with which solar radiation can be estimated and the Typical Meteorological Year for Ulaanbaatar, Mongolia.

Weather databases used for this study are obtained from two different sources: one is the National Climate Data Center (NCDC) that archives values of weather elements received from stations all over the world [17]; the other is the Mongolian Information and Research Institute of Meteorology Hydrology and Environment (IRIMHE) that measures and records weather elements for every three hours.

A solar model to estimate global solar radiation on the horizontal surface was developed for Ulaanbaatar because there is not any solar data included in either of the databases except for observational solar data for one year in the IRIMHE database. Estimated global solar radiation using the developed model was validated with the observational data of Ulaanbaatar for the year of 2015.

Using the solar radiation estimated with the developed model and observational data of other air elements, the Typical Meteorological Year was developed for Ulaanbaatar which enables a process of building simulation.

Abbreviations:

$\theta(t)$ k^{th} observed dry bulb temperature [^{0}C];

k	Sequential number of observed dry bulb temperature at three-hour interval [-];
n	n^{th} term of the Fourier series [-];
t	Local standard time [h];
I_0	Solar constant [1366W/m^2];
I_{sc}	Extraterrestrial solar radiation above atmosphere [W/m^2];
n_d	Number of the day starting from January 1st [-];
CC	Total cloud cover [tenth];
T_n, T_{n-3}	Dry bulb temperature at n and n-3 hour respectively [^{0}C];
φ	Relative humidity [%];
h	Solar altitude angle [degree];
k_T	Clearness index which means that the ratio of radiation on the ground surface to the radiation above the atmosphere [-];
I	Global solar radiation on horizontal surface [W/m^2];
k_n	Direct beam transmittance [-];
I_n	Direct normal solar radiation on the earth surface [W/m^2];
I_d	Diffuse solar radiation on the earth surface [W/m^2];
A_1, A_2, A_3, A_4	Solar angle function coefficients [-];
FS_i	Finkelstein-Shafer statistic [-];
w_i	Weight of the air element [-];
δ_i	Absolute difference between the long term cumulative distribution function and year cumulative distribution function at x_i [-];
(i = 1, …, n)	n is the number of daily readings in the month [-];
θ_i	Temperature to connect neighboring months smoothly [^{0}C];

θ_i' Temperature of the end date of the previous month [^{0}C];

θ_i'' Temperature of the beginning date of the following month [^{0}C].

2.2 Data sources

The observational data used in this chapter were obtained from two kinds of weather databases as shown in Table 2.1. One is the Integrated Surface Data (ISD) archived at the National Climate Data Center (NCDC). The ISD database is composed of observational weather data collected from the Automated Weather Network, the Global Telecommunication System and the Automated Surface Observing System with over 20,000 stations that are located throughout the world [17]. We used the historical weather data from the period of 2006 – 2015 in this study. The weather elements included in the ISD data are dry bulb temperature, dew point temperature, wind speed, wind direction, visibility, sea level pressure, station pressure and cloud cover at high, middle and low levels. There is missing data for cloud cover and existing data is expressed with the words: clear, scattered, broken, overcast, obscured, partial obscured rather than digital numbers. Therefore, cloud cover data in ISD database was replaced with the observational data obtained from another database of the Mongolian Information and Research Institute of Meteorology Hydrology and Environment (IRIMHE). Apart from the total cloud cover data for the same period as the ISD database, the observational global and direct normal solar radiation data on horizontal surface at three-hour intervals for 2015 are included in IRIMHE database.

Dry bulb temperatures of two sources were compared to verify their similarities. Figure 2.2 shows relationship between temperatures given in two databases. The NCDC conducts quality controlling for all the data received from the partner stations over the world by checking range and time continuity [18]. The correlation coefficient of dry bulb temperatures is 0.99 which means the dry bulb temperature data in ISD is reliable. Finally, the ISD database that includes dry bulb temperature, dew point temperature, wind speed, and cloud cover data is used for this chapter, but the total cloud cover data is replaced with the data obtained from the IRIMHE due to its high reliability.

Table 2.1 Databases and elements included

Database source type	Elements	Period
ISD database[18]	• Wind direction • Wind speed • Total cloud cover • Cloud cover at low level • Cloud cover at middle level • Cloud cover at high level • Visibility • Dry bulb temperature • Dew point temperature • Sea level pressure • Station pressure	2006-2015
IRIMHE database	• Total cloud cover	2006-2015
	• Global solar radiation on horizontal surface • Direct solar radiation on horizontal surface	2015

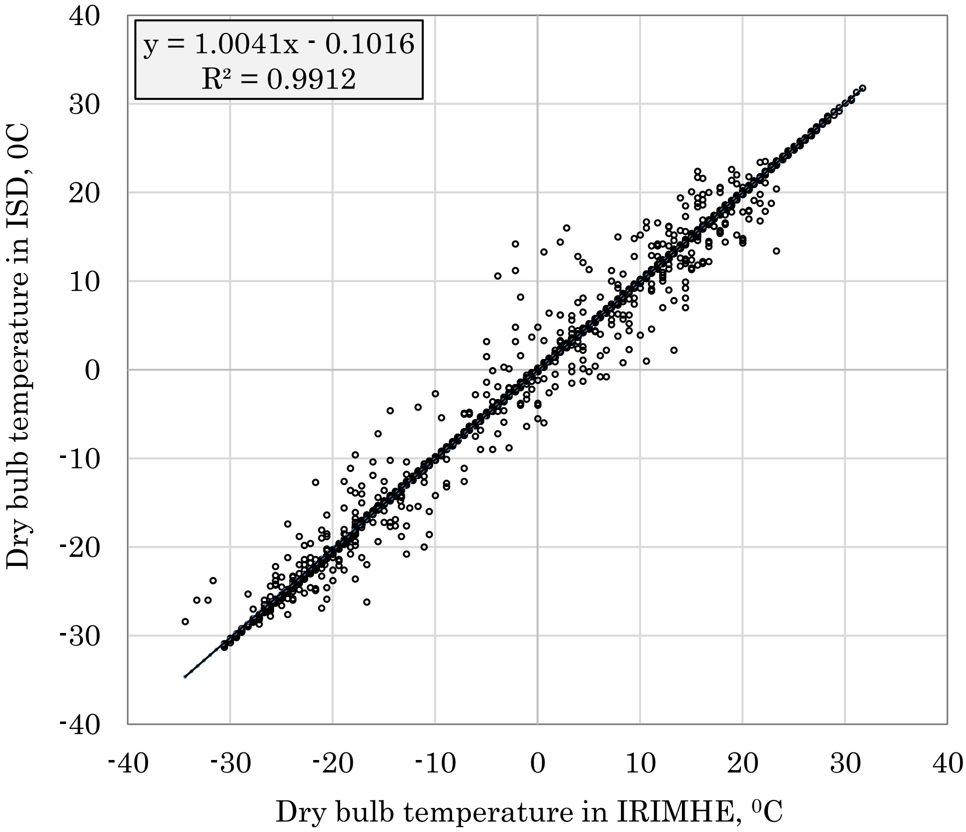


Fig.2.2 Relationship between dry bulb temperatures of IRIMHE and ISD databases

The three-hour data in the ISD database was interpolated into hourly values because most building simulation programs require hourly weather data. Dry bulb temperature was interpolated with the double Fourier series [19]. The first Fourier series interpolates dry bulb temperature for the daytime. The Fourier series assumes data at the beginning of a day is equal to that at the end of that day which was not always true in the case of dry bulb temperature. The second Fourier series was conducted to interpolate temperature data in the connection period of two consecutive days starting from 2 pm of a previous day through 11 am of a next day. Equations used for interpolation are as follows:

$$\theta(t) = b_0 + \sum_{n=1}^{M} a_n \sin\left(n\frac{\pi}{12}t\right) + \sum_{n=1}^{M} b_n \cos(n\frac{\pi}{12}t) \quad (2.1)$$

$$a_n = \frac{1}{4}\sum_{k=1}^{8} \theta(k) sin\frac{n\pi k}{4} \quad (2.2)$$

$$b_n = \frac{1}{4}\sum_{k=1}^{8} \theta(k) cos\frac{n\pi k}{4} \quad (2.3)$$

$$b_0 = \frac{1}{8}\sum_{k=1}^{8} \theta(k) \quad (2.4)$$

Figure 2.3 presents an example of dry bulb temperature interpolation. After double use of the Fourier series dry bulb temperature between two consecutive days are connected smoothly. The dew point temperature, wind speed and cloud cover were interpolated in the same way as dry bulb temperature.

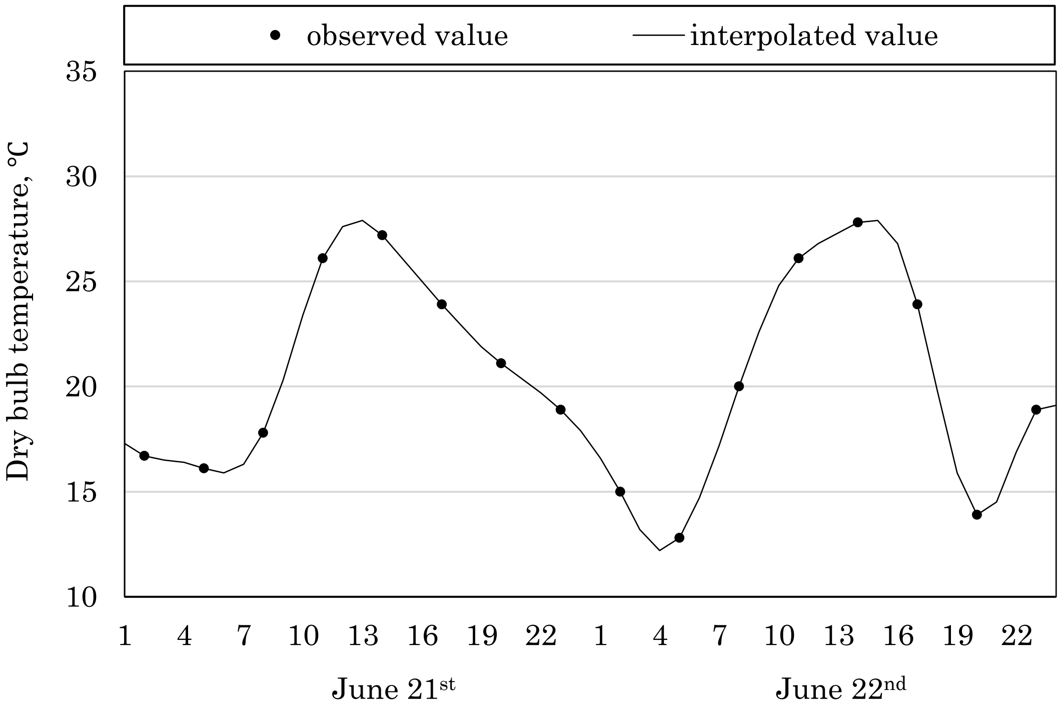


Fig.2.3 Interpolation of dry bulb temperature for June 21st to June 22nd, 2006

2.3 Improvement of the solar radiation model

Comparing with other elements, solar radiation is observed at very few locations. As mentioned before, hourly solar data is not fully available for both databases obtained. Therefore, it is necessary to develop a method that will estimate solar radiation for Ulaanbaatar.

Akasaka et al. developed a solar radiation model taking a sunshine hour as the main parameter [20]. It is difficult to use this model for Ulaanbaatar because there is not any data on sunshine hour ratio in the database which we obtained.

Zhang et al. developed a solar model using temperature increase, relative humidity, wind speed and cloud cover for China and other Asian locations including

5 locations in Mongolia [9]. The model developed in their research is needed to be verified by the observational data.

A model to estimate solar radiation for Ulaanbaatar is improved with use of observational cloud cover data. Firstly, the main parameters are identified by finding out the correlation between observed global solar radiation and other weather elements for Ulaanbaatar.

When solar radiation is absorbed by the earth, the ground temperature will rise. Heat is transmitted from the earth surface to the air through convection and as a result air temperature increases with time delays. Therefore, there should be some relationship between solar radiation and air temperature increases, which is also proved by life experiences. Figure 2.4 shows the relationship between observational global solar radiation and a temperature increases for 2015. The correlation coefficient is 0.58 which implies temperature increases may be selected as one of the parameters of the solar model.

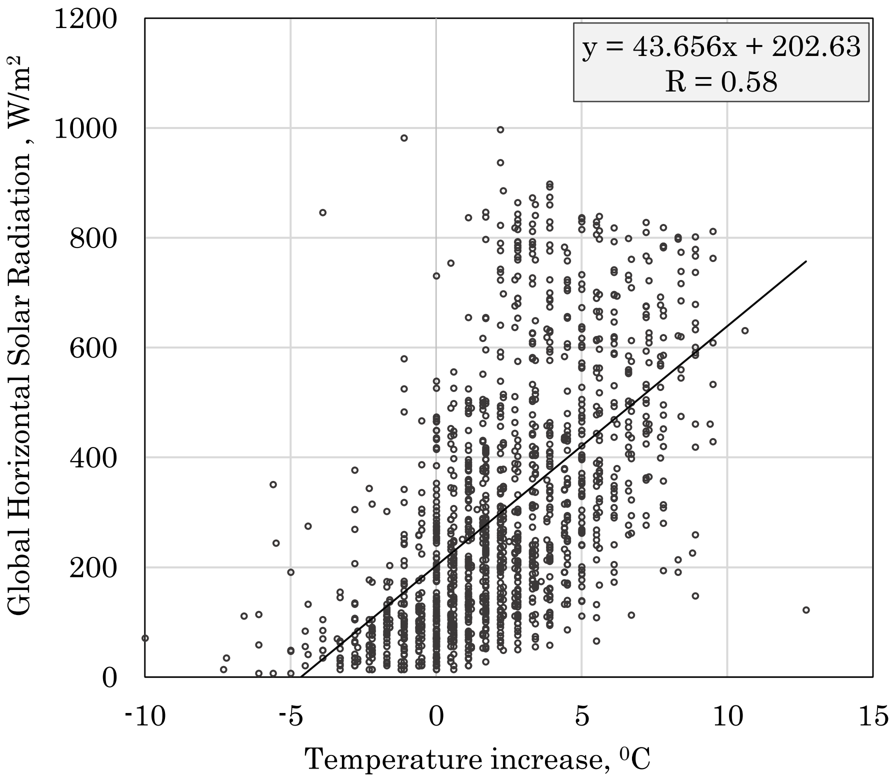


Fig.2.4 Relationship between temperature increase and observational global solar radiation for 2015

Correlation between relative humidity and solar radiation was examined for Chinese locations in previous studies [21]. Figure 2.5 shows the relationship between observational solar radiation and relative humidity for Ulaanbaatar using observational data of 2015. The correlation coefficient is equal to 0.42 therefore, relative humidity was chosen as another parameter. However relative humidity is not absolutely independent to air temperature, it is selected as one of the parameters to improve preciseness of the model.

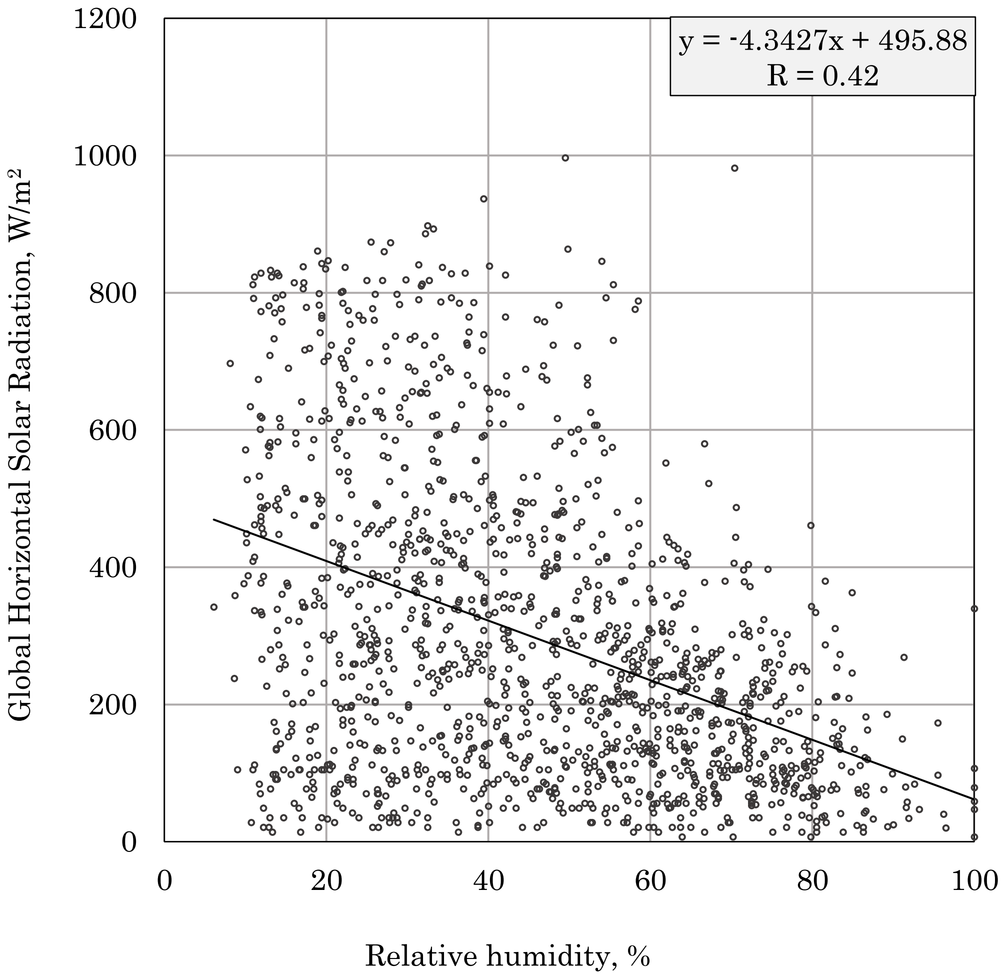


Fig.2.5 Relationship between relative humidity and observational global solar radiation for 2015

In order to select the next parameter relationship between cloud cover and the observational solar radiation is examined as shown in Fig.2.6. The correlation coefficient is 0.29 and 0.38 with linear and quadratic approximations, respectively. Therefore, the quadratic approximation is used in the solar model.

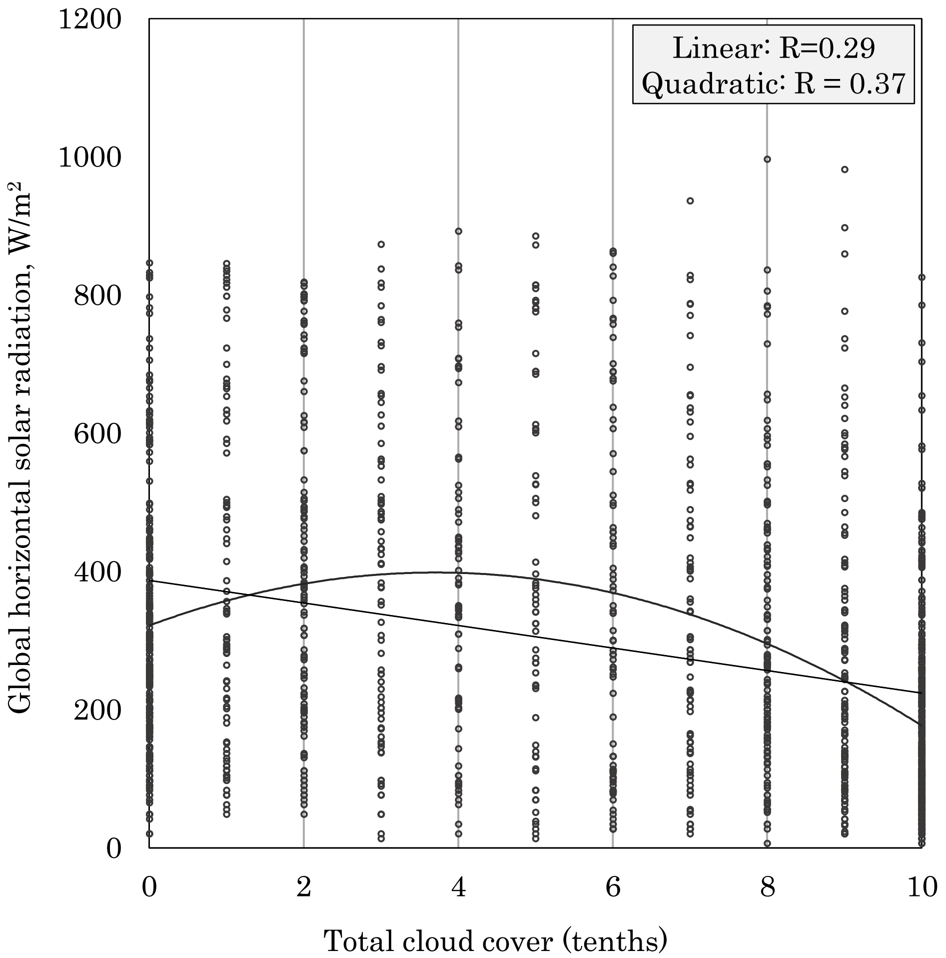


Fig.2.6 Relationship between cloud cover and observational global solar radiation for 2015

As discussed above, temperature increase, relative humidity, and total cloud cover were chosen as the parameters of the solar model. Wind speed was excluded because the relationship between wind speed and the observational solar radiation data was weak.

Solar radiation on the ground is related to the extraterrestrial radiation, and the values of the extraterrestrial radiation are defined in different ways. The National Aeronautics and Space Administration (NASA) stated that average solar extraterrestrial radiation above atmosphere is equal to 1365.4±1.3 W/m^2 in 1990 [22] based on the total irradiance monitor on solar radiation and climate experiment. The American Society of Heat Refrigeration and Air Conditioning Engineering (ASHRAE) suggested to use values of 21st day of each month for engineering calculations which vary depending on earth-sun distance [23]. Duffie et al. proposed an equation to estimate the extraterrestrial solar radiation depending on earth-sun distance changing with the number of days starting from 1st January [24] as shown in equation (2.5):

$$I_{sc} = I_0 \left\{1 + 0.033cos\left(\frac{2\pi n_d}{365}\right)\right\} \tag{2.5}$$

Values of the extraterrestrial solar radiation determined by the different sources mentioned above are compared in Fig.2.7. The extraterrestrial radiation does not change throughout a month according to the ASHRAE method and errors by the Duffie method are the smallest among all the three. Therefore, the Duffie method was selected to estimate the extraterrestrial solar radiation in this study.

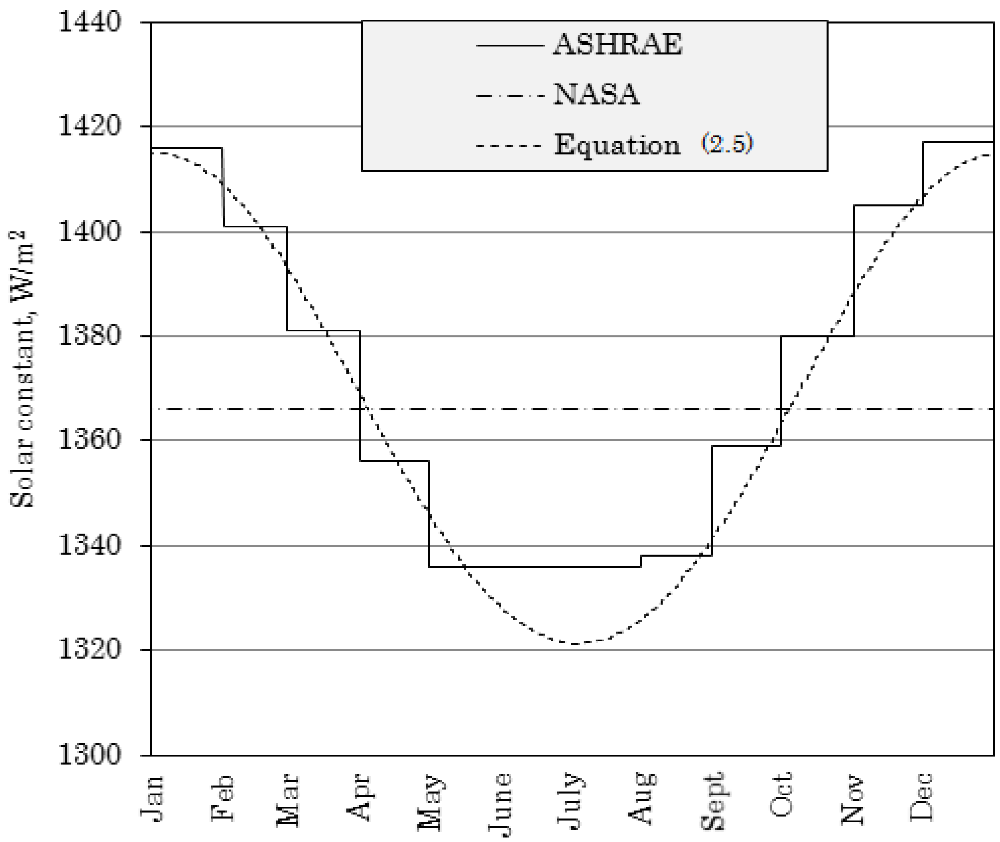


Fig.2.7 Extraterrestrial solar radiation comparison by various methods

Using the extraterrestrial solar radiation estimated by equation (2.5) and dry bulb temperature increase, relative humidity, total cloud cover as parameters an equation (2.6) to estimate global solar radiation on the horizontal surface in Ulaanbaatar was developed:

$$\mathrm{I} = \left[I_{sc} \cdot \sin(h) \left\{ 0.6496 + 0.2564 \left(\frac{CC}{10}\right) - 0.5762 \left(\frac{CC}{10}\right)^2 + 0.0130(T_n - T_{n-3}) - 0.0017\varphi \right\} - 12.364 \right] / 0.906 \quad (2.6)$$

The constants in equation (2.6) are determined by the least square method against observational solar data for 2015. The relationship between estimated solar radiation using the equation (2.6) and observed solar radiation for the year of 2015 is presented in Fig.2.8. The RMSE is 69 W/m², which implies the global solar radiation on the horizontal surface can be estimated with limited errors.

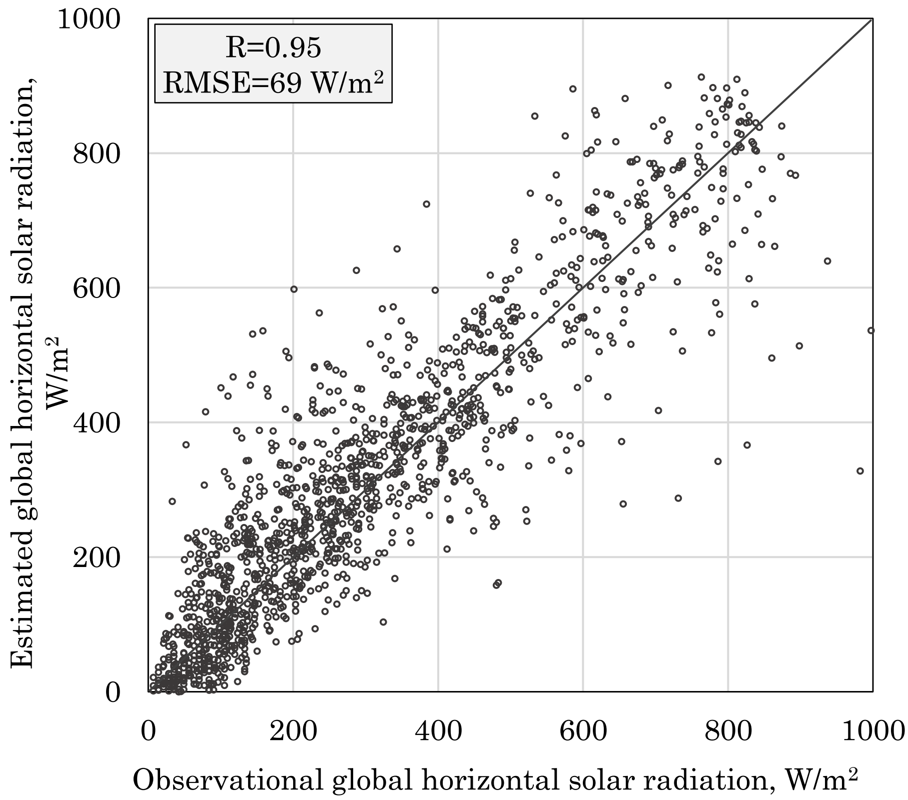


Fig.2.8 Correlation between observational and estimated solar radiation using the model developed for Ulaanbaatar

In order to see improvement of the model developed in this study, the model developed for Beijing, China to estimate solar radiation was compared with the observational solar data in 2015. Figure 2.9 shows the correlation between global radiation for observations and estimations by the Beijing model. The RMSE is 73.5W/m^2, which is 6.5% larger than that of RMSE shown in Fig.2.8. A comparison of the estimated solar radiation with equation (2.6) and the observed values for several sample days is shown in Fig.2.10. The hourly values agree with estimations by equation (2.6) well.

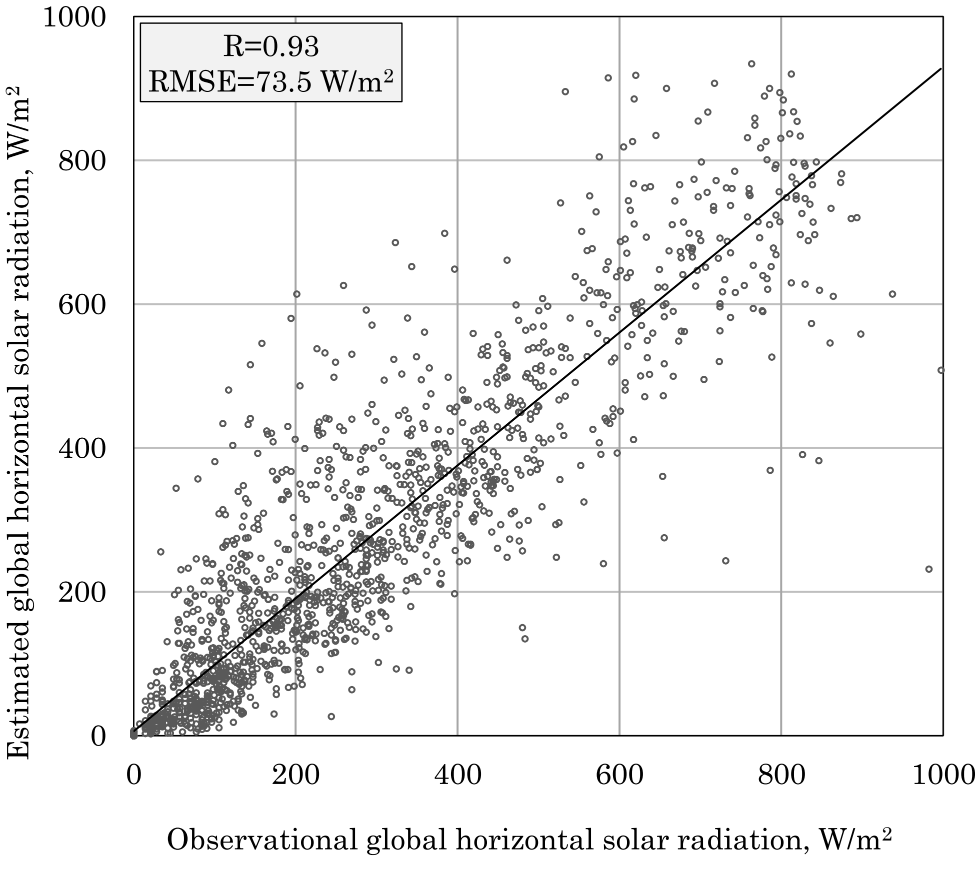


Fig.2.9 Correlation between observational and estimated solar radiation using the model developed for Beijing

Accumulated monthly estimates and observations of global solar radiation are compared in Fig.2.11, where the two bars agree with each other in most of the months throughout the year except for March and May where estimations with equation (2.6) are slightly larger than the estimation.

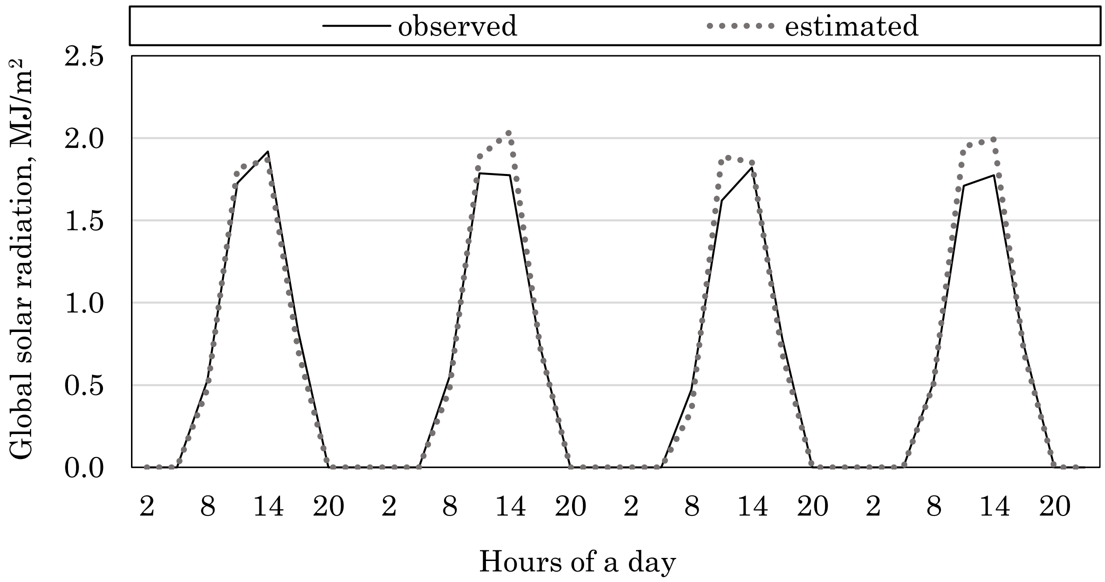


Fig.2.10 Sample of day series of hourly estimated and observed solar radiation from 2nd October to 4th October 2015

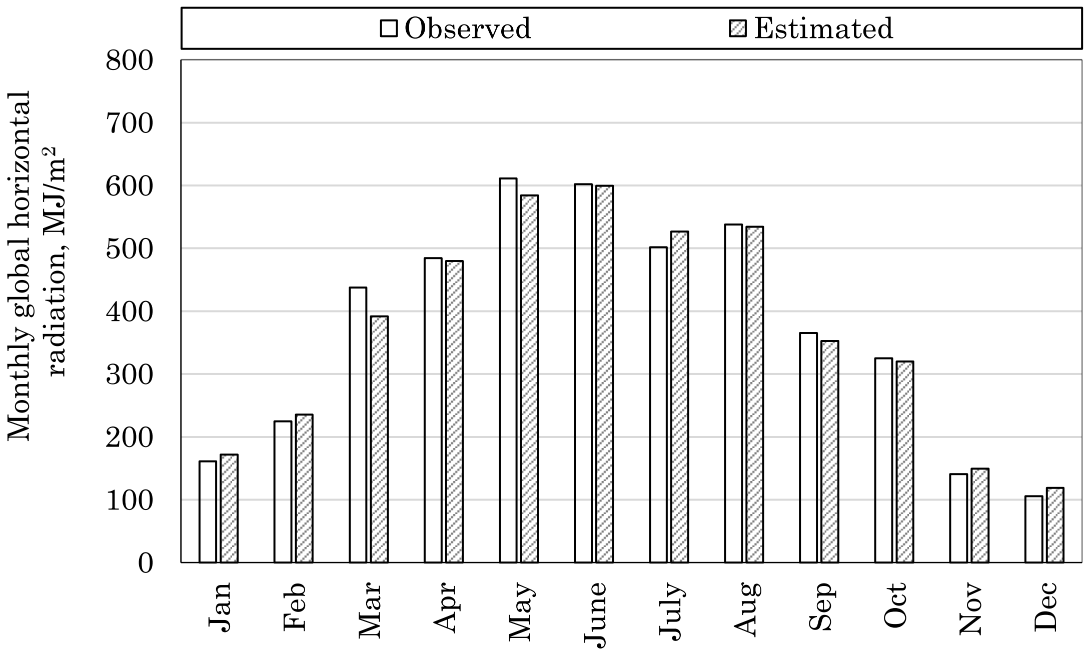


Fig.2.11 Monthly observed and estimated global solar radiation comparison for Ulaanbaatar, Mongolia in 2015

Global horizontal solar radiation is needed to be separated into direct normal and diffuse components for building simulations. Zhang method to separate global horizontal solar radiation into direct normal and diffuse components using Gompertz function was used similarly in this study [25]. Equations (2.7) - (2.10):

$$k_T = \frac{1}{I_0 sinh} \tag{2.7}$$

$$k_n = A_1 \cdot A_2^{-A_3 A_2^{-A_4 k_T}} \tag{2.8}$$

$$I_n = k_n \cdot I_0 \tag{2.9}$$

$$I_d = I - I_n \cdot sinh \tag{2.10}$$

Values of $A_1, A_2, A_3,\ A_4$ are determined by the equations (2.11) - (2.14):

$$A_1 = -0.1556 sin^2 h + 0.1028 sinh + 1.3748 \tag{2.11}$$

$$A_2 = 0.7973 sin^2 h + 0.1509 sinh + 3.035 \tag{2.12}$$

$$A_3 = 5.4307 sinh + 7.2182 \tag{2.13}$$

$$A_4 = 2.990 \tag{2.14}$$

Correlation between direct radiation on the horizontal surface from equations (2.7) - (2.14) and observations for the year of 2015 are shown in Fig.2.12 to check the applicability of Gompertz function for Ulaanbaatar. The correlation coefficient is 0.97 with root mean square error of 42 W/m^2. Therefore, the Gompertz function used to separate global radiation into direct normal and diffuse components for Ulaanbaatar due to high correlation and small errors. The smaller error (42 W/m^2) found for direct normal radiation comparing to the error shown in Fig.2.8 is the diffuse radiation is more difficult to estimate than the direct one; the estimation error of the diffuse radiation is included in the estimation error of the global horizontal radiation.

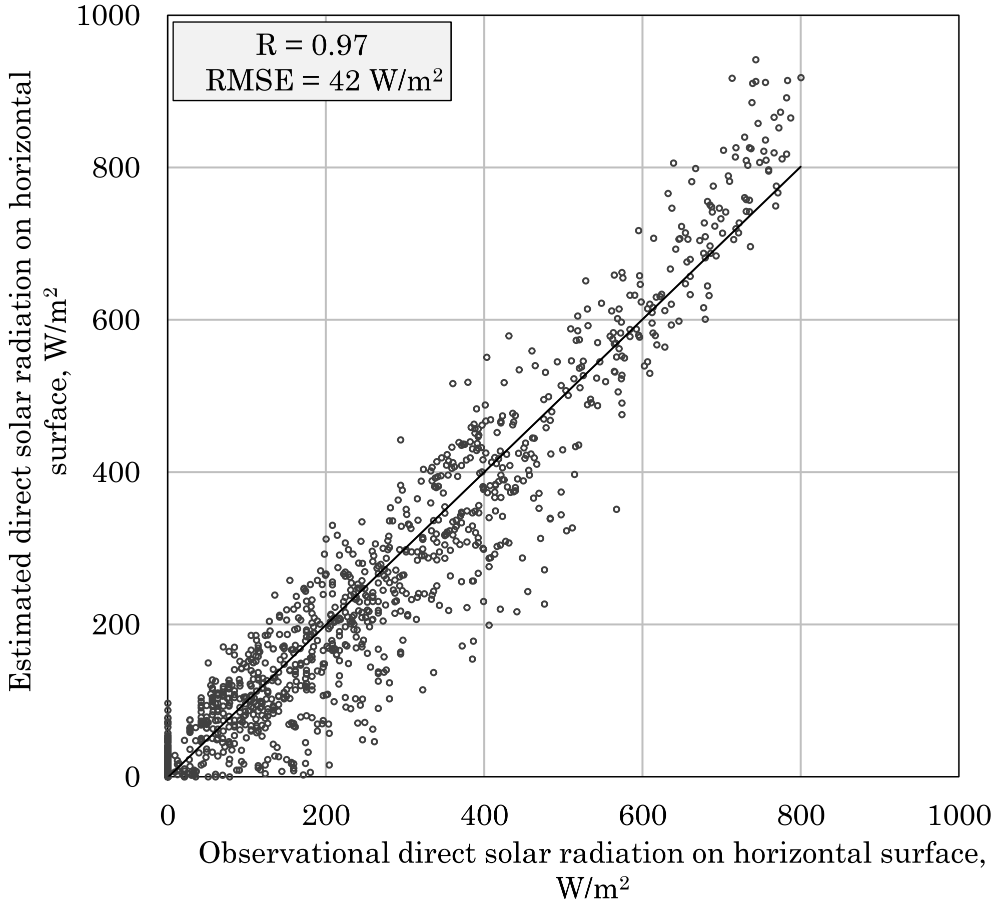


Fig.2.12 Correlation between direct normal radiations from estimation and observations for 2015

2.5 Development of the Typical Meteorological Year

Typical meteorological year (TMY) consists of 12 typical meteorological months (TMMs) where each element is close to the average of the historical years considered. The main elements used for TMM selection are dry bulb temperature, dew point temperature, wind speed and global solar radiation on the horizontal surface. The global solar radiation on the horizontal surface was estimated with the developed model. The selection of TMMs followed the method by comparing the standard deviations of each element developed in a previous study [19]. The procedure of TMM selection is as follows:

1. Select the months whose average dry bulb temperature, dew point temperature, global solar radiation, and wind speed are within the range of 0.6 times than the

standard deviation. If no candidate left in this step the second step will be carried out. If there are more than one candidate fourth step will be followed;

2. Select the months whose average dry bulb temperature, dew point temperature, global solar radiation, and wind speed are within the range of 0.8 times than the standard deviation. If no candidate left in this step the third step will be carried out. If there are more than one candidate fourth step will be followed;
3. Select the months whose average dry bulb temperature, dew point temperature, global solar radiation, and wind speed are within the range of the standard deviation. If no candidate left in this step the fourth step will be carried out;
4. Compare the weighted sum values of the remaining months and select the whose weighted sum is the smallest. Weighted sum was estimated according to NCDC guideline with equation (2.15) - (2.16) [26].

$$\mathrm{WS} = \sum(w_i FS_i) \tag{2.15}$$

$$FS_i = \frac{1}{n}\sum_{i=1}^{n} \delta_i \tag{2.16}$$

The smaller Finkelstein-Shafer statistic means structure of variable is closer to the average year. Table 2.2 shows weights of the dry bulb temperature, dew point temperature, wind speed and global solar radiation on horizontal surface according to their importance for the selection procedure.

Table 2.2 Weights of the variables

Dry bulb temperature			Dew point temperature			Wind speed		Global solar radiation
Max	Min	Average	Max	Min	Average	Max	Average	
1/24	1/24	2/24	1/24	1/24	2/24	2/24	2/24	12/24

The selected twelve TMMs are shown in Table 2.3 along with the years selected from 10 years. The developed TMY consists of hourly data of weather elements such as dry bulb temperature, relative humidity, humidity ratio, global solar radiation on the horizontal surface, direct normal solar radiation, diffuse radiation, wind direction, wind speed, total cloud cover, and station and sea level pressures. The TMY containing 8760-hour data is saved in a text file. The format of the TMY file is shown in Fig.2.13. Since the TMY consists of typical months that are selected from different years, there might be discontinued gaps for temperature data between the end of a month and the beginning of next month. This was corrected by equation (2.17):

$$\theta_i = \frac{12-i}{12}\theta_i' + \frac{i}{12}\theta_i'' \qquad (2.17)$$

Dry bulb and dew point temperatures have become continuous series data after connecting them smoothly using equation (2.17).

Table 2.3 Comparison of 10-year average and monthly average of TMMs

Month	Years when TMMs are selected	Hourly global solar radiation, MJ/m^2		Dry bulb temperature, ^{0}C		Dew point temperature, ^{0}C		Wind speed, m/s	
		Daily average of 10 year	Daily average of selected months	Daily average of 10 year	Daily average of selected months	Daily average of 10 year	Daily average of selected months	Daily average of 10 year	Daily average of selected months
Jan	2007	5.5	5.3	-22.1	-21.5	-26.0	-24.6	1.4	1.2
Feb	2009	8.5	8.6	-17.9	-19.0	-22.9	-23.8	1.9	1.9
Mar	2009	12.6	12.5	-7.7	-8.7	-15.6	-16.0	2.6	2.8
Apr	2012	16.4	16.2	3.0	2.7	-10.4	-11.2	3.3	3.1
May	2006	18.9	18.7	10.2	8.6	-4.7	-5.3	3.7	3.7
Jun	2006	18.7	19.7	17.0	16.0	4.0	4.6	3.4	3.6
Jul	2015	17.6	16.9	19.4	19.9	9.3	8.4	2.9	2.9
Aug	2009	16.2	16.4	17.2	16.6	7.4	8.3	2.8	2.9
Sept	2006	14.3	15.3	10.7	10.9	-0.4	-0.2	2.8	3.0
Oct	2008	9.6	9.7	1.5	0.8	-7.0	-6.4	2.4	2.5
Nov	2011	5.7	5.6	-10.3	-10.2	-15.7	-16.0	2.0	2.0
Dec	2010	4.2	4.1	-19.3	-18.9	-23.0	-23.3	1.6	1.6

MON	DAY	HOUR	LOCT	TEM	RH	X	TH	NR	DF	WD	WS	CC	AZ	HT	AP
12	30	18	17.1	-24.6	66	3.8	0	0	0	10	2.4	0	999	0	876.2
12	30	19	18.1	-25.1	69	3.9	0	0	0	10	1.6	0	999	0	876.1
12	30	20	19.1	-25.6	70	3.7	0	0	0	13	.9	0	999	0	876.0
12	30	21	20.1	-26.4	70	3.5	0	0	0	13	.9	0	999	0	876.1
12	30	22	21.1	-26.9	70	3.3	0	0	0	13	.9	0	999	0	876.2
12	30	23	22.1	-27.2	69	3.2	0	0	0	2	.9	0	999	0	876.3
12	30	24	23.1	-27.6	68	3.0	0	0	0	2	.6	0	999	0	876.3
12	31	1	.1	-27.9	68	2.9	0	0	0	2	.3	0	999	0	876.4
12	31	2	1.1	-28.3	69	2.8	0	0	0	3	.0	0	999	0	876.4
12	31	3	2.1	-28.9	71	2.8	0	0	0	3	.6	0	999	0	876.3
12	31	4	3.1	-29.2	73	2.8	0	0	0	3	1.2	0	999	0	876.2
12	31	5	4.1	-28.9	73	2.8	0	0	0	4	1.8	0	999	0	876.1
12	31	6	5.1	-28.3	71	3.0	0	0	0	4	1.8	0	999	0	876.1
12	31	7	6.1	-27.7	70	3.1	0	0	0	4	1.8	0	999	0	876.0
12	31	8	7.1	-27.3	70	3.2	0	0	0	6	1.8	0	999	0	876.0
12	31	9	8.1	-27.1	70	3.3	16	238	9	6	1.8	0	-51	1	876.2
12	31	10	9.1	-26.6	70	3.4	144	773	25	6	1.8	0	-40	8	876.3
12	31	11	10.1	-25.6	66	3.5	280	1057	17	5	1.8	0	-27	14	876.5
12	31	12	11.1	-24.1	60	3.6	377	1197	9	5	2.2	0	-13	17	876.0
12	31	13	12.1	-22.4	53	3.8	399	1197	10	5	2.7	0	1	18	875.6
12	31	14	13.1	-21.1	49	3.9	369	1201	9	5	3.1	0	15	17	875.1
12	31	15	14.1	-20.6	49	4.0	289	1208	5	5	2.7	0	29	13	875.3
12	31	16	15.1	-20.9	51	4.1	142	975	11	5	2.2	0	42	7	875.5
12	31	17	16.1	-21.7	55	4.1	0	0	0	7	1.8	0	53	0	875.7
12	31	18	17.1	-22.4	57	4.1	0	0	0	7	1.8	0	999	0	875.9
12	31	19	18.1	-22.8	58	4.0	0	0	0	7	1.8	0	999	0	876.0
12	31	20	19.1	-23.0	59	3.9	0	0	0	4	1.8	0	999	0	876.2
12	31	21	20.1	-23.1	59	3.9	0	0	0	4	1.8	0	999	0	876.3
12	31	22	21.1	-23.5	61	3.9	0	0	0	4	1.8	0	999	0	876.4
12	31	23	22.1	-24.4	63	3.7	0	0	0	4	1.8	0	999	0	876.5
12	31	24	23.1	-25.6	65	3.4	0	0	0	4	1.8	0	999	0	876.5

```
MON ---> MONTH
DAY ---> DAY
HOUR---> HOUR
LOCT---> LOCAL TIME IN HOUR
TEM ---> DRY-BULB TEMPERATURE IN DEGREE CELSIUS
RH  ---> RELATIVE HUMIDITY IN %
X   ---> HUMIDITY RATIO IN 0.1 G/KG
TH  ---> TOTAL HORIZONTAL SOLAR RADIATION IN W/M2
NR  ---> SOLAR RADIATION IN NORMAL DIRECTION IN W/M2
DF  ---> DEFUSE SOLAR RADIATION IN W/M2
WD  ---> WIND DIRECTION IN ONE-16TH
WS  ---> WIND SPEED IN ONE-TENTH M/S
CC  ---> CLOUD COVER IN ONE-TENTH
AZ  ---> SOLAR AZIMUTH IN DEGREE; 999 MEANS BEFORE SUN-RISING
HT  ---> SOLAR ALTITUDE IN DEGREE; 0 MEANS BEFORE SUN- RISING
AP  ---> ATMOSPERIC PRESSURE IN hPa
```

Fig.2.13 Format of the TMY weather file for Ulaanbaatar

2.1 Summary

The main conclusions from this chapter are:

- The solar radiation on the horizontal surface was modeled as equation (2.6) for Ulaanbaatar using observational data obtained from the NCDC and IRIMHE. Errors caused by the solar model developed in this study are smaller than those of the Beijing model by 6.5%;
- Using the dry bulb temperature, dew point temperature, wind speed and global horizontal solar radiation the TMY weather data was developed for Ulaanbaatar from a 10-years data period of 2006-2015. The TMY consists of 8760 hourly data of air elements. Further, the TMY is uploaded into the building energy simulation program for dynamic analyses.

CHAPTER 3
Investigation of indoor environment and energy consumption of apartments

3.1 Introduction

With the economic growth in Mongolia [1], people's living standard has been improving. As a result, energy consumption for residences has increased, which contributes to severe air pollution and energy shortages in recent years.

Currently there are three coal-fired cogeneration power plants and one heat-only plant supplying thermal energy to the district heating network in Ulaanbaatar. Total thermal energy produced is 6,265 Tcal in 2016 [27]. All plants have reached their utmost capacity and there would be shortages if energy consumption continues to increase [5]. So, energy conservation of residences is an urgent issue to deal with.

So far there have been conducted some studies on thermal environment of apartment buildings in Ulaanbaatar. Endo et al. [11] investigated the energy consumption and the indoor environment of the apartment building with insulated brick and insulated lightweight concrete structures in Ulaanbaatar. Ishikawa et al. [12] investigated the indoor environment of apartment buildings with precast ceramsite panel structure in Ulaanbaatar. They defined the heat loss coefficient for the buildings by measurement. None of these studies, however, could cover all the structure types, therefore it is impossible for them to compare energy consumption by structure types.

The purposes of Chapter 3 are to make clear energy consumption and the indoor environment of apartments through surveying and measurement. Apartment buildings in Ulaanbaatar with different types of structure are focused on and the indoor environment and the heat loss coefficient are clarified by questionnaire survey and measurement.

The questionnaire survey was conducted for 374 apartments with different structure types as shown in Fig.3.1 in order to get a general overview of apartments and households. Furthermore, 18 apartments are selected for measuring indoor environment elements such as air temperature, relative humidity and CO_2 concentration. The ventilation rate was calculated using CO_2 concentration data to estimate heat loss through ventilation. Finally, the heat loss coefficients of the apartment buildings with different structure types were compared with each other.

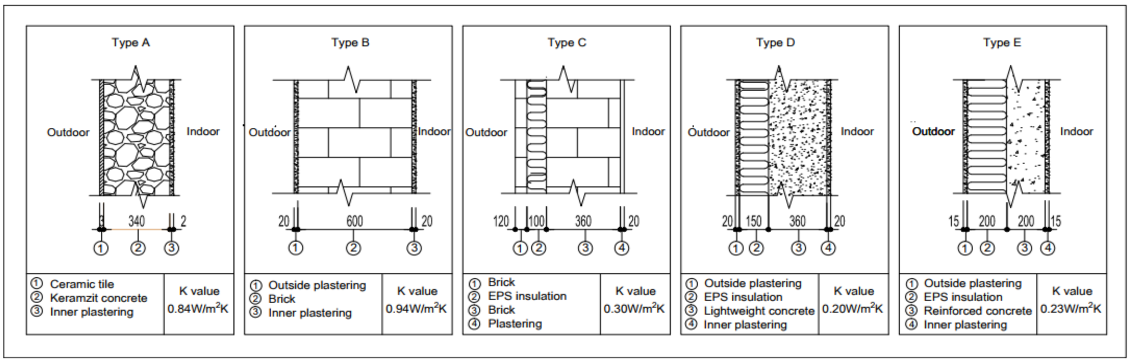


Fig.3.1 Cross sections of different structure types for the external walls

Abbreviations:

V	Ventilation rate [m^3/h];
m	CO_2 emission through exhaling [m^3/h];
p	CO_2 concentration in indoor air [ppm];
p_0	CO_2 concentration in outdoor air [ppm];
Q	Heat loss coefficient [W/ m^2K];
k_i	Heat transfer coefficient of the external wall [W/m^2 K];
A_i	Surface area of each external envelope [m^2];
A_f	Floor area of the apartment [m^2];
c_p	Specific heat of air [J/kgK];
ρ	Air density [kg/m^3];
Q_D	Space heating energy throughout heating season per household [GJ];
Q_H	Heating energy used for hot water supply throughout heating season per household [GJ];
HDD	Heating degree-days at 18 ^{0}C of room temperature [^{0}C.day].

3.2 Outline of the investigation

3.2.1 Methodology of the surveying and measurement

The questionnaire survey was conducted in order to obtain general information and indoor thermal comfort of the apartment buildings because the available statistical data was not sufficient. The questionnaire consists of general geometrical information, social information about households, thermal comfort and energy saving behavior of the households as shown in the Appendix A. Heating consumption was not asked in the questionnaire because the cost of consumed thermal energy is paid based on the heated floor area and there is no heat meter for each apartment. More than 400 questionnaires were distributed to households in different apartment buildings but 374 of them are fully answered.

Figure 3.2 shows the percentage of building type where the surveyed apartments are existed in. 32% of surveyed apartments are non-insulated brick, 27% are insulated brick, 24% are insulated light-weight concrete block and insulated reinforced concretes, 17% are precast ceramsite buildings, respectively.

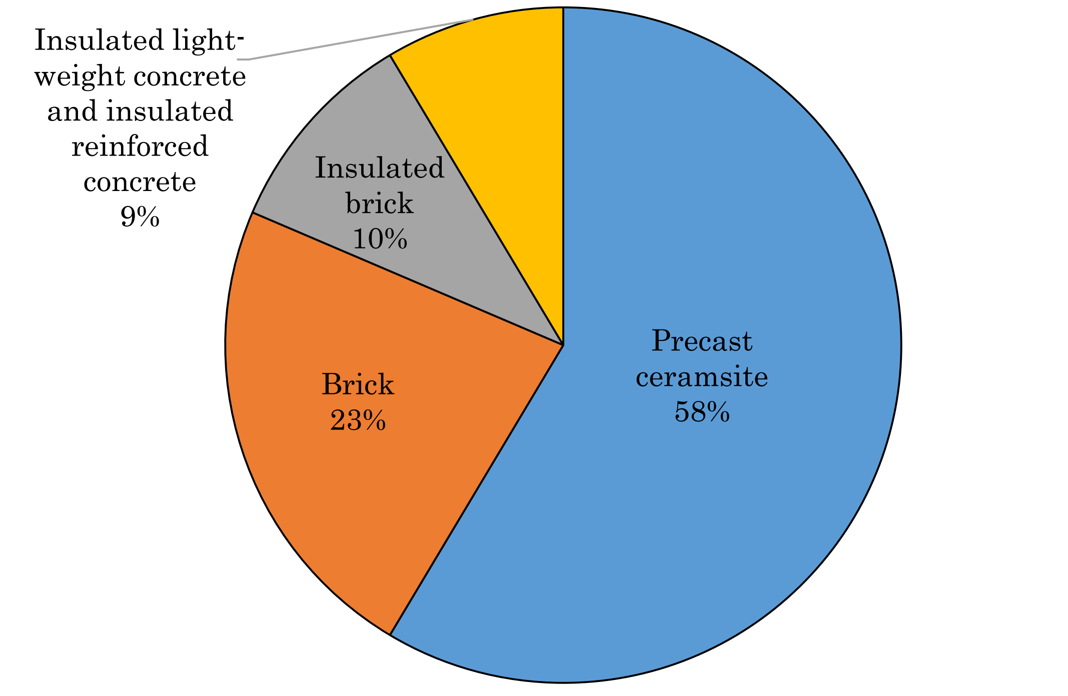


Fig.3.2 Surveyed building structure types

Eighteen of all surveyed apartments were randomly selected for measuring the indoor environment. All of the 18 apartments were measured for seven days. Residents spend most of their time in living rooms during the day and in most cases living rooms were used as bedrooms at night due to the lack of bedrooms. So, living rooms were chosen for measurement. The measuring period was divided into day and night because the activities were different. Measurements on the indoor environments of the apartment buildings were carried out during January - March,

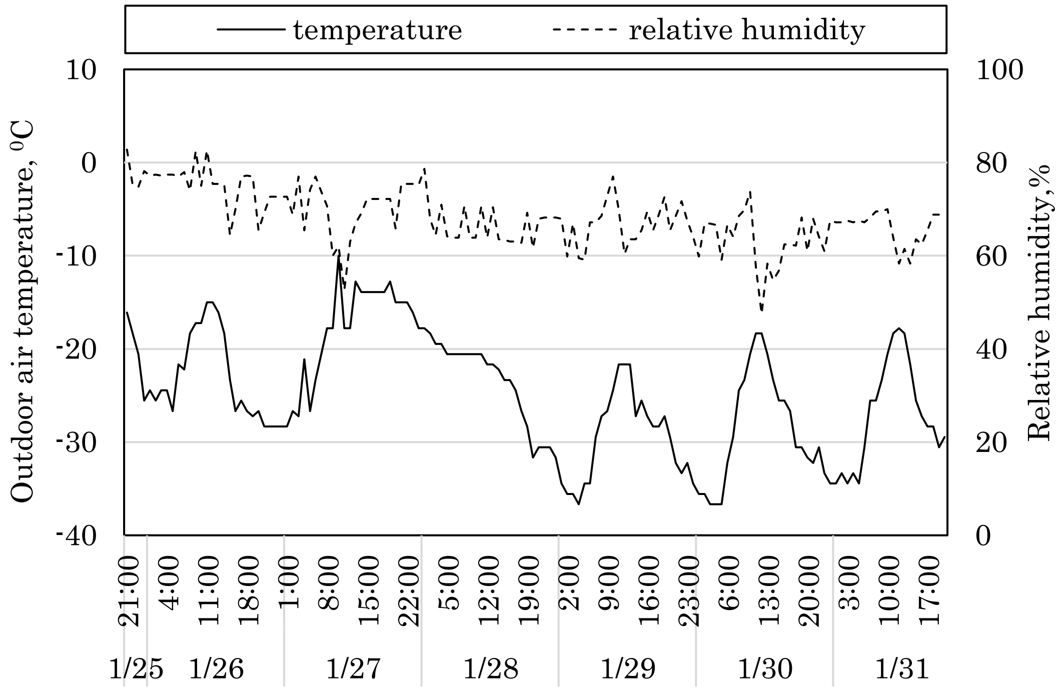
2017. Indoor air temperature, relative humidity and CO_2 concentration were measured and recorded using data loggers (TR-76Ui, T&D Corporation) in each living room at 1.0-1.5 m above floor level as shown in Photo 3.1. Measuring intervals are 10 minutes for each equipment. Measuring equipment and their accuracies are shown in Table 3.1.

The weather data during measurement period obtained from the National Climate Data Center [17]. Measurements of the indoor environment were conducted during four periods, the outdoor air temperature and humidity during which are shown in Fig.3.3. The outdoor air temperature during the last period (Mar.13-19, 2017) was higher than that of other periods because of the change of the seasons.

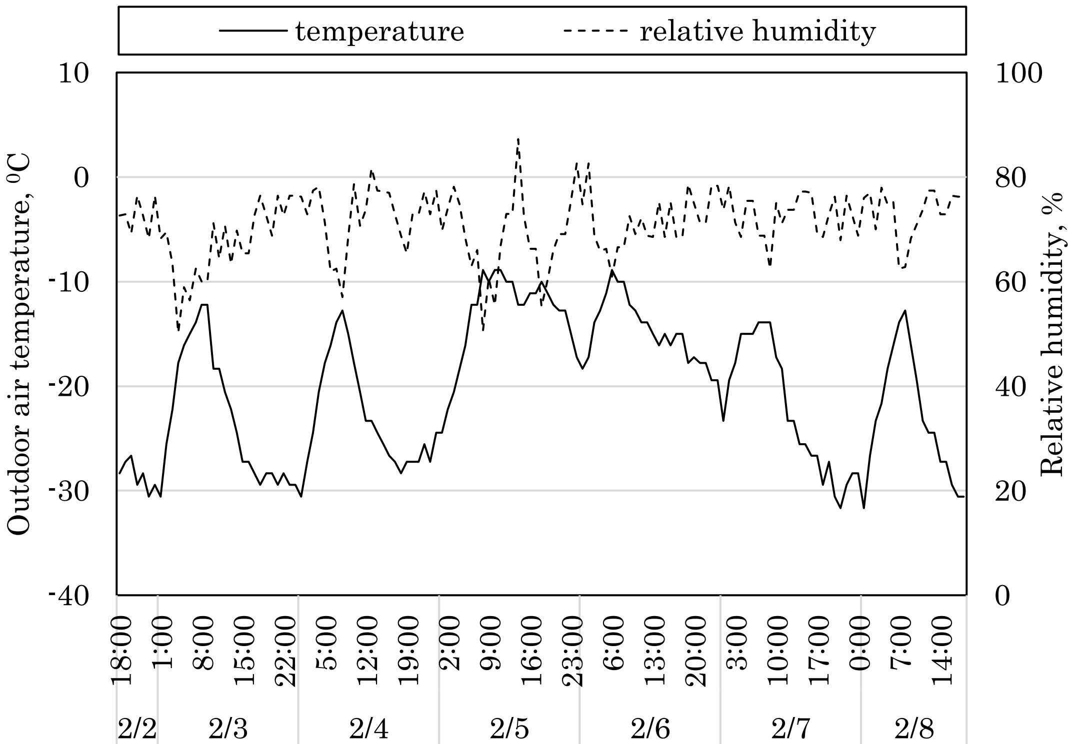
Photo 3.1 Installation of measuring equipment

Table 3.1 Measuring equipment

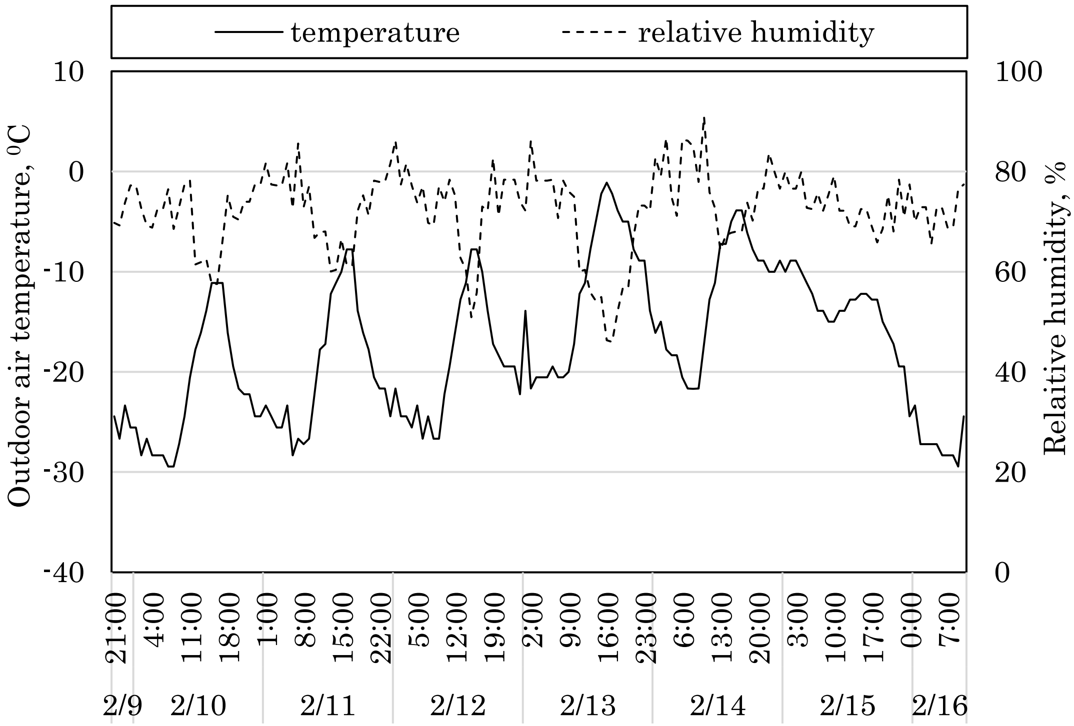
Equipment model	Elements	Accuracy
TR-76Ui	Air temperature	±0.5 ^0C
TR-76Ui	Relative humidity	±5%
TR-76Ui	CO_2 concentration	±50ppm



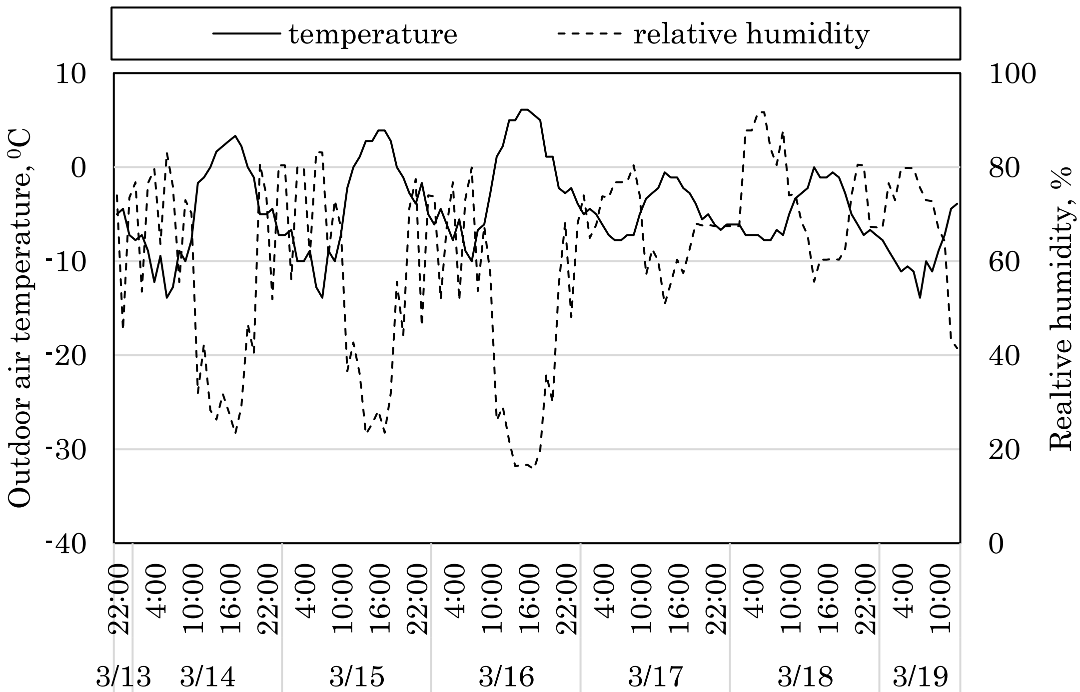
(a) The first period (Jan.25-31, 2017)



(b) The second period (Feb.2-8, 2017)



(c) The third period (Feb.9-16, 2017)



(d) The fourth period (Mar.13-19, 2017)

Fig.3.3 Outdoor air temperature and relative humidity during measurement periods

3.2.2 History of residential buildings

Ulaanbaatar has a history of more than 300 years [28]. Initially people of the Ulaanbaatar city used to live in the Gers which mean felt-insulated tents with wood frames. Even now some people live in the Gers because of their convenience to build and affordable price. Right after the revolution in 1921 building and construction sectors developed rapidly in the process of modernization.

The earliest residential buildings were built in the 1950's with 640 mm thick brick walls. In 1970's the Soviet technology using precast ceramiste panels for construction was introduced for residential buildings. Heat loss of these two structure types is large because there is no insulation on the external envelopes.

In 1997 the building code was updated, and thermal resistance requirement of the external envelopes were strengthened in order to save energy. All the buildings built after 1998 became insulated according to the code. After the year of 2000 insulated brick structure was introduced to Mongolia for residential buildings but did not last long because of its high labor consumption and heavy weight.

In 2010 two types of new technologies were developed such as lightweight concrete block structure and full concrete structure with thermal insulation. These two technologies are considered advanced due to high thermal resistance and high resistance to the earthquakes.

In 2014, 42.3% of total households in Ulaanbaatar live in apartment buildings and the rest households live in detached houses and the Gers [29]. All the structure types mentioned above with their heat transfer coefficient are shown in Fig.3.1. Heat transfer coefficient is the smallest for Type D (0.20 W/m^2 K) while it is the largest for Type B (0.94 W/m^2 K). The insulation material used for the external walls of types C, D and E is expanded polystyrene (EPS). Thickness of the insulation varies between 100 mm – 200 mm depending on the type of the main structure as shown in Fig.3.1.

3.2.3 Outline of investigated apartments

The outline of all the measured 18 apartments is summarized in Table 3.2. There are natural exhaust ventilation shafts in kitchens, toilets and bathrooms in all apartment buildings as shown in Fig.3.4.

Fresh air is supplied into the room by opening the window which is hard to control. Space heating devices such as radiators or steel convector as shown in Photo 3.2 are installed in the buildings that connect with the district heating system except Type E. Thermal energy is supplied by a heat-only boiler for Type E. Old buildings such as Type A and B have cast iron radiators originally unless the households replaced it with the steel convector. Cast iron radiator could be extended or removed by pieces while the steel convector is produced as a whole unit.

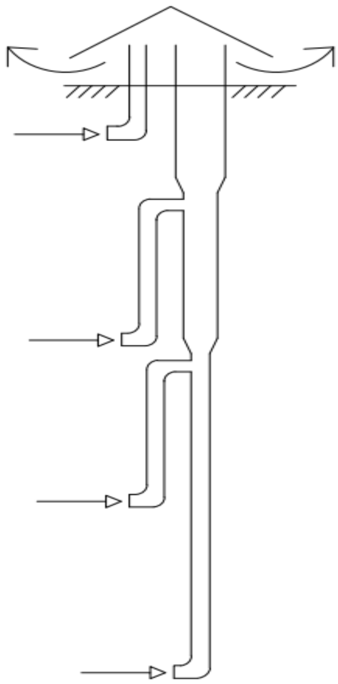


Fig.3.4 Natural ventilation shaft

a. Cast iron radiator

b. Steel convector

Photo 3.2 Space heating devices in the apartment

Table 3.2. Outline of the measured apartments

Structure type	Number	Floor/Total story	Orientation of the main window in living room	Extension of heating device	Total floor area, m^2	No. of residents	Built year
Type A (Precast ceramsite)	A1	3/5	N	Yes	60.5	5	1972
 View of building with A3	A2	2/9	N	No	85.0	2	1986
	A3	8/9	E	Yes	54.5	5	1987
Type B (Non-inlulated Brick)	B1	2/5	S	Yes	54.7	5	2000
	B2	4/4	E	No	52.0	2	1962
 View of building with B2	B3	3/3	E	No	86.0	4	1956
	B4	3/5	S	No	35.0	5	1990
TypeC (Insulated brick)	C1	6/6	E	No	NA	3	2000
	C2	6/6	W	No	56.0	3	2010
 View of building with C4	C3	5/12	E	No	58.0	4	2013
	C4	3/5	S	No	72.0	3	2004
Type D (Insulated light weight block)	D1	11/12	N	No	47.0	4	2010
	D2	7/12	E	No	40.0	3	2016
 View of building with D3	D3	11/12	S	No	48.0	2	2014
	D4	7/12	N	No	50.0	4	2013
	D5	7/12	N	No	59.0	5	2012
Type E (Insulated concrete)	E1	4/12	W	No	37.0	5	2016
 View of building with E1 and E2	E2	9/12	W	No	35.0	5	2016

3.3 Results of the surveying

The majority (87%) of surveyed apartments are self-owned and the rest are rental. The locations of the surveyed apartments are given by districts in the map shown in Fig.3.5.

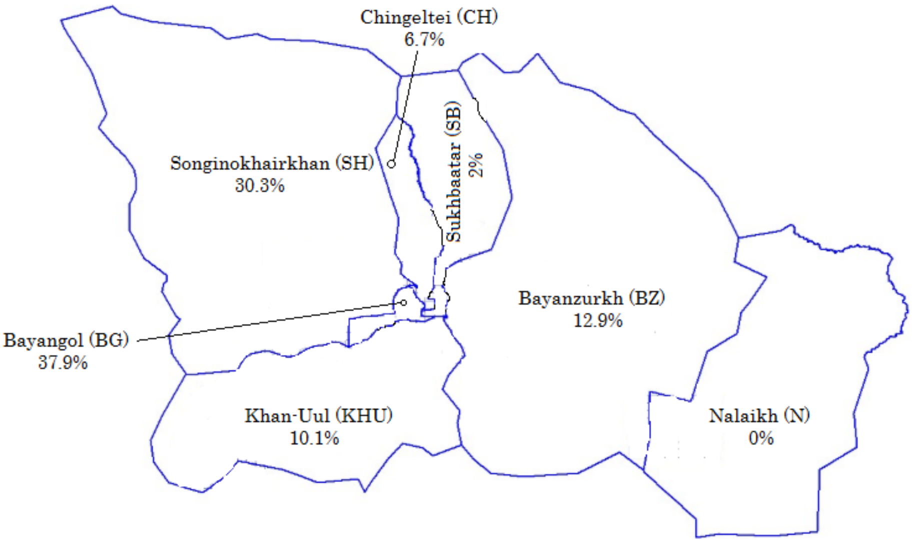


Fig.3.5 Locations of the surveyed apartments by districts

Questionnaire respondents are adults and 43% of them are male, and 57% are female. The age and occupation of the respondents are shown in Fig.3.6 and Fig.3.7.

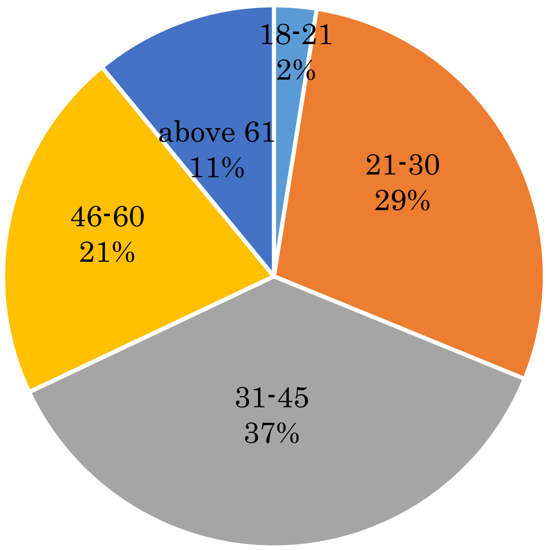


Fig.3.6 Ages of the questionnaire respondents

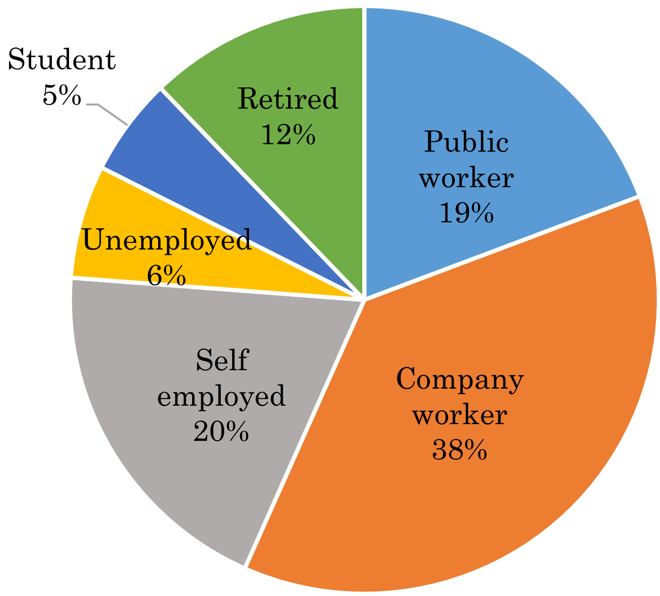


Fig.3.7 Occupation of the questionnaire respondents

The households are composed of couples with their children, couples with their parents, households with their relatives, couple without children and single person. Surveyed household structure is shown in Fig.3.8. The percentage of couple with their children is larger than other groups.

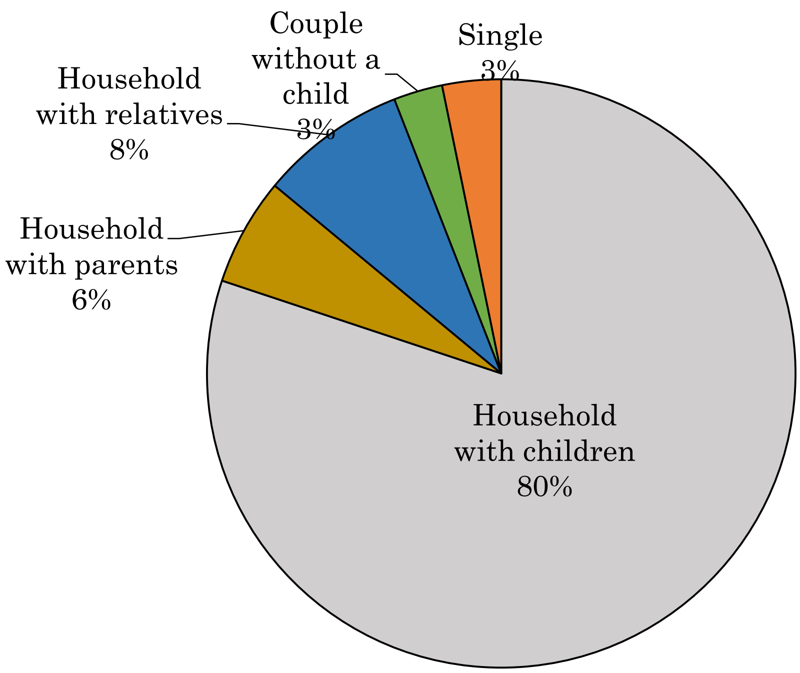


Fig.3.8 Household structure

Number of residents can be found in Fig.3.9 and households that have four to five residents account for the largest portion.

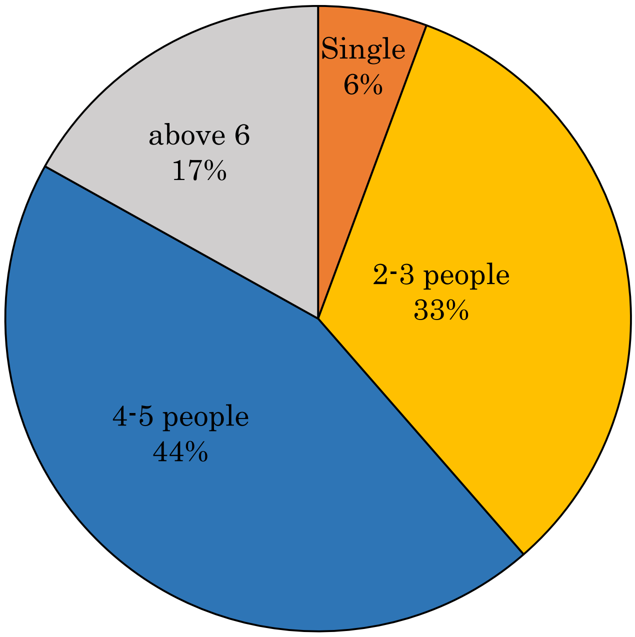


Fig.3.9 Resident number of households

Monthly incomes of the surveyed and measured households are shown in Fig.3.10, respectively. Monthly income of the measured households is equally divided into two groups such as 210 - 420 USD and 420 - 840 USD while the income of the surveyed households is divided into four categories. The economic condition of measured households is slightly better than surveyed ones by chance.

Fig.3.11 shows the floor area of each surveyed and measured apartments. Floor area of the measured apartments is larger than those surveyed, which might be related to the household income shown in Fig.3.10. Fig.3.11 shows the floor area of each surveyed and measured apartments. Floor area of the measured apartments is larger than those surveyed, which might be related to the household income shown in Fig.3.10.

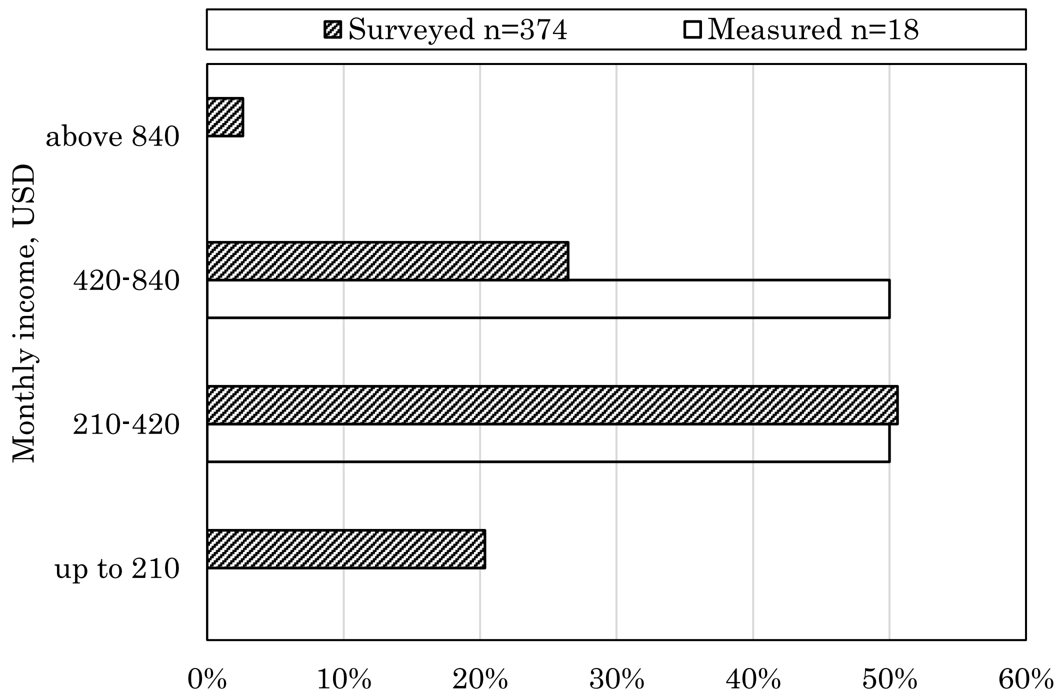


Fig.3.10 Monthly income of households

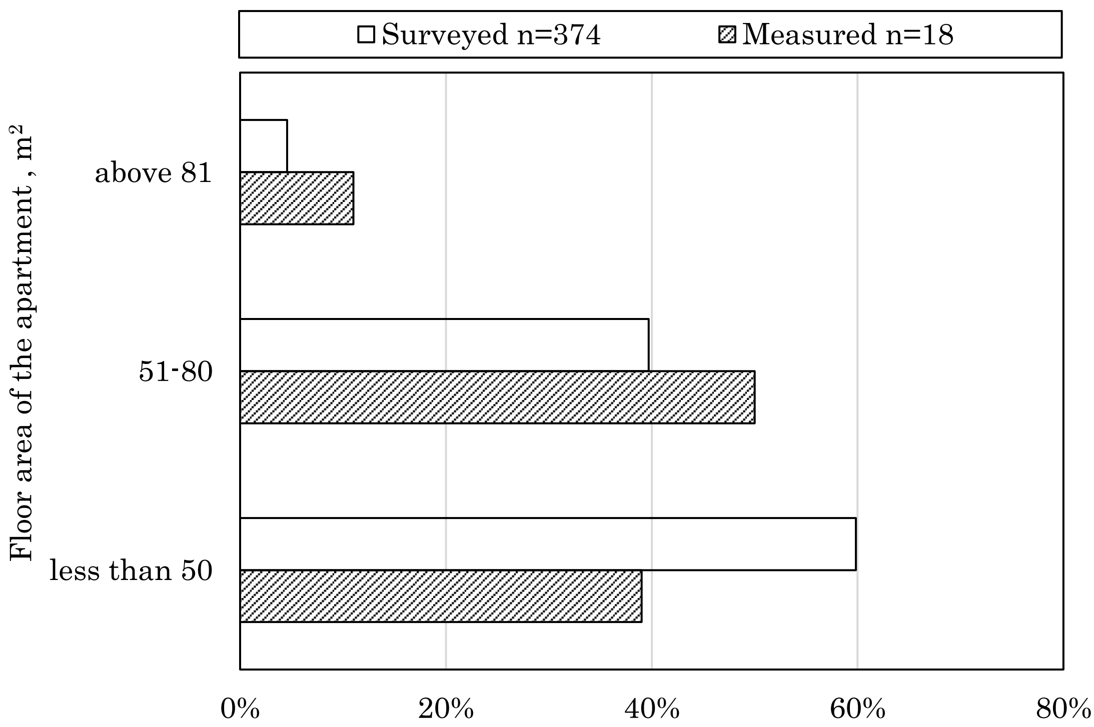


Fig.3.11 Floor area for an apartment

The indoor thermal environment of each apartment was evaluated in questionnaires by residents. As seen in Fig.3.12, 28% were very satisfied, 59% were satisfied and remaining 13% were dissatisfied with their indoor thermal environment.

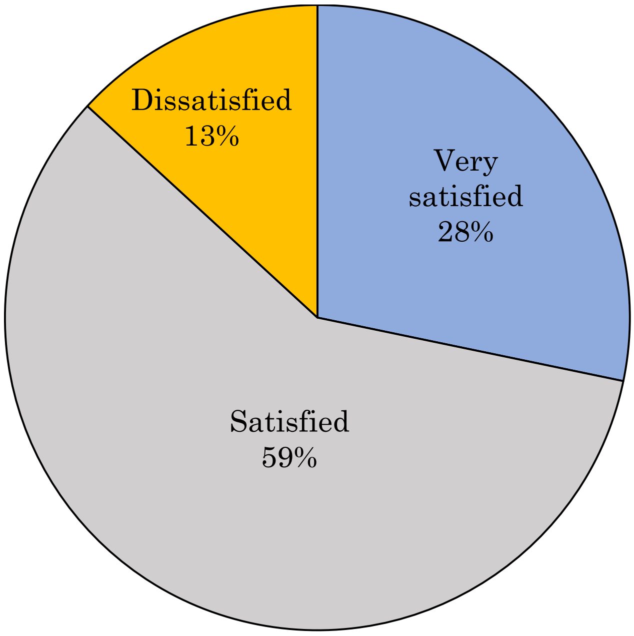
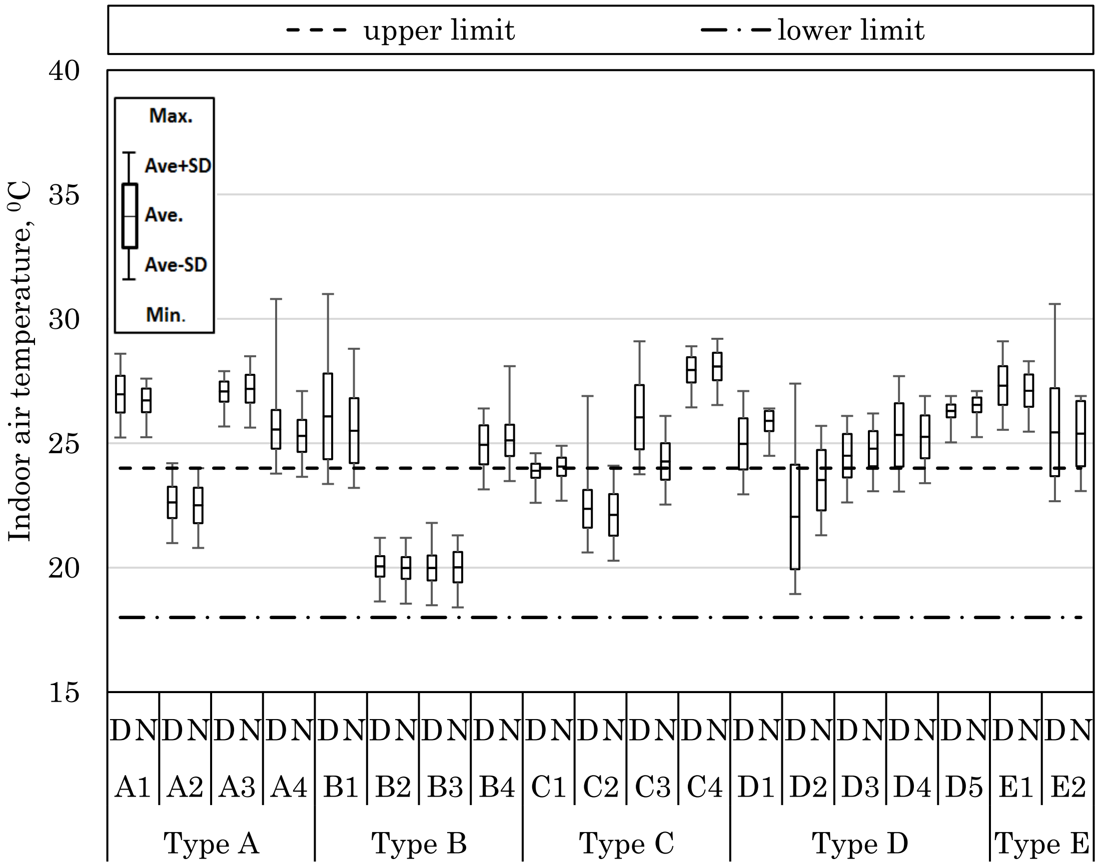


Fig.3.12 Evaluation of indoor thermal environment

3.4 Results of the measurement

3.4.1 Indoor air temperature

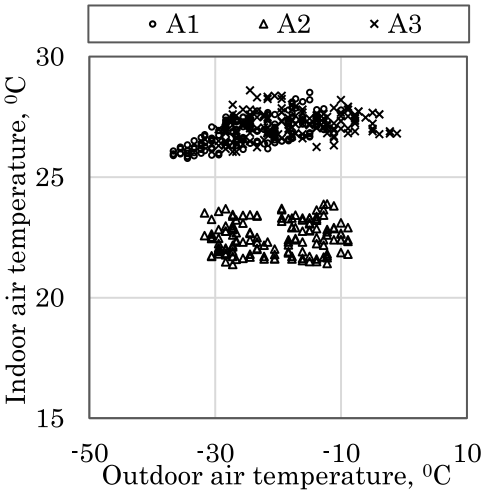
The measuring period was separated into day time (9:00-20:00) when some members go to work or to school, and night time (20:00-9:00) when all the members are gathered together at home. Figure 3.13 shows the standard deviations, maximum, minimum and average values of indoor air temperatures of the apartments. The average indoor air temperature of measured apartments is equal to 24.7 ^{0}C throughout day and night time. The highest average air temperature for Type C is 27.9 ^{0}C, in contrary the lowest is 20.0 ^{0}C for Type B apartments. The standard deviations of indoor air temperature during day time are larger than that of night time, which is assumed to be related to the air exchange behavior of the households. Households ventilate their apartments through opening windows occasionally when the indoor air temperature is too high, or the residents want to let in fresh air. These periods can be identified by significant drops in room temperature. According to the national standard [30], the upper limit air temperature is 24 ^{0}C while the lower limit is 18 ^{0}C for residential buildings. Indoor air temperature is higher than 24 ^{0}C for 66.7%, and between 18 ^{0}C – 24 ^{0}C for the rest hours. The indoor air temperature differs even within the same structure type.



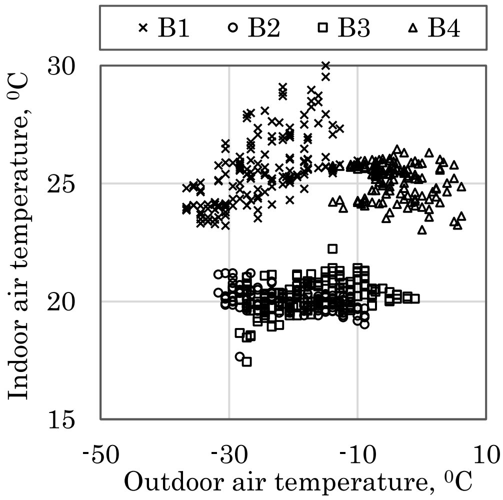
*D:Day time; N:Night time

Fig.3.13 Indoor air temperature in day and night time

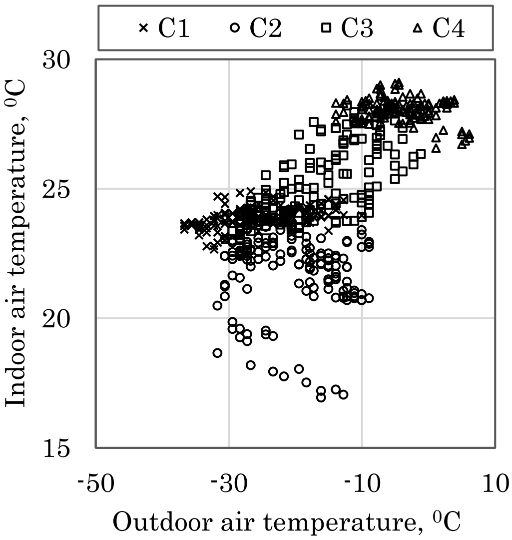
Figure 3.14 shows the relationship between indoor and outdoor air temperatures. In spite of the low outdoor air temperature, the indoor air temperature is kept above 20 ^{0}C in each apartment for most hours, which agrees with the studies of Ishikawa [12] and Endo [11].



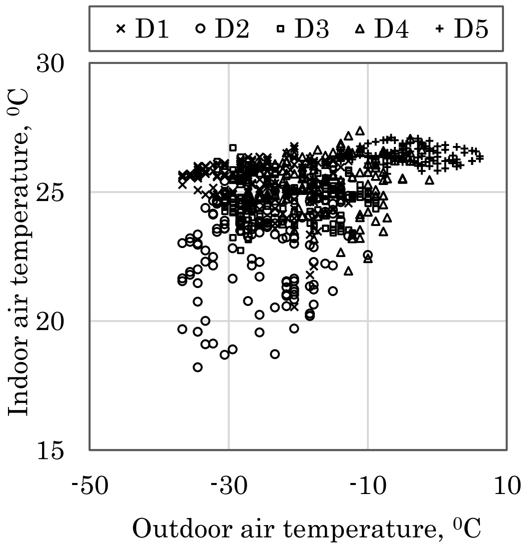
(a) Type A



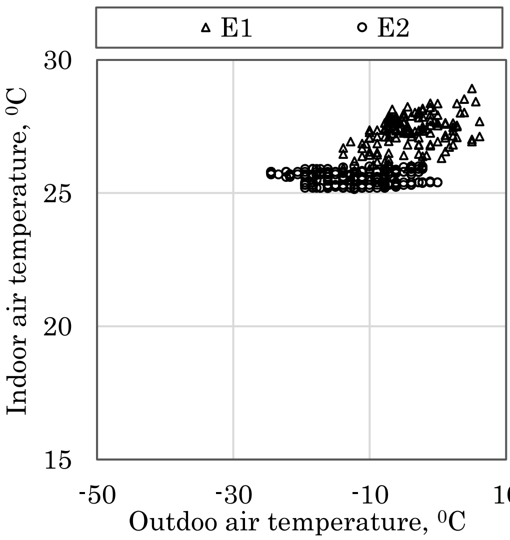
(b) Type B



(c) Type C



(d) Type D



(e) Type E

Fig.3.14 Relationship between indoor and outdoor air temperatures

3.4.2 Indoor air relative humidity

We compared indoor relative humidity of the apartments in day and night time as shown in Fig.3.15. The average indoor relative humidity was between 9% - 29% in day time and 10% - 30% during the night time, respectively, except for the B2 apartment. Relative humidity is lower than the national standard [30] level for most of the apartments. The highest average value in day time is 40% for B2 apartment and the lowest one is 9% for A3 apartment. Relative humidity was comparatively high in B2 apartment because of lower air temperature shown Fig.3.13 and Fig.3.14 (b).

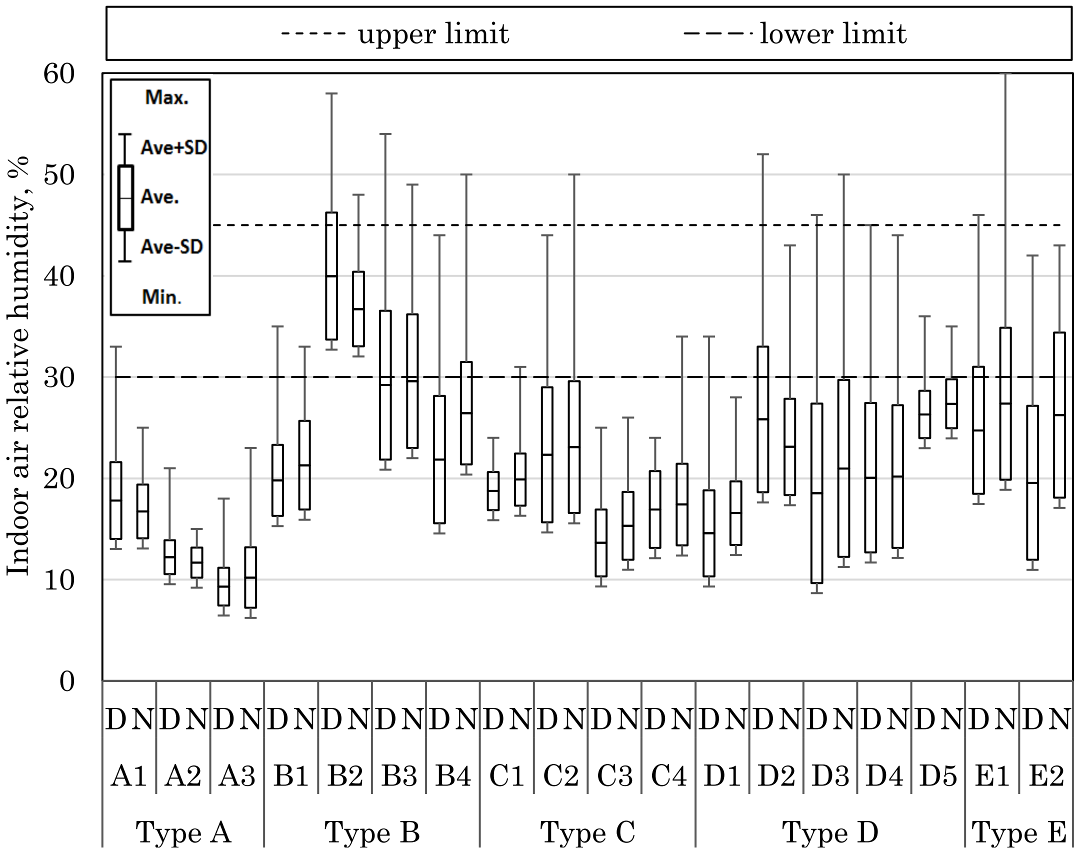


Fig.3.15 Indoor air relative humidity in day and night time

3.4.3 Thermal comfort

In order to clarify the indoor thermal environment of the apartments both indoor air temperature and relative humidity were plotted in the psychrometric chart by their structure types. Thermal comfort zone is drawn according to the ISO7730 [31]. In this chapter, we distinguished zones that are out of comfort zone into five zones such as Hot zone, Hot – Dry zone, Dry zone, Cold – Dry zone and Cold zone as shown in Fig.3.16. Table 3.3 shows the conditions of air temperature and relative humidity for the zoning of thermal comfort.

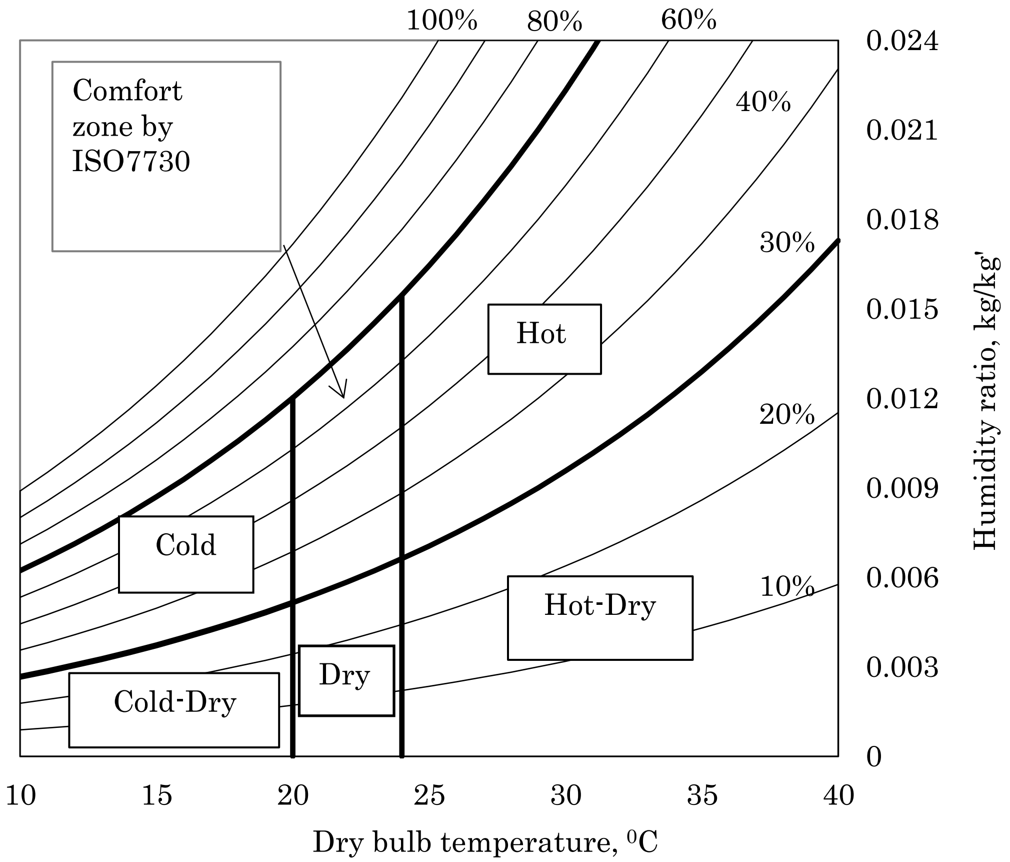


Fig.3.16 Indoor thermal environment zones

Table 3.3. Parameters of the indoor environment zones

No.	Zone	Indoor air temperature, θ	Indoor relative humidity, φ
1	Hot	θ >24 ⁰C	30%<φ ≤70%
2	Hot-Dry	θ >24 ⁰C	φ ≤30%
3	Dry	20⁰C<θ ≤24 ⁰C	φ≤30%
4	Cold-Dry	θ ≤20 ⁰C	φ ≤30%
5	Cold	θ ≤20 ⁰C	30%<φ ≤70%

Figure 3.17 shows the thermal indoor environment of Type A apartments. All the plots for the three apartments are out of Comfort zone. Plots for apartments A1 and A3 are in Hot - Dry zone and that for A2 are in Dry zone. Residents of A1 and A3 apartments have extended their radiators by themselves. Residents of A2 apartment, however, did not extend the radiators as others did, so that heat emitted to the apartment is less than other apartments, which results in lower indoor air temperature.

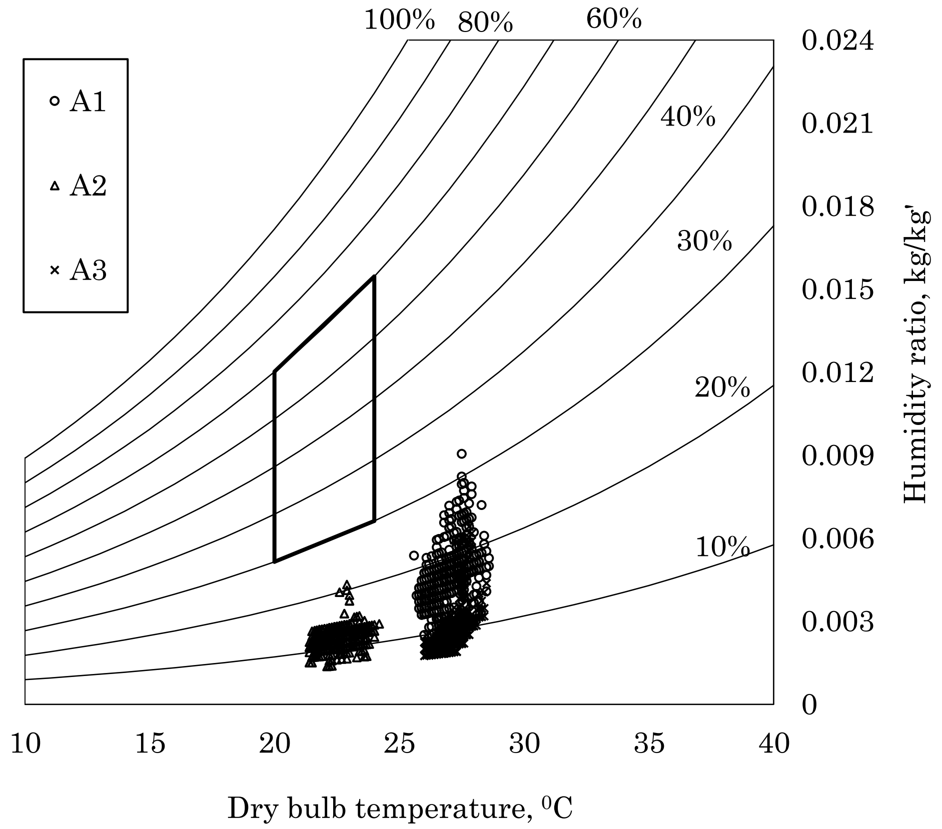


Fig .3.17 Thermal comfort of Type A apartments

Indoor thermal comforts of Type B apartments are given in Fig.3.18. Thermal environment is sometimes in Comfort zone and sometimes in Cold - Dry for B2 and B3 apartments as plotted in the psychrometric chart. Those two apartments have lowest temperatures and highest relative humidity as shown in Fig.3.13 and Fig.3.15 accordingly. The lower room temperature for B2 and B3 apartments is caused by roofs that enhance heat loss. The plots for B1 and B4 apartments distribute in Dry, Hot-Dry and Hot zones.

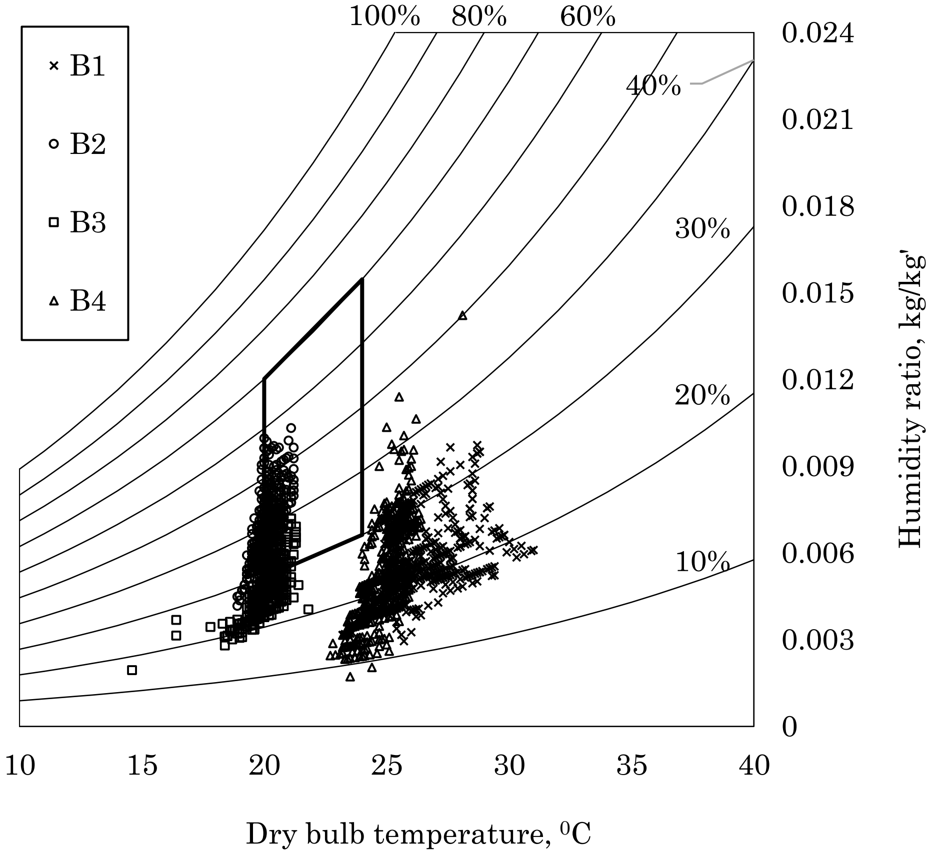


Fig.3.18 Thermal comfort of Type B apartments

Figure 3.19 shows the indoor thermal environment of the Type C apartments. Plots for C1, C3 and C4 are in the Hot-Dry zone while that for C2 is divided into Comfort and Dry zones for most hours.

Thermal comforts of the Type D apartments are shown in Fig.3.20. Plots for Type D apartments distribute widely in Hot, Hot – Dry and Dry zones while that for D2 apartment are in Comfort zone in most hours. Relative humidity for D2 is higher due to comparatively lower temperature.

The indoor environment of both E1 and E2 apartments is divided into Hot, Hot - Dry and Dry zones as seen in Fig.3.21. In some hours relative humidity increases significantly in E1 due to human activities such as cooking or shower.

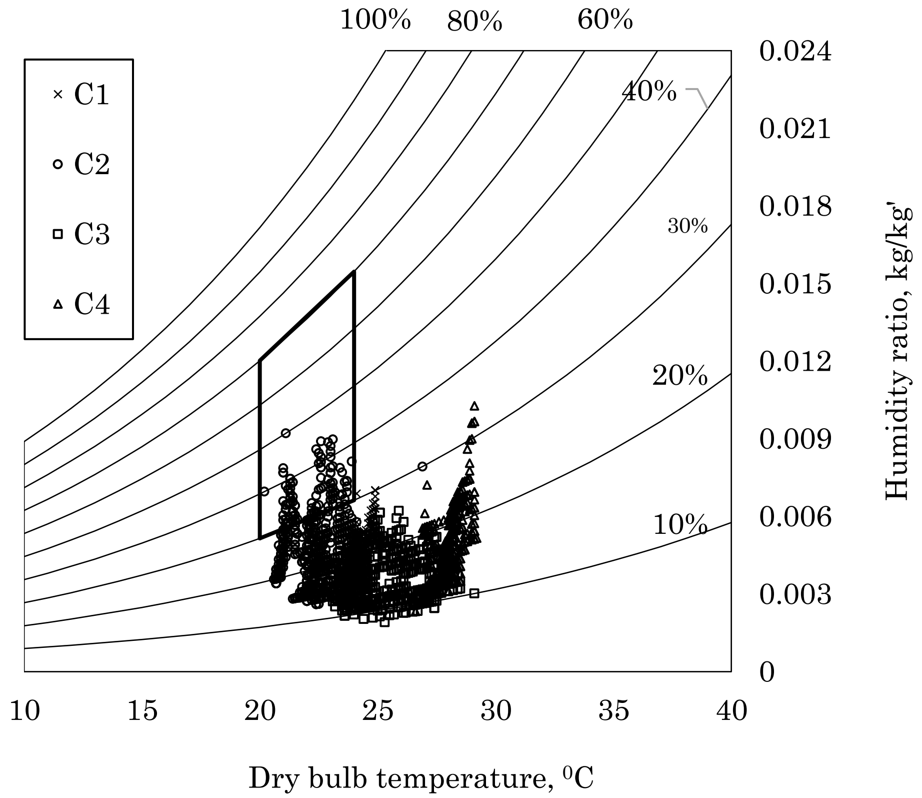


Fig.3.19 Thermal comfort of Type C apartments

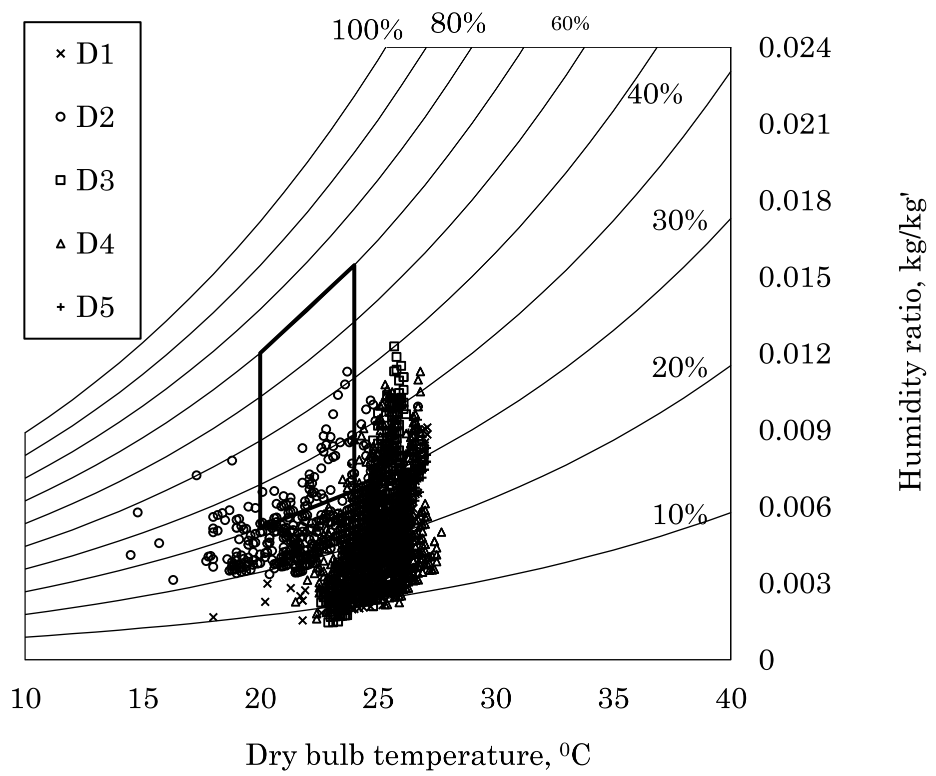


Fig.3.20 Thermal comfort of Type D apartments

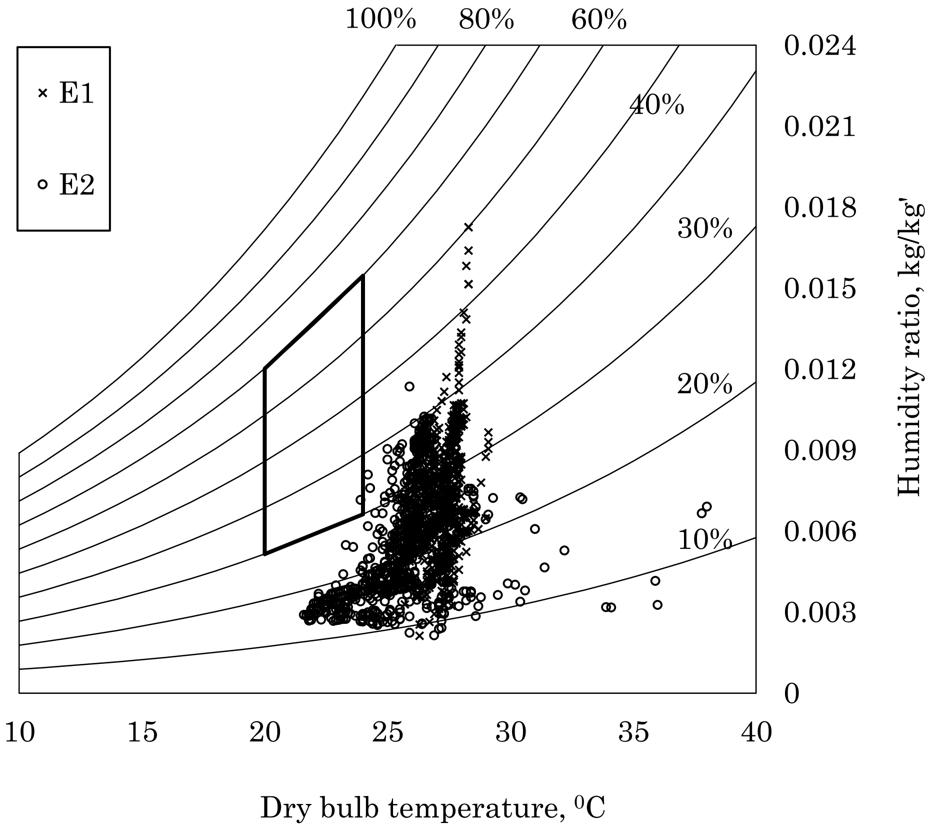


Fig.3.21 Thermal comfort of Type E apartments

3.4.4 Indoor air CO_2 concentration

Because no gas is used in all the apartment buildings people's exhale is the only source of CO_2. Therefore, indoor CO_2 concentration is influenced by the number of people who emits CO_2 through exhaling. The number of people varies throughout a day. Average, maximum, minimum, and standard deviation values of the indoor air CO_2 concentration for all type of buildings are shown in Fig.3.22. The average CO_2 concentration is 972 ppm during the day time and 1,134 ppm during night time, respectively, which is within the Mongolian standard [32]. The maximum CO_2 concentration is 1,835 ppm during night time while it is 1,362 ppm during the day time. The minimum CO_2 concentration is 624 ppm which does not differ significantly during day and night time for A2 apartment. In some cases, living rooms are used as bedrooms in the night time due to the lack of bedrooms. Those apartments might have higher CO_2 concentration during the night time than day time.

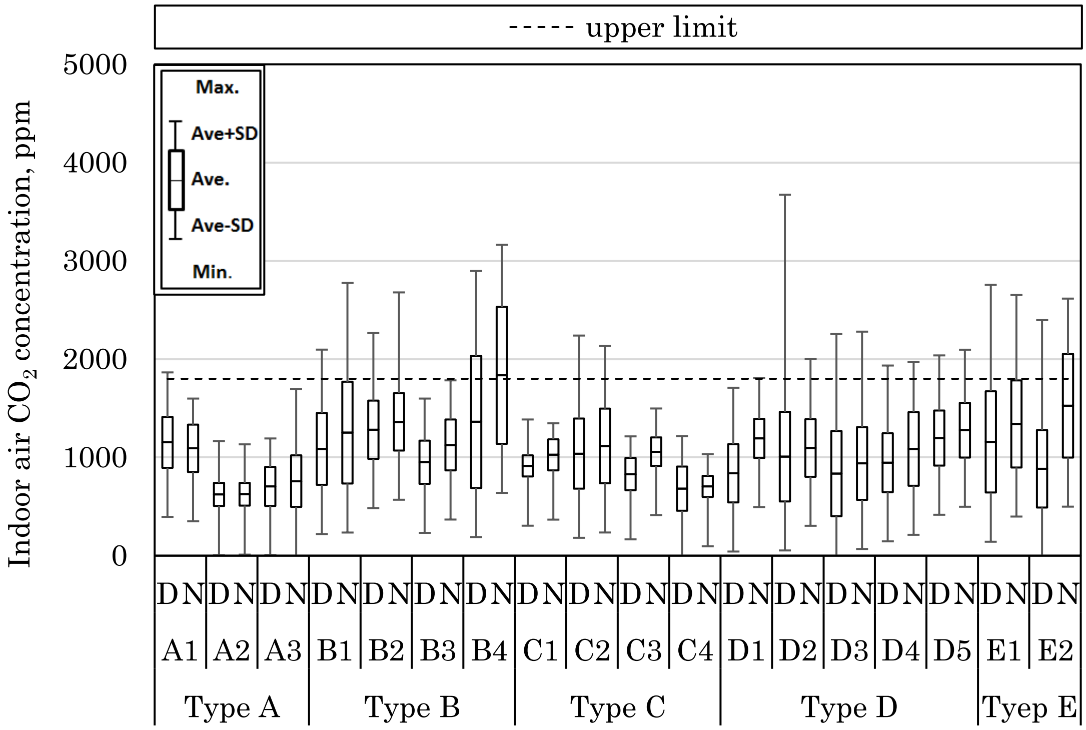


Fig.3.22 Indoor air CO_2 concentration in day and night time

3.5 Estimation of the ventilation rate and the heat loss coefficient

3.5.1 Ventilation rate

As mentioned in Section 3.2.3 natural ventilation shafts are installed in the kitchens and restrooms of the apartment buildings. Exhausted air flows through the vertical shaft with the stack effect. Residents sometimes open windows to adjust room temperature and let in fresh air. Therefore, the period when the window is open is excluded from the results. The period of opening windows is judged by the sudden drop of CO_2 concentration. The ventilation rate of each apartment is estimated by Equation (3.1) [33].

$$V = \frac{m}{(p-p_0)\cdot 10^{-6}} \qquad (3.1)$$

The ventilation rate and air change rate estimation results of 18 apartments are given in Fig.3.23 and Fig.3.24, respectively. The average ventilation rate is 59 m^3/h, the maximum is found in A3 apartment equaling to 105 m^3/h, the minimum is found in D1 apartment equaling to 34 m^3/h. The highest air change rate is 1.4 h^{-1} for A2 apartment which is located lower floor of the building facing to wind direction. In contrary the lowest one is found 0.23 h-1 for D1 apartment. It is hard to say that the ventilation rate is similar within the same type according to Fig.3.23 and Fig.3.24. Because although the building type is the same, the building quality may differ depending on the year it was built, maintenance, construction technology and location of the apartment etc.

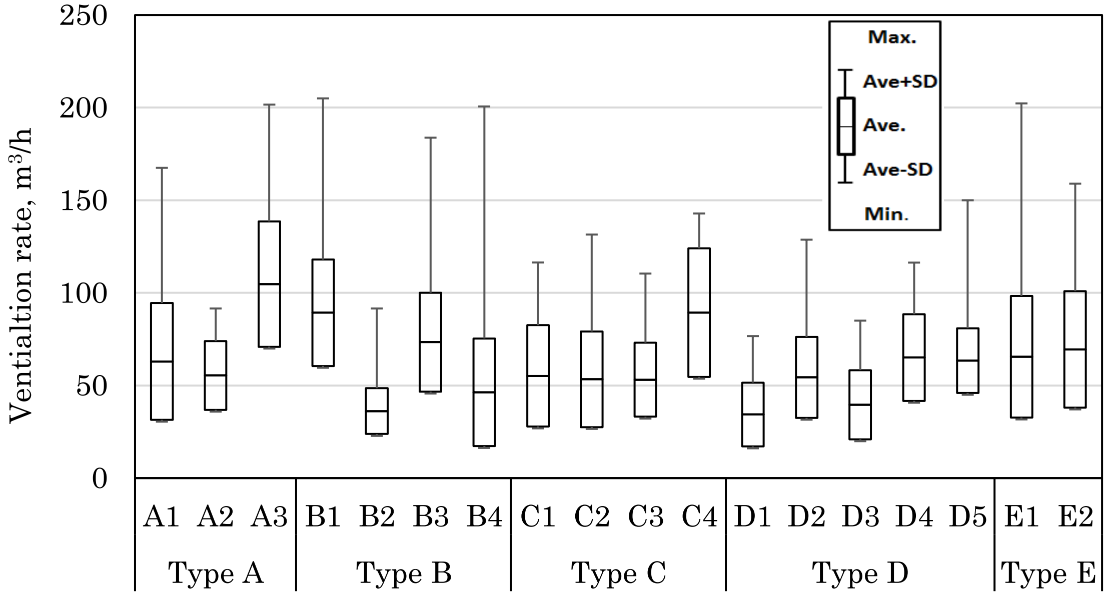


Fig.3.23 The ventilation rate of the apartments

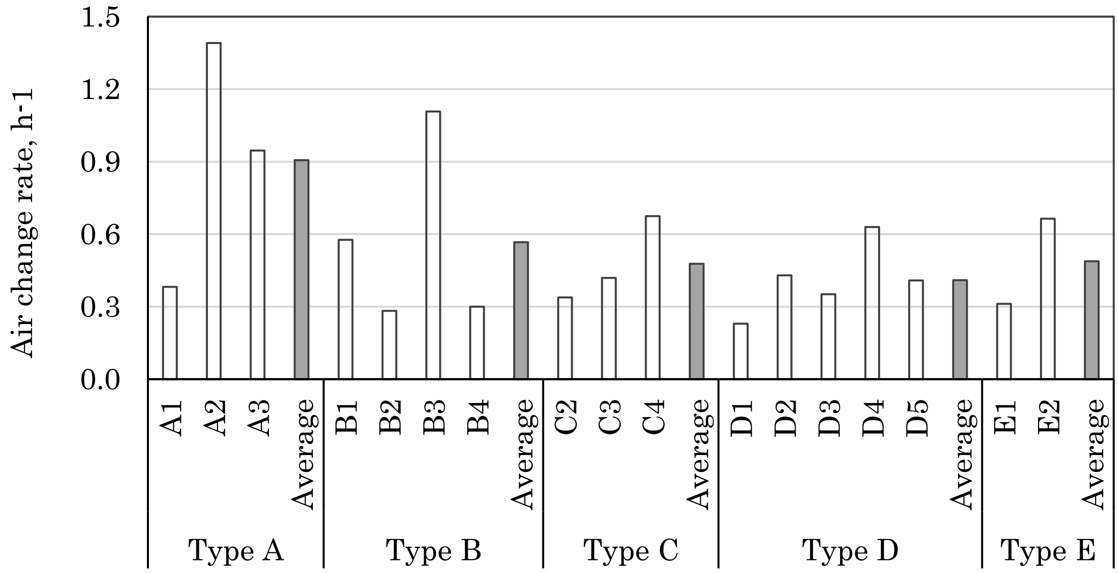


Fig.3.24 Air change rate of the apartments

3.5.2 Heat loss coefficient

According to its definition, the heat loss coefficient of the apartments is estimated by Equation (3.2). using the heat transfer coefficient of the building envelops given in Fig.3.1 and the ventilation rate given in Fig.3.23.

$$Q = \frac{\sum(k_i \cdot A_i)}{A_f} + \frac{c_p \cdot \rho \cdot V}{3600 \cdot A_f} \qquad (3.2)$$

The average heat loss coefficient for measured apartments is compared in Fig.3.25 and Table 3.4. The heat loss coefficient for insulated types C, D and E is less than 1.0, while that for the uninsulated types A and B is larger than 1.0. Heat loss through ventilation is the largest for Type E, despite the ventilation rate shown in Fig.3.23 is not particularly large. This is because the floor area of Type E is smaller than other types, which enlarges heat loss by ventilation per square meter of the floor area. According to Fig.3.25, 25% to 65% of total heat is lost through ventilation in apartment buildings in Ulaanbaatar. The maximum heat loss coefficient for Type B is larger than that of Type D by 107%, which implies that there will be approximately 52% energy saving if the heat loss coefficient of Type B is reduced to 0.74 W/m^{2}K as Type D.

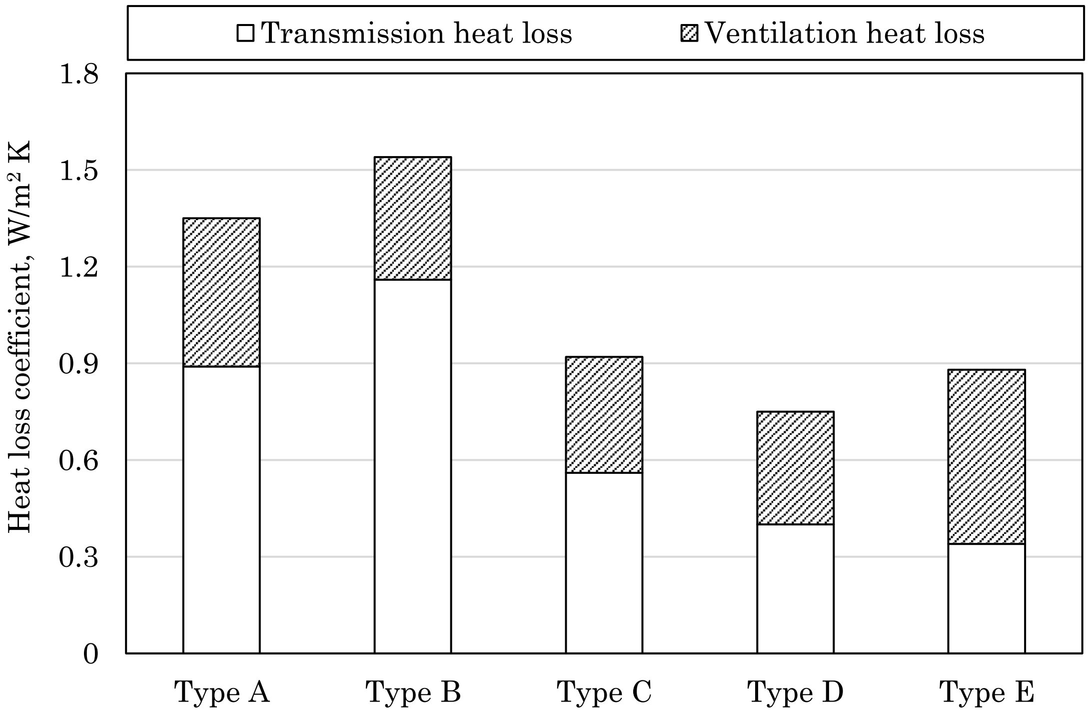


Fig.3.25 The heat loss coefficient by each type

Table 3.4 Values of the heat loss coefficient by structure types

Structure type	Heat loss coefficient by transmission, W/(m^2K)	Heat loss coefficient by ventilation, W/(m^2K)	Heat loss coefficient, W/(m^2K)
Type A	0.89	0.45	1.34
Type B	1.16	0.37	1.53
Type C	0.56	0.35	0.91
Type D	0.40	0.34	0.74
Type E	0.34	0.52	0.86

3.6 Unit energy consumption of the insulated apartments

3.6.1 Outline of the district heating system

The medium of the district heating system is hot water (temperature is 150 ^{0}C, the pressure is 16 atm) which is produced in the co-generation power plants. The schema of the substation system and location of the heat meter is shown in Fig.3.26. The hot water is supplied to the heat exchangers of a heating system and a hot water supply system, respectively. The substation could supply heat to either a single building or a group of buildings.

The medium of the primary circuit (district heating) does not mix with the mediums of the secondary circuit. Instead it heats up the mediums of the secondary circuit. Supply water of secondary circuit is heated up to 90 ^{0}C for the space heating system and 55 ^{0}C for the hot water supply system, respectively.

3.6.2 Outline of the investigation unit energy consumption

District heating energy consumption is measured only in the primary circuit by the individual heat meter as shown in Fig.3.26. District heating energy consumption records of 2017 for the 21 insulated buildings such as Type D and Type E were collected from the designated authorities. The outline of the buildings considered is given in Table 3.5. All the apartments in Ulaanbaatar are connected to the central electricity network and each household has an individual electricity meter in the

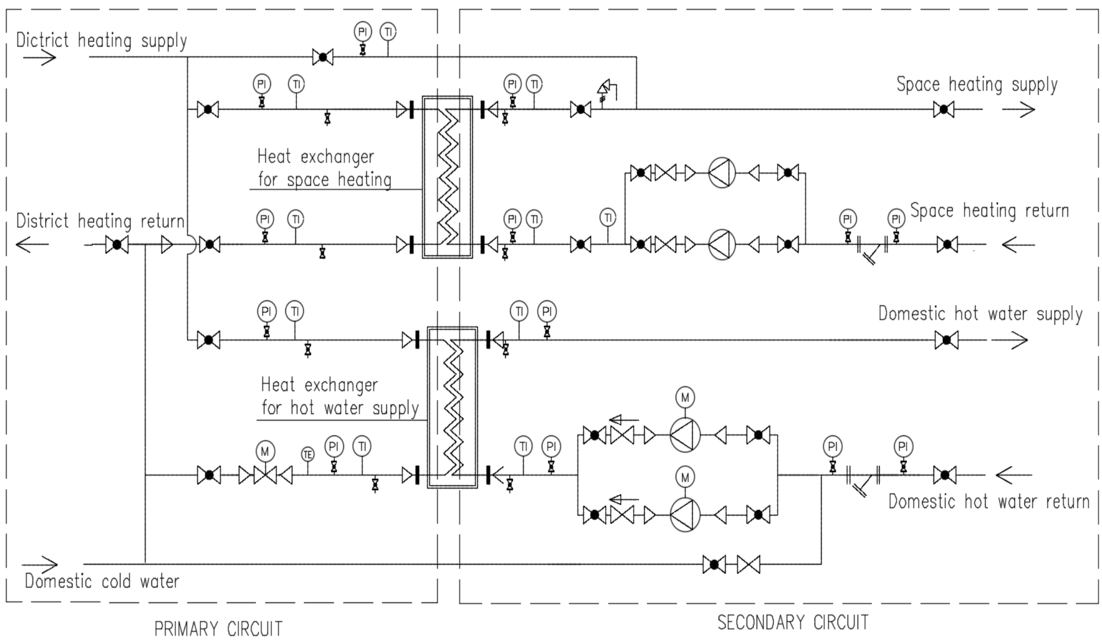


Fig.3.26 Substation schema of the district heating system

apartment. The annual electricity consumption was obtained from 278 households in five buildings among above mentioned 21 buildings. Outdoor air temperature and relative humidity during 2017 were downloaded from the archived database of the National Climate Data Center [17] as shown in Fig.3.27. Average temperature for heating season (September 15th to May 15th) is -9.3 ^{0}C. The value of heating degree-days in 2017 is 6552 ^{0}C·days.

Table.3.5 Outline of the buildings that has energy consumption records

ID	District	Building stories	Number of households	Total floor area, m^2	Average floor area of the households, m^2	Structure
1	SH	5	36	1575	43.7	Type I
2	BG	9	57	3380	59.3	
3		10	114	7095	62.2	
4		9	83	5580	67.2	
5		12	67	4576	68.3	
6		10	34	3500	102.9	
7		9	88	8640	98.2	
8		6	44	2016	45.8	
9		6	20	1260	63.0	
10	SB	5	16	1185	74.0	
11		10	77	3626	47.0	
12		5	49	1678	34.2	
13		6	16	1030	64.4	
14		12	120	5011	41.7	
15	BZ	12	176	13208	69.3	
16		12	144	10062	64.5	
17		12	536	36272	62.5	
18	SH	12	84	4104	48.8	Type II
19		13	66	3081	46.7	
20		6	89	5524	62.0	
21		12	95	5126	53.9	

SH-Songinokhairkhan district; BG-Bayangol district; SB-Sukhbaatar district; BZ-Bayanzurkh district

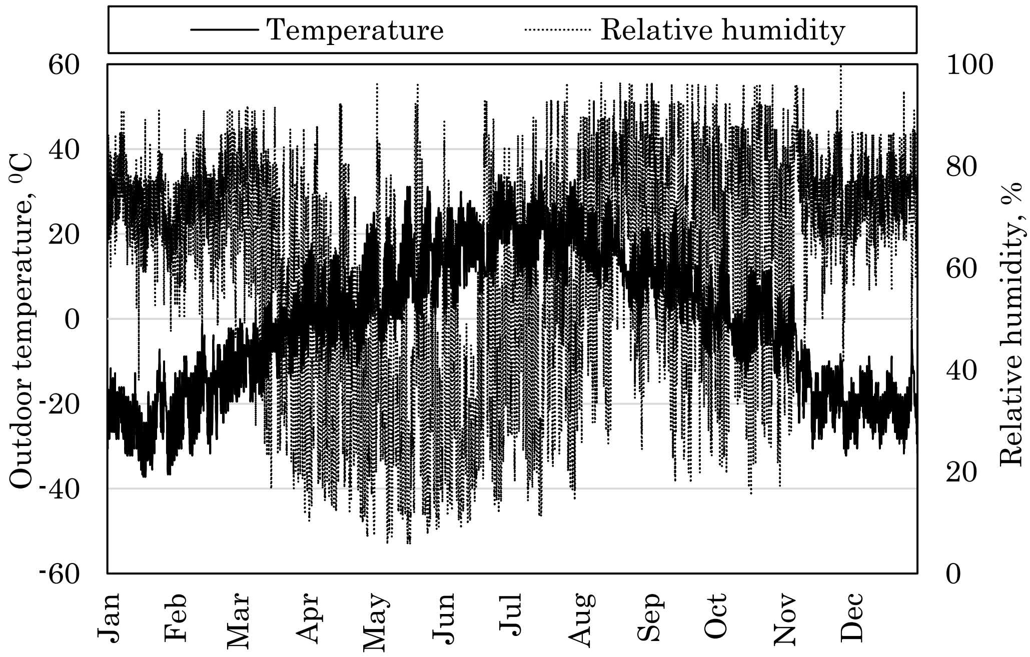


Fig.3.27 Outdoor air temperature and relative humidity for 2017

3.6.3 District heating consumption for the insulated apartments

District heating energy used for space heating and hot water supply systems was measured by the heat meter installed in each substation. Monthly records during 2017 for all the 21 buildings were obtained. The maximum, minimum, average and standard deviations of the monthly district heating energy for each household are shown in Fig.3.28. Annual district heating energy of the household is 56.8 GJ. There is no space heating during summer and district heating energy is used only for hot water supply. The highest district heating energy consumption is 8.9 GJ in January due to the lowest outdoor air temperature occurred and the lowest is 0.9 GJ in August due to the comparatively low hot water consumption. The standard deviation of the district heating energy is comparatively high.

The district heating energy used in summer shows energy used for hot water supply system since the space heating system is not operated. But the hot water consumption in July and August varies from that of June due to reduction in number of residents because some residents leave the apartments for summer vacations. In this section, hot water consumption in June is referred for other months except July and August due to unavailability of the recorded data.

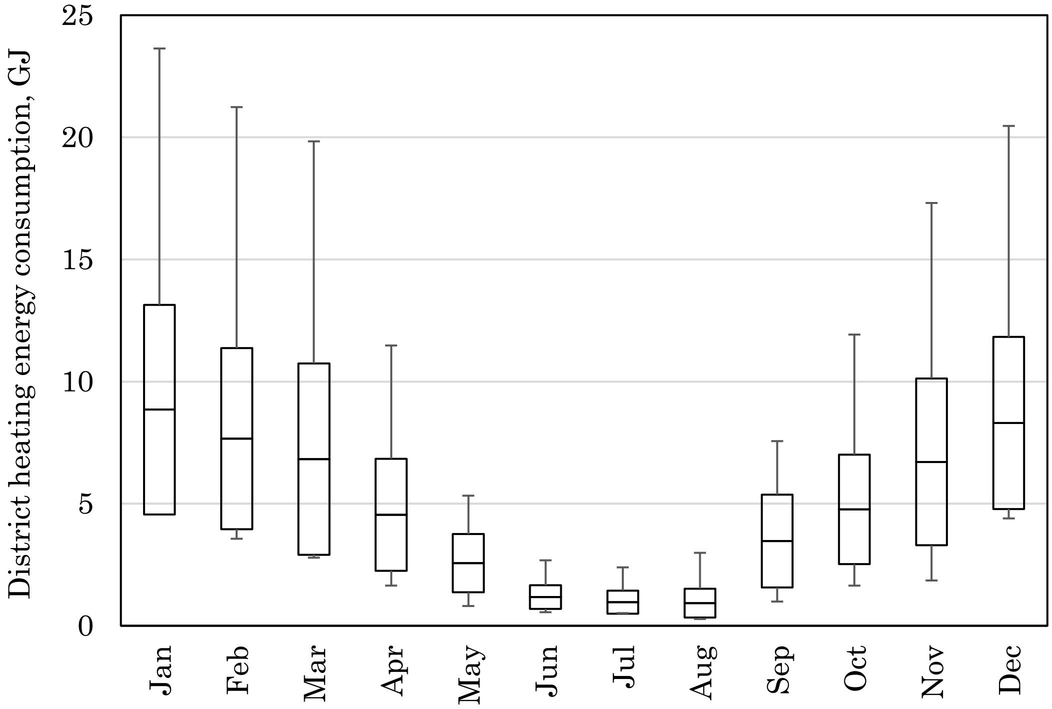


Fig.3.28 District heating energy of insulated apartment

District heating is separated into energy for space heating and hot water supply, respectively to estimate the average heat loss coefficient for considered buildings. Fig.3.29 shows heating energy used for space heating and hot water supply, respectively during heating season. The heating energy used for hot water supply is assumed to be 0.6 GJ in September and May while it is equal to 1.2 GJ for other months, because the heating season starts on 15th September and ends on 15th May.

The lowest value for space heating is 2.0 GJ in May and the largest is 7.7 GJ in January due to low outdoor temperature. Annual space heating energy is 44.1 GJ. According to Fig.3.29, 82% of the district heating is used for space heating and the remaining 18% is used for hot water supply throughout the heating season.

The average of the floor area of the households is 60.9 m^2 and the average building story is 9 for the investigated 21 buildings. Using those values, the heat loss coefficient was estimated with Equation (3.3).

$$\mathrm{Q} = \frac{(Q_D - Q_h)\cdot 10^9}{24\cdot 3600\cdot A_f\cdot HDD} \qquad (3.3)$$

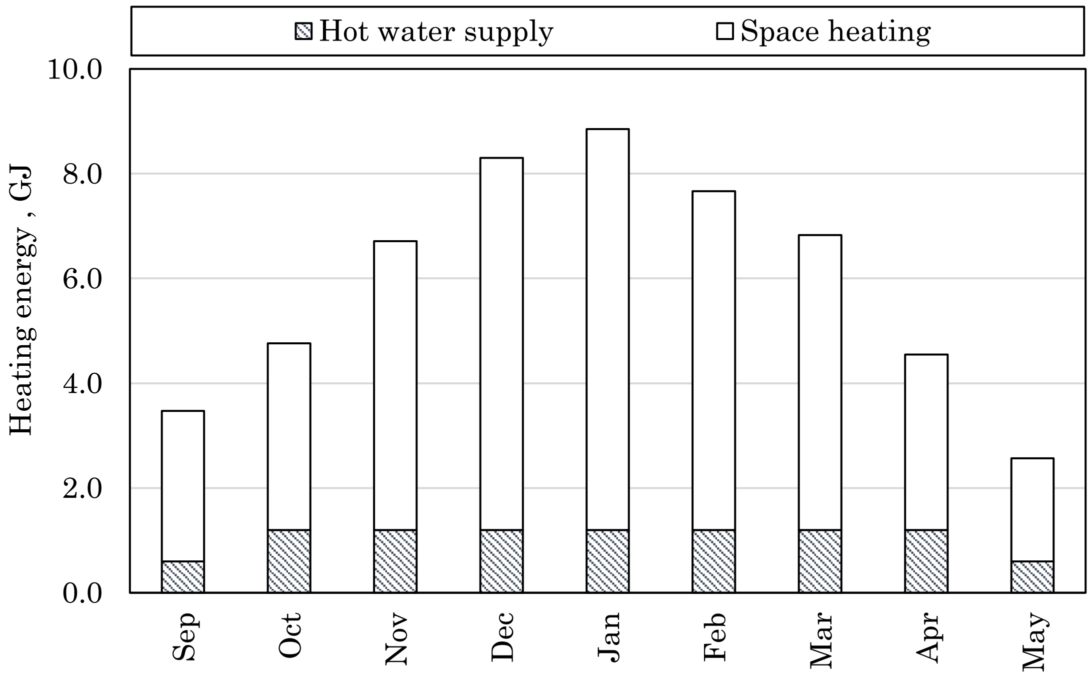


Fig.3.29 District heating energy by systems

The heat loss coefficient is 1.0 W/(m^2K) which is higher than the values estimated with the Equation (3.2). Suppose the external wall for each household is 27.5 m^2 (2.7 m ceiling height) and the window area is determined 18% from the external wall area as stated in the building code [34] to estimate the transmission heat loss coefficient for each household. The floor is ignored due to the existence of the heated basement floor in each building. Roof area for each household is calculated by dividing a total roof area by the number of households. As a result, the transmission heat loss coefficient is 0.33 W/(m^2K) which is similar to the value shown in Table 3.3 while the ventilation heat loss coefficient is higher. Because as mentioned in the section 3.6.1 the ventilation rate varies among apartments with the same structures due to the building quality, built year, maintenance and construction technology.

3.6.4 Electricity consumption for the insulated apartments

Electricity is used for lighting and electronic appliances for all households. None of the household uses electricity for heating and hot water supply. Therefore, there is no air conditioner in the building due to the low outdoor air temperature during summer. Electricity consumption is measured by the meter installed for each household. The maximum, minimum, average and standard deviations of the monthly electricity consumption of the 278 households is shown in Fig.3.30. Monthly electricity consumption is smaller for summer months because some of the residents leave for summer vacations. Electricity consumption for each household is small comparing to the district heating energy consumption. Electricity consumption fluctuates between 0.5 GJ and 0.7 GJ throughout the year. The standard deviations of the electricity consumption do not vary significantly throughout the year. The annual electricity consumption of the household is 7.1 GJ.

3.6.5 Unit energy consumption for the insulated apartments

The average floor area of one household is 60.9 m^2. The unit energy consumption is the annual energy consumption for each household. The unit energy consumption of each household living in insulated buildings (Type D and Type E) is 63.8 GJ as shown in Fig.3.31. Energy consumption reaches its peak in December and January when outdoor temperature drops, and smallest is occurred in summer three months when space heating is stopped, and number of hot water users become smaller.

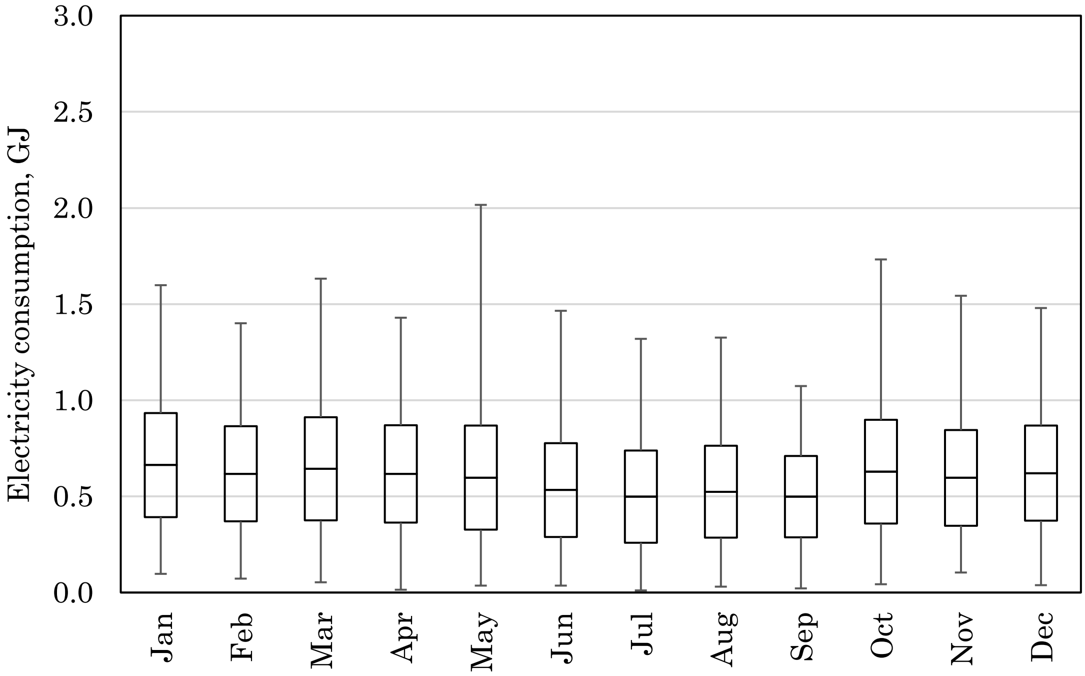


Fig.3.30 Electricity consumption of the households

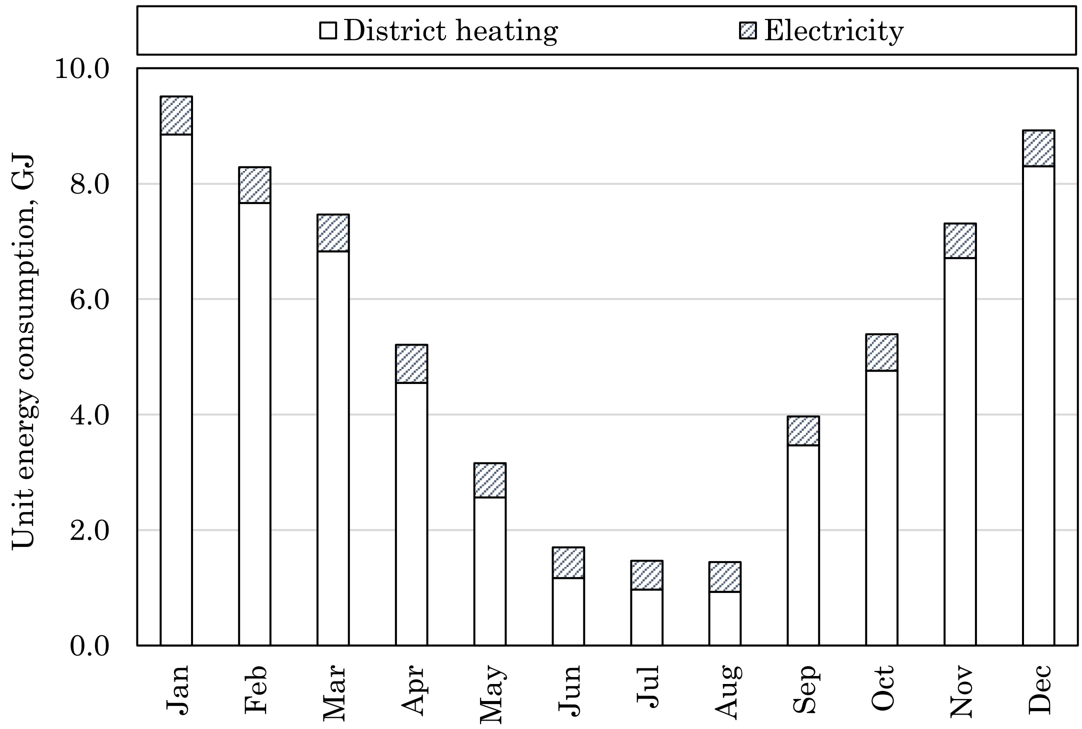


Fig.3.31 Unit energy consumption of insulated apartment

3.7 Summary

In this chapter, 374 apartments with different structure types were surveyed and 18 apartments were selected for measuring indoor thermal environment. The main findings from this chapter are:

- The indoor air temperature of the apartment building is higher while relative humidity is lower than the Mongolian standard as well as ISO 7730 standard for most hours;
- Energy savings can be achieved by lowering the temperature in Hot - Dry and Hot zones to adequate level. In order to realize this, extension of radiators by the residents should be prohibited by rules;
- Average indoor CO_2 concentration is between 624 ppm and 1,835 ppm which is nearly within the Mongolian standard;
- The ventilation rate by the natural ventilation system is between 34 m^3/h - 105 m^3/h;

- The heat loss coefficient is between 0.74 W/m^2 K and 1.53 W/m^2 K for apartment buildings. Significant energy savings can be expected for Type A and B by thermal retrofitting;

The following conclusions can be drawn for the insulated structure Type D and Type E only:

- The average district heating consumption throughout the year is 56.8 GJ including hot water supply for insulated structures (Type D and Type E). Among this 44.1 GJ energy is used for space heating system and 12.7 GJ is used for hot water supply;
- The average electricity consumption throughout the year is 7.1 GJ per household. Electricity consumption does not differ significantly from month to month;
- The average unit energy consumption of the insulated buildings is 63.8 GJ.

CHAPTER 4
Investigation of indoor environment and energy consumption of the Gers

4.1 Introduction

The air quality of Ulaanbaatar is very poor which exceeds limits of the World Health Organization in recent years [35]. The sources creating serious air pollution are: cogeneration power plants; heat-only boilers; stoves; and transportation. About 25% of the harmful PM10 are emitted from the stoves for cooking and heating purposes of the Gers and detached houses at the Ger area [6].

Residents of Ulaanbaatar live in several types of dwellings such as apartment buildings, detached houses and the Gers. The apartment buildings are located at the center of the city and connected to the district heating system. Meanwhile, detached houses and the Gers are located at the suburban Ger area where stoves are used for the space heating. The Ger area occupies approximately 11,094 ha land of the northern part of the city as shown in Fig.4.1 [36]. Total 57.7% of the residents live in the Ger area in 2014 and about half of them live in the Gers because of their affordable price [29].

Ⓐ: Locations of Ger-1 to Ger-3　　Ⓑ: Locations of Ger-4 to Ger-10

Fig.4.1 Residential zones of the Ulaanbaatar

The Ulaanbaatar city mayor approved a resolution to redevelop the Ger area by changing existing detached houses and the Gers with apartment buildings in 2013.

In total 3,516 households (1.8% of the residents living in the Ger area) have been involved in the project for three years [37]. Unfortunately, the project is delayed due to some technical and financial reasons. Therefore, the Gers will be used for a long time as one of the main three types of dwellings in Ulaanbaatar.

The purpose of this chapter is to clarify the energy consumption and the indoor environment of the Gers in Ulaanbaatar based on surveying, measurements, and simulations.

Very few studies have been carried out for the indoor environment of the Gers. Ishikawa et al. investigated the indoor temperature and humidity of six Gers, estimating that energy consumption per square meter and the heat loss coefficient are 3.05 GJ/m^2 and 17.2 W/(m^2K), respectively [13]. However, the value of the heat loss coefficient had to be examined for it was related to the invalid assumption of the ventilation rate.

Niu et al. investigated thermal defect and thermal environment of the Gers in Inner Mongolia, China through thermographic images and CFD analyses [38]. They identified the temperature distribution under uneven felt thickness by the thermal images.

Fifty-nine households living in the Gers were surveyed and 10 of them were selected for measuring indoor air temperature, relative humidity, CO and CO_2 concentrations. The ventilation rate was estimated from the indoor CO_2 concentration and the heat loss coefficient of the measured Gers was estimated based on the coal consumed throughout the measurement period.

Abbreviations:

V	Ventilation rate [m^3/h];
m	CO_2 emission through exhaling [m^3/h];
p	CO_2 concentrations in indoor [ppm];
p_0	CO_2 concentrations in outdoor air [ppm];
Q	Heat loss coefficient [W/K];

H_g Internal heat gain from the coal burning [W];

$\Delta\theta$ Average of the indoor and outdoor air temperature difference [K];

A_f Floor area of the Ger [m^2];

d Measuring period [day];

m_c Coal consumption throughout measuring period [kg];

ε Thermal energy efficiency of a stove [%];

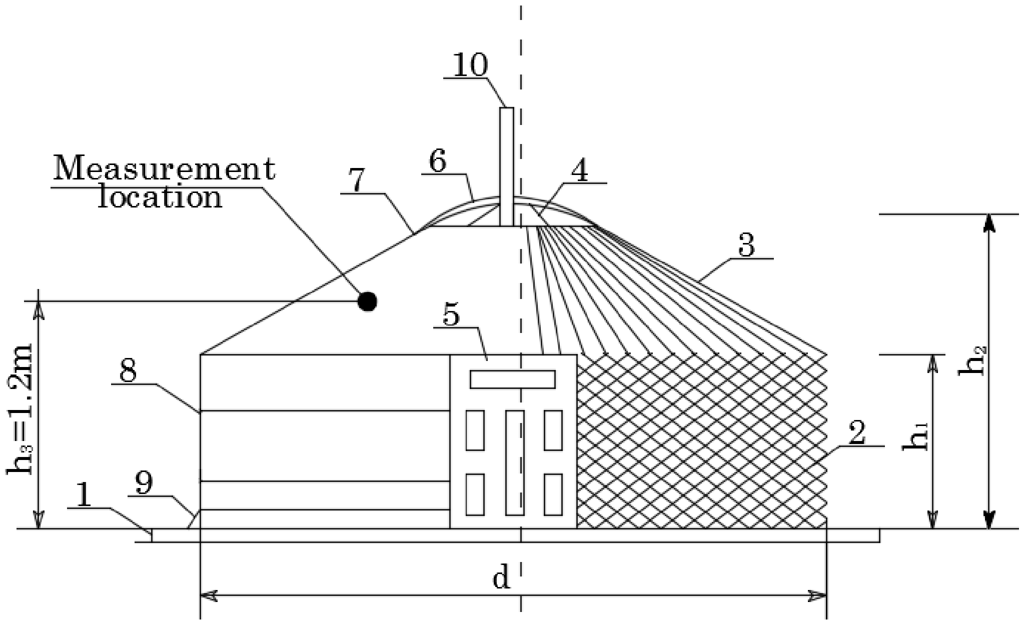
c Specific heat capacity of the coal [J/(kg)].

4.2 Outline of the investigation

4.2.1 Outline of the Gers

The Gers were used by the nomads before the Ulaanbaatar city was established. With a continuous movement towards the city due to the centralization of the economy, the population living in Gers has also been increased [39]. The Gers usually consist of a wooden structure and wool felt insulation as shown in Fig.4.2. Size of the Gers is determined by the number of wall sections connected to each other. The most common size of the Gers used in Ulaanbaatar has five wall sections [40]. Floors of the Gers are made of wood placed directly on the earth or on the concrete base. Doors of the Gers are made of wood shown in Photo 4.1 (a) and a windbreak room is attached outside of the door for some Gers as shown in Photo 4.1 (b) to prevent cold air from coming in when the door opens. There is a single glass window for allowing daylight and ventilation on the top of the Gers.

None of the Gers are connected to the district heating due to the low energy efficiency, financial and technical obstacles. Coal-fired stoves as shown in Photo 4.2 are used for heating and cooking. Stoves are classified into Traditional and Turkish ones, and energy efficiencies for both types is 76% [41].



1 Earth
2 Wooden wall structure
3 Wooden beam
4 Single glass top opening
5 Wooden door
6 Top opening cover
7 Top wool felt insulation
8 Wall wool felt insulation
9 Earth covered with water resistant material
10 Chimney

Fig.4.2 Structure of the Ger

(a) Ger without a windbreak room (b) Ger with a windbreak room

Photo 4.1. Outside view of the Ger

a. Traditional stove b. Turkish stove

Photo 4.2. A stove in the Gers used for heating and cooking

4.2.2 Methodology of the questionnaire survey and measurement

Surveying was conducted for 59 Gers located in the suburban Ger area as shown in Fig.4.1. Questionnaire consists of information related to social status such as family structure, number of residents and monthly income, geometrical dimensions, electric devices, coal consumption, heating and cooking methods as attached in the Appendix B. The questionnaires were distributed and collected by visiting each Ger.

Ten Gers located in the north east part of the Ulaanbaatar were selected for measuring indoor environment elements such as air temperature, relative humidity, CO and CO_2 concentrations. Locations of the measured Gers are marked with A and B in the Fig.4.1. Data logger (TR-76Ui, T&D Corporation) for measuring indoor air temperature, relative humidity and CO_2 concentration was hung from the west-northern beam at 1.2 m height from the floor level as shown in Photo 4.3.

Indoor CO concentration was measured with IAQ monitor (model 2211, Kanomax Co.Ltd) for five Gers due to equipment availability. The measuring interval for the data logger and CO monitoring was set at 10 minutes. Coal consumption per fueling was weighted with a hand scale as shown in Photo 4.4. Measuring equipment and their accuracies are shown in Table 4.1. There were two measuring periods: one is

February 16th - 21st and another one is March 4th - 11th, 2017. The outline of the measured Gers is given in Table 4.2.

Photo 4.3 Location of measuring equipment in the Ger

Photo 4.4 Weighting coal consumption by a hand scale

Table 4.1 Measuring equipment

Equipment model	Elements	Accuracy
TR-76Ui	Air temperature	±0.5 ^{0}C
TR-76Ui	Relative humidity	±5%
TR-76Ui	CO_2 concentration	±50ppm
Kanomax 2211	CO concentration	±3%
OCS-20A	Coal weight	±20g

Table 4.2 Outline of the measured Gers

ID	Number of residents	Number of felt layers	Windbreak room	Coal consumption, kg/day	Geometric dimensions			
					Floor diameter (d), m	Wall height (h_1), m	Height from floor to top opening, (h_2), m	Floor area, m^2
Ger-1	5	2	yes	13.8	5.7	1.5	2.6	25.5
Ger-2	1	3	no	16.4	4.6	1.4	2.2	16.6
Ger-3	3	2	no	12.2	4.5	1.4	2.3	15.9
Ger-4	4	3	no	14.4	4.6	1.5	2.2	16.6
Ger-5	6	3	no	10.4	5.3	1.5	2.4	22.1
Ger-6	3	3	no	14.7	5.4	1.4	2.3	22.9
Ger-7	5	2	yes	20.1	5.0	1.4	2.0	19.6
Ger-8	4	2	yes	14.7	5.3	1.4	2.5	22.1
Ger-9	4	2	no	15.9	5.0	1.5	2.3	19.6
Ger-10	2	2	no	14.0	4.8	1.4	2.3	18.1

4.3 Results of the surveying

Questionnaire respondents are adults and 56% of them are male, and 44% are female. The age and occupation of the respondents are shown in Fig.4.3 and Fig.4.4.

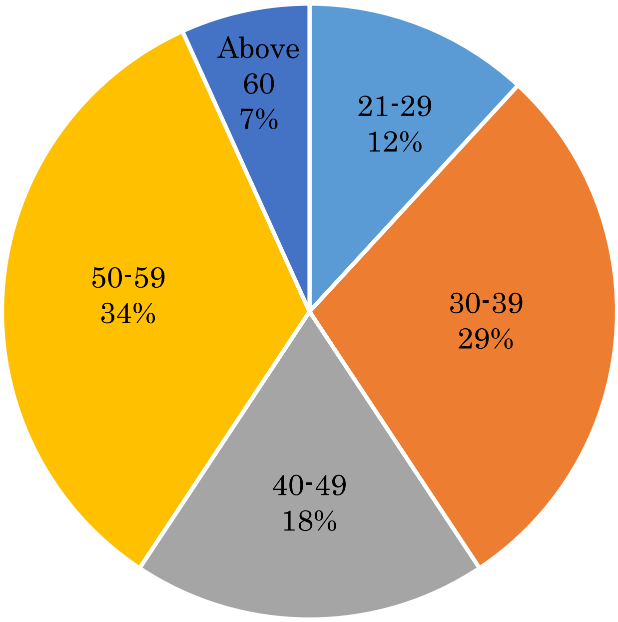


Fig.4.3 Ages of the questionnaire respondents

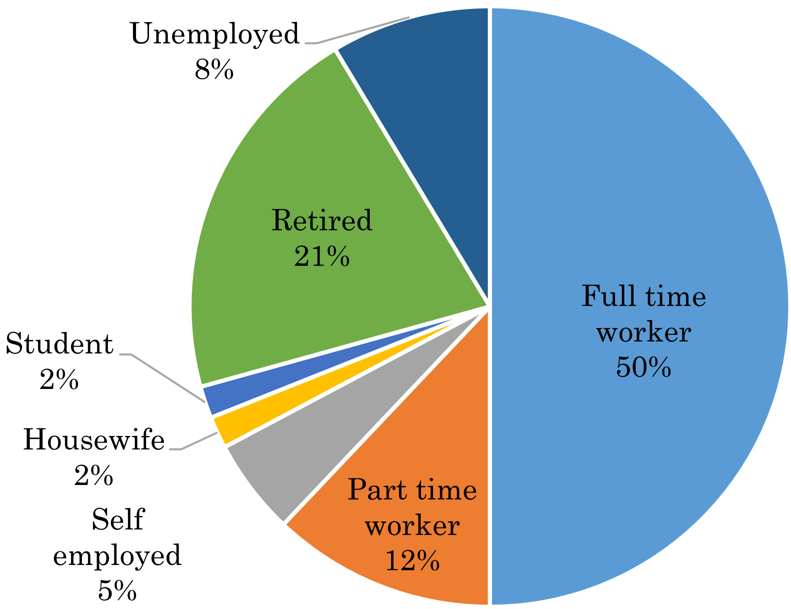


Fig.4.4 Occupation of the questionnaire respondents

The family structure is classified into seven categories according to the relationship of the residents as shown in Fig.4.5. A couple living with children is the largest category for the respondents and measured Gers. There are some differences in the other categories between the surveyed and measured Gers by chance.

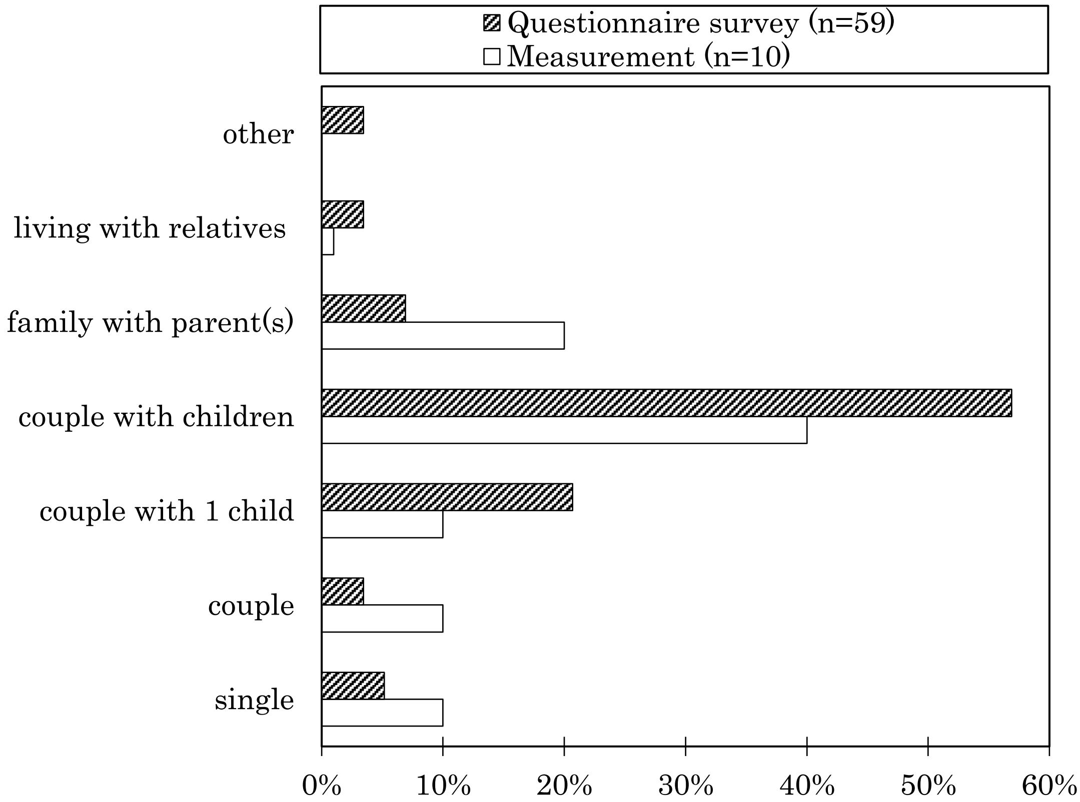


Fig.4.5 Family structure of households

The monthly income of the households is divided into four groups as shown in Fig.4.6. The largest portion of the monthly income is 125-250 USD and below 125 USD for the measured and surveyed Gers, respectively. The percentage of the surveyed households with income above 415 USD is 10%. There are no households that belong to the upper two groups in monthly income for measured ones accidentally.

The family's size of the surveyed Gers is given in Fig.4.7. The group with four to five people contains the largest percentage from the survey.

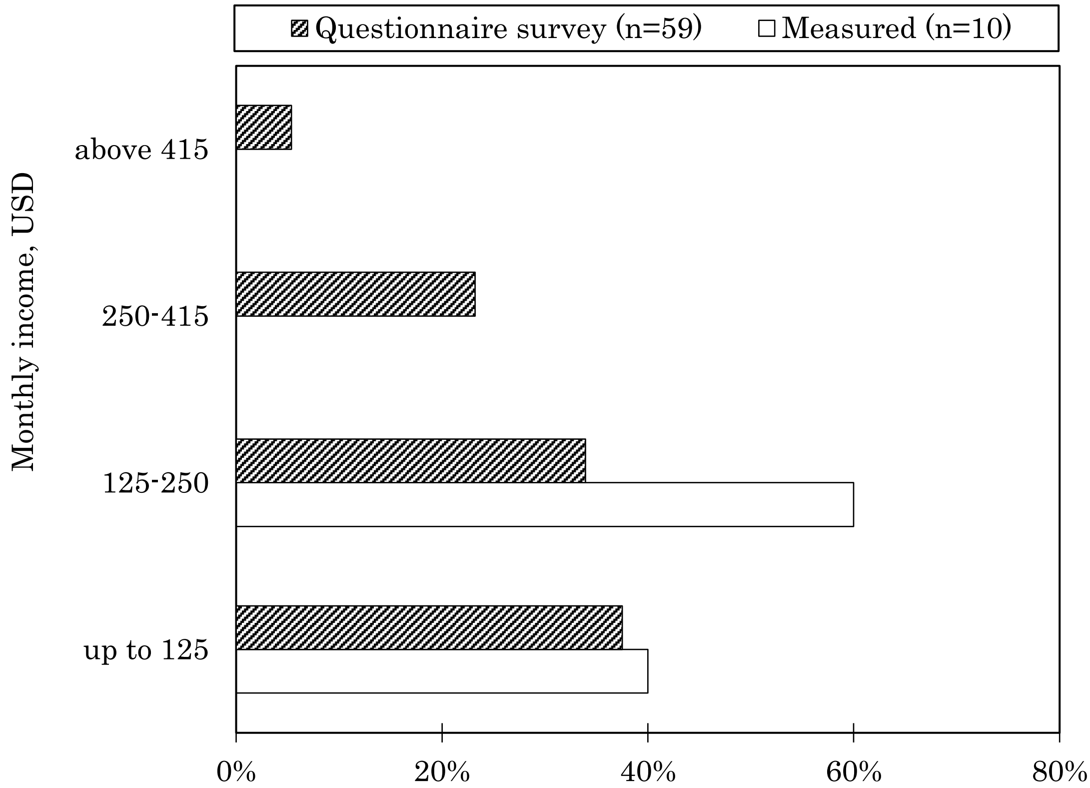


Fig.4.6 Monthly income of households

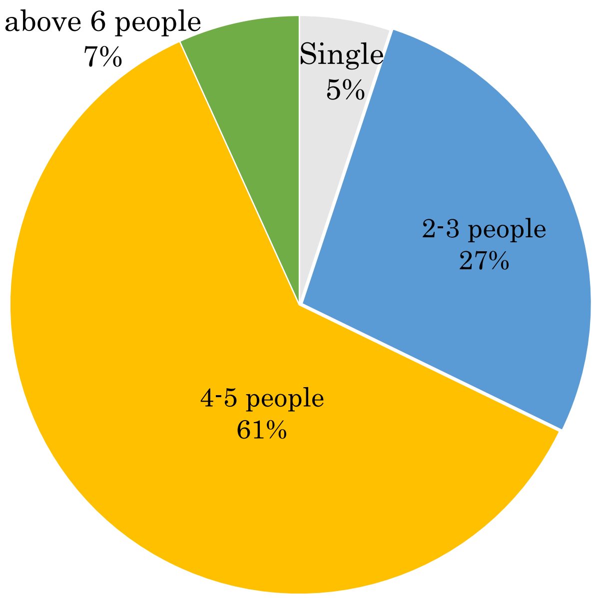


Fig.4.7 Family size of households

Typically, doors of the Gers face south, and whenever the door opens cold air comes inside directly. Some of the households attach a windbreak room to the door to prevent cold air from coming in when the door opens. As shown in Fig.4.8 the percentage of the Gers with or without a windbreak room is 43% and 57%, respectively.

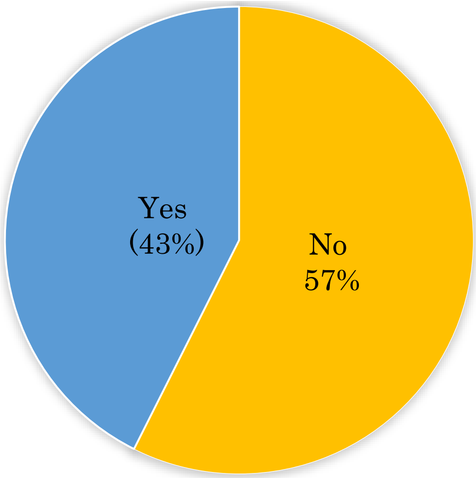


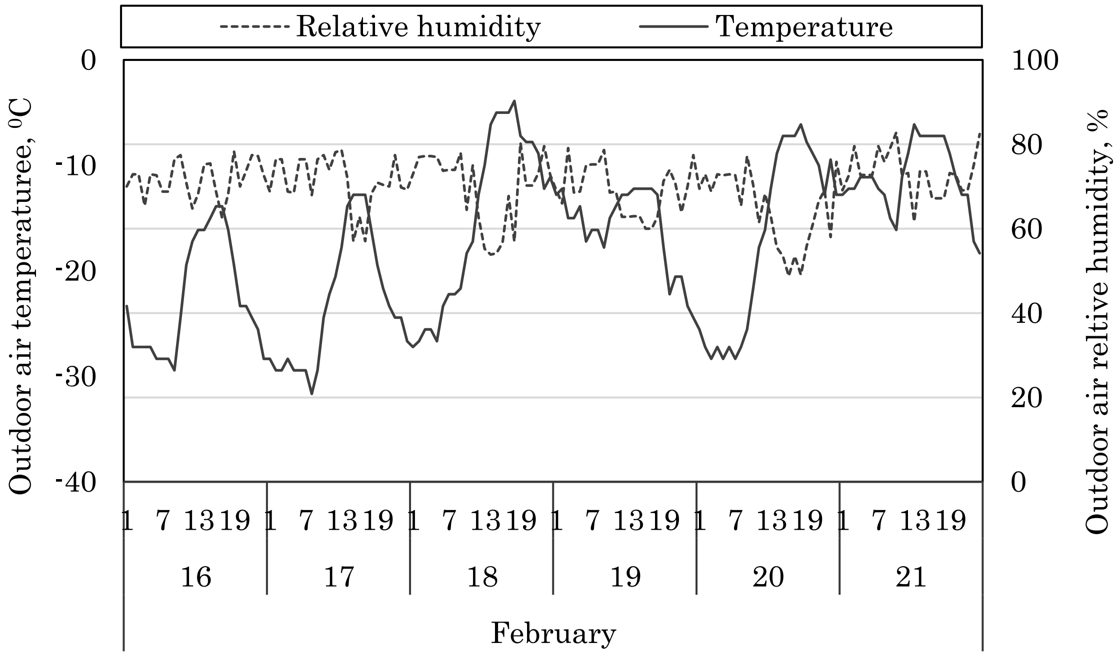
Fig.4.8 Existence of the windbreak room

4.4 Results of the measurement

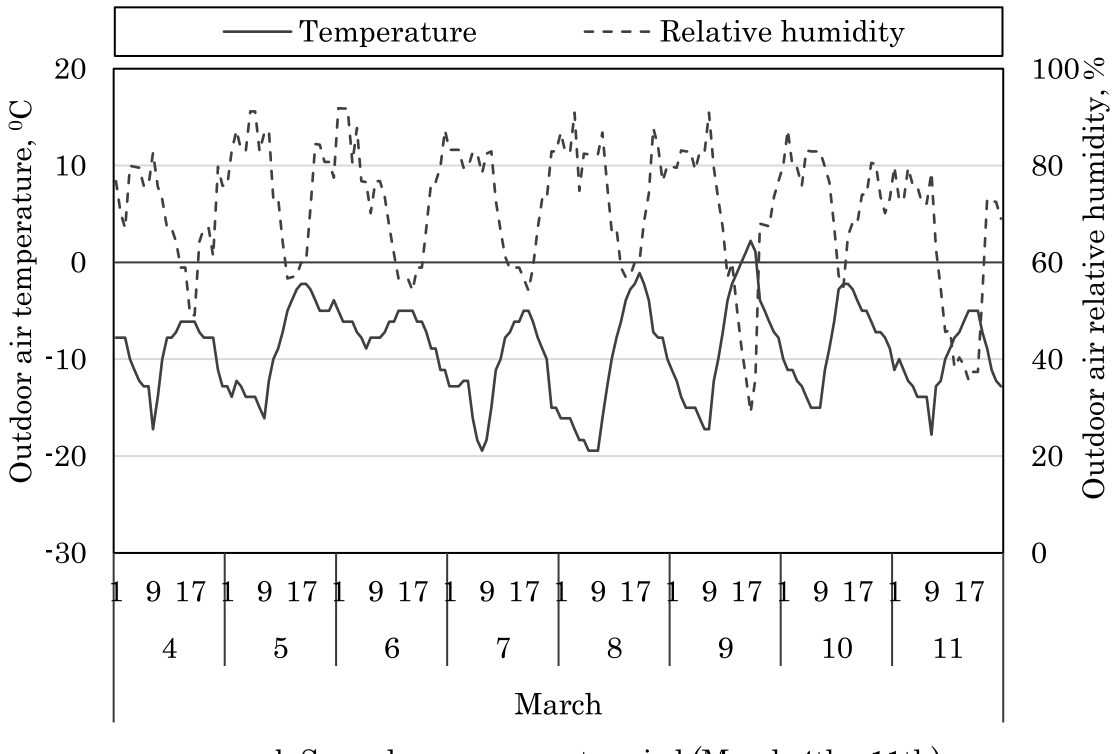
4.4.1 Indoor air temperature

As mentioned above, the measurement is carried out in two periods. The outdoor weather elements such as air temperature and relative humidity during the measuring periods were downloaded from the National Climate Data Center website [17] and shown in Fig.4.9(a) and (b). The outdoor temperature during the first measurement period is between -31.7 ^{0}C to -3.9 ^{0}C, and -19.4 ^{0}C to 2.2 ^{0}C in the second period. The average outdoor temperature is -17.2 ^{0}C for the first period and -9.3 ^{0}C for the second period.

We differentiated days into daytime (9:00 - 20:00) and nights into nighttime (20:00 - 9:00). The standard deviations, maximum, minimum and average values of the indoor air temperatures are given in Fig.4.10. Indoor air temperature depends on the stove usage behavior and heat loss of the Ger structure in each Ger. The average of the maximum temperatures during daytime is 41.4 ^{0}C while the average of the minimum temperatures during nighttime is 8.0 ^{0}C.



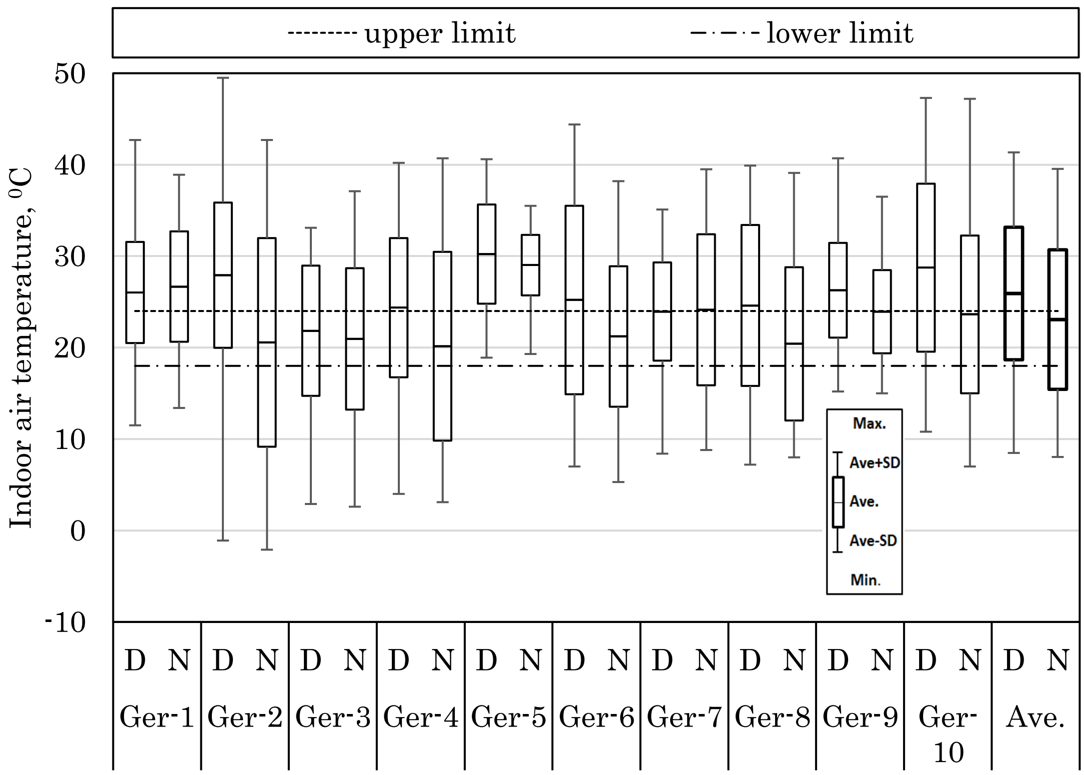
a. First measurement period (February 16th - 21st)



b.Second measurement period (March 4th - 11th)

Fig.4.9 Outdoor air temperature and relative humidity during measurement periods

Air temperature difference between the maximum and minimum is large for the Gers, with the exception of Ger-1, Ger-5 and Ger-9 where small children reside. The standard deviations of these three Gers are smaller than the other Gers, implying that households with small children tend to keep a stable indoor air temperature for thermal comfort of their children. The minimum air temperature in other Gers without small children drops below 10 ^{0}C. The average air temperature during nighttime is lower than the average air temperature during daytime for most of the Gers. This is because coal in stoves has burnt out before being fed in next morning. Furthermore, the overall average air temperature is 25.9 ^{0}C and 23 ^{0}C during daytime and nighttime, respectively. The average air temperature of the measured Gers is compared with the upper and lower limit of the air temperatures stated in the Mongolian standard [30]. The upper limit of the indoor air temperature is 24 ^{0}C while the lower limit is 18 ^{0}C regarding to the standard. In addition, average air temperature is higher than the upper limit for most of the Gers but it is within the acceptable range during daytime or during nighttime for few Gers.



*D:Daytime; N:Nighttime

Fig.4.10 Indoor air temperature in daytime and nighttime

4.4.2 Indoor air relative humidity

The average, maximum, minimum, and standard deviations of the indoor air relative humidity during daytime and nighttime are shown in Fig.4.11. According to the Mongolian standard [30] the acceptable maximum relative humidity of the indoor air is 45% while the minimum is 30% during winter. The average indoor air relative humidity is lower than the acceptable minimum level for all the Gers. The lowest average relative humidity is found 12% for Ger-2 during nighttime. The highest average relative humidity is 31% for Ger-4 during the daytime. The difference in the average relative humidity between daytime and nighttime is insignificant. The highest relative humidity reached levels of 93% for Ger-9 during the daytime. We confirmed that this is related to the activities taken by the household such as washing and cooking etc. The overall average of relative humidity is 21.6% and 20.9% during daytime and nighttime, respectively.

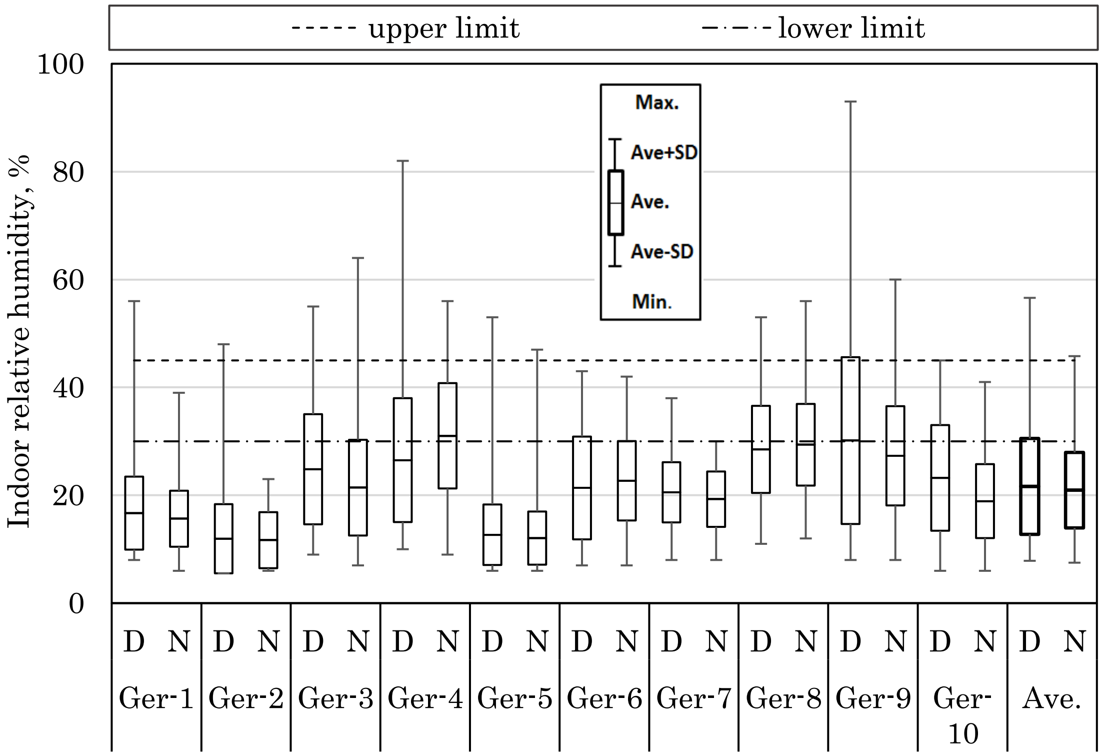
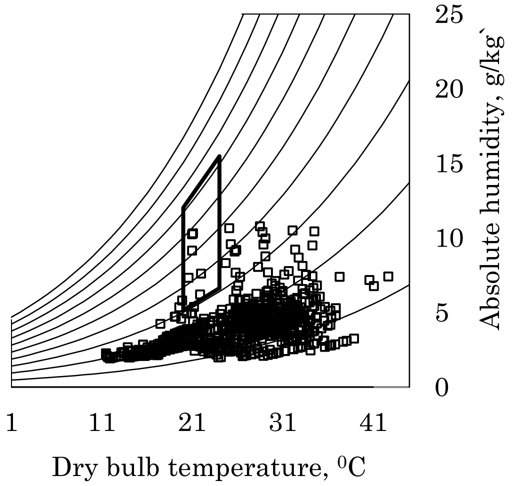


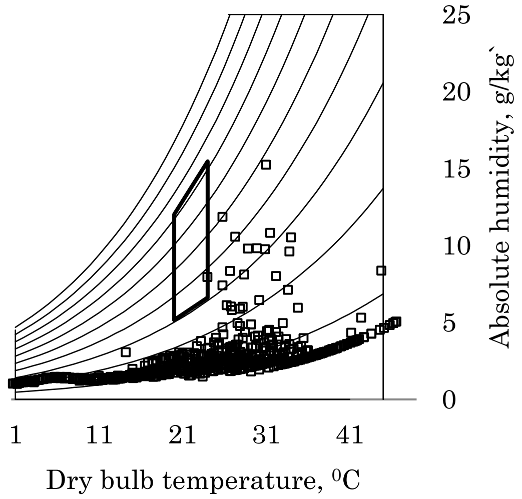
Fig.4.11 Indoor air relative humidity in daytime and nighttime

4.4.3 Thermal comfort

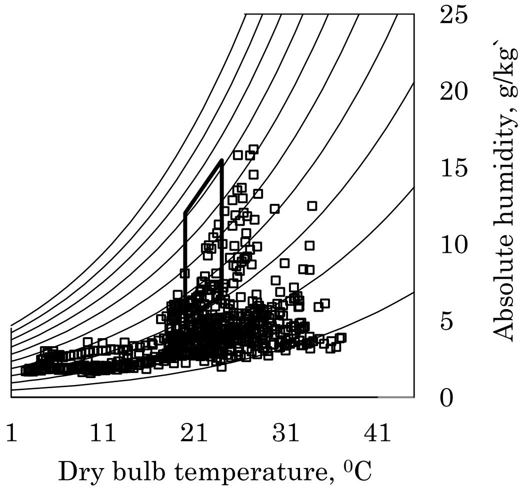
Thermal comfort of the Gers is analyzed in the psychrometric charts as shown in Fig.4.12. Very few plots fall into the comfort zone for the Gers. But there are a few hours within the comfort zone for the Ger-3, Ger-4, Ger-9 because of the comparatively high relative humidity. Indoor environments of the Gers are in Cold or Cold-Dry zones in the early morning, while it is in Dry, Hot-Dry and Hot zones during the daytime.



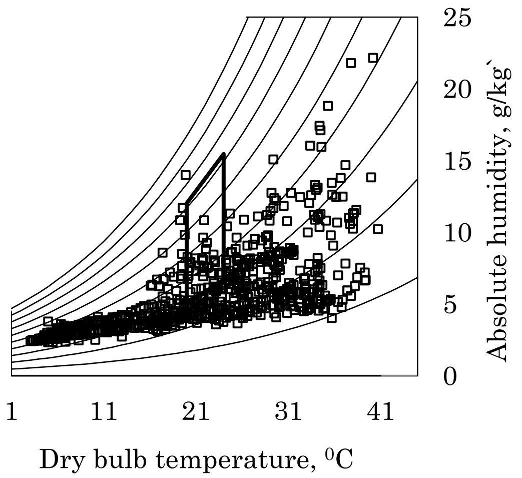
(a) Ger-1



(b) Ger-2



(c) Ger-3



(d) Ger-4

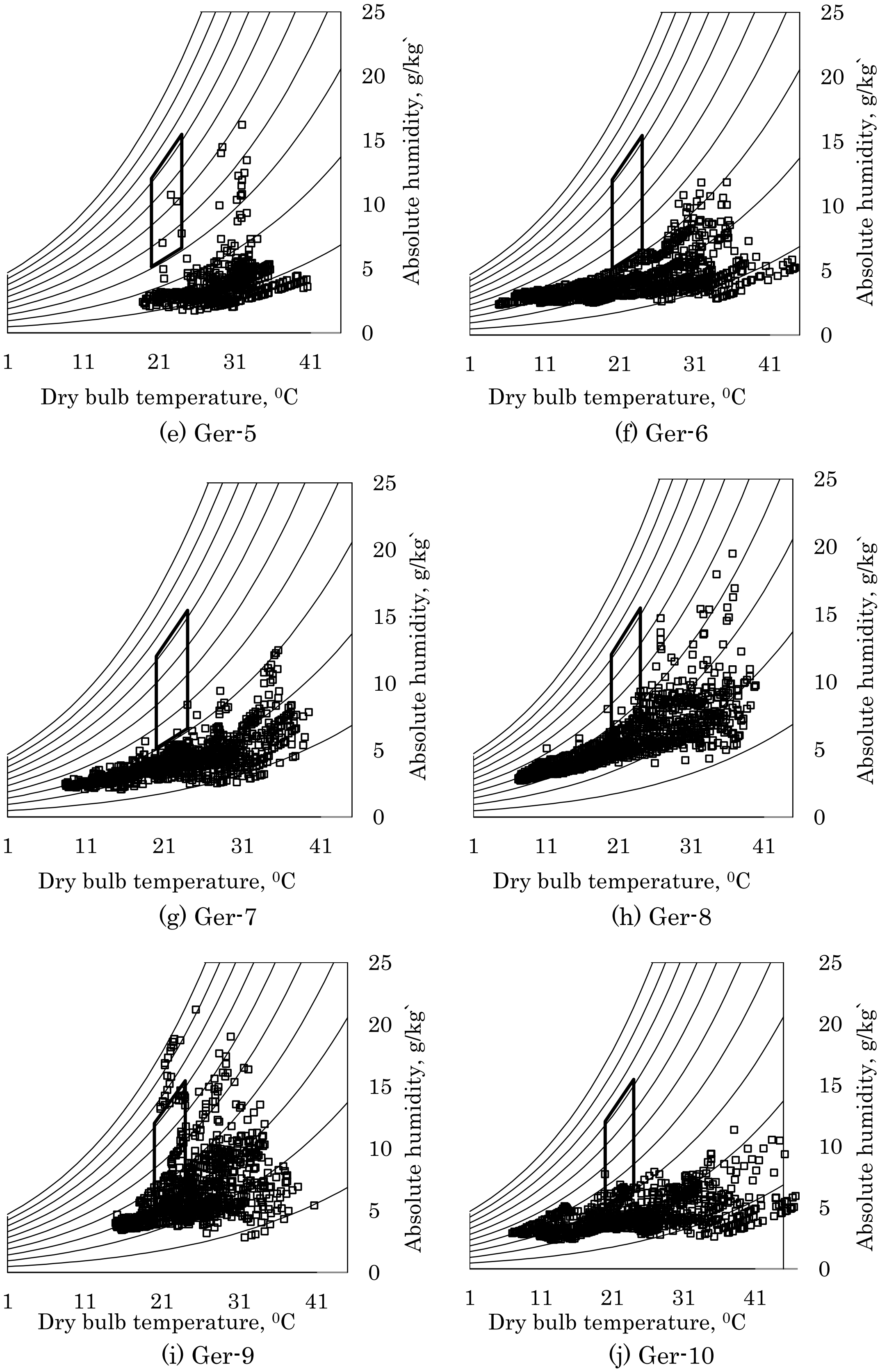


Fig.4.12 Thermal comfort of the Gers

4.4.4 Indoor air CO concentration

CO concentration was measured only for five Gers for 24 hours each. Figure 4.13 represents the daily average, standard deviation and maximum CO concentration of the measured Gers. There is no standard for indoor CO concentration in Mongolia. The daily averages of CO were compared with the acceptable maximum value of 10 ppm as stated in the Japanese Law for Maintenance of Building Service [43]. The average CO concentration is between 1.9 ppm - 5.4 ppm. The average CO concentration does not exceed the limit of 10ppm for all the Gers. Accordingly, side effects of poor indoor quality were low for the measured Gers. Symptoms existence for any member of household such as dizziness, throat pain, eye irritation and allergy were asked in the questionnaire. The percentage of dizziness and eye irritation for family members were 6.8% and 10.2%, respectively. The maximum value of CO occasionally exceeds 10ppm for Ger-6, Ger-7, and Ger-10. The sudden increase of CO concentration is correlates to the cooking in the Gers. All households cook on the stove at least once a day, typically in the evening. The top cover of the stove is replaced with a pot at the time of cooking. During the period of cooking, flue gas spreads inside the Gers, resulting in the increase of CO concentration during certain hours.

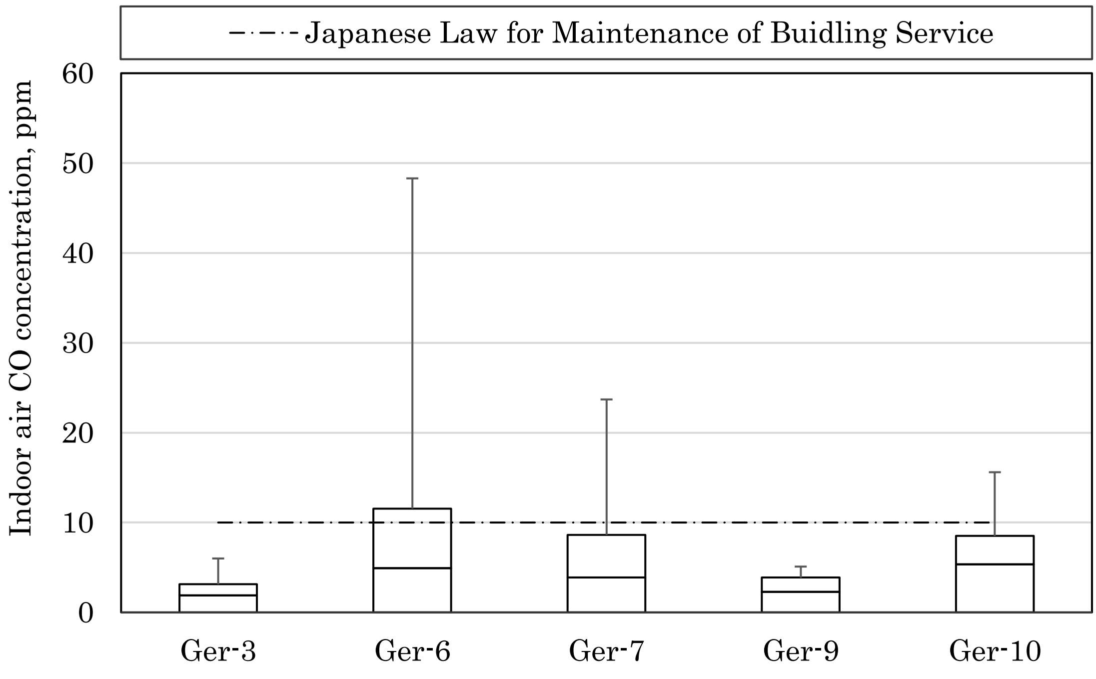


Fig.4.13 Daily value of indoor air CO concentration

4.4.5 Indoor air CO_2 concentration

Figure 4.14 shows the indoor CO_2 concentration of the Gers. CO_2 concentration is compared with the acceptable maximum of 1,800 ppm stated in the Mongolian standard [32] during daytime and nighttime accordingly. The average CO_2 concentration is 958 ppm and 1,262 ppm during daytime and nighttime, respectively. There are some cases when CO_2 exceeds the maximum limit for the Gers, with the except of Ger-1, Ger-2, Ger-6. The smallest value of CO_2 was 478 ppm and 400 ppm during daytime and nighttime, respectively for Ger-2.

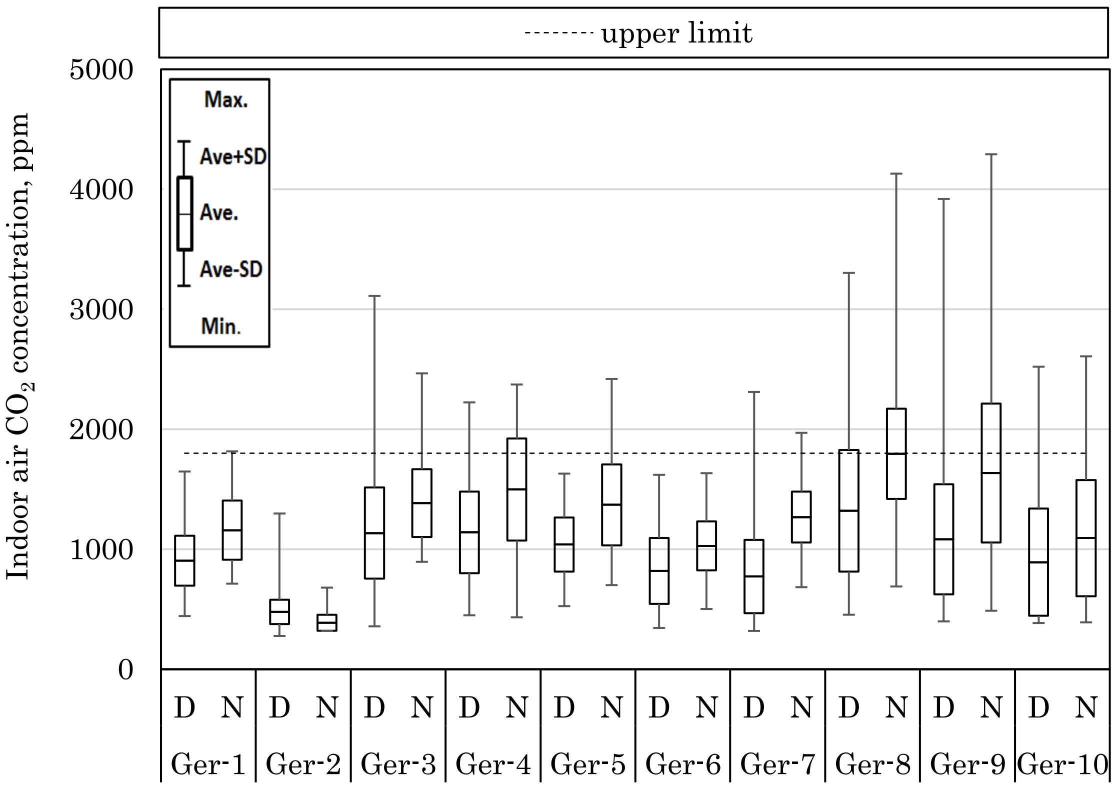


Fig.4.14 Indoor air CO_2 concentration in daytime and nighttime

4.5 Estimation of the ventilation rate and the heat loss coefficient

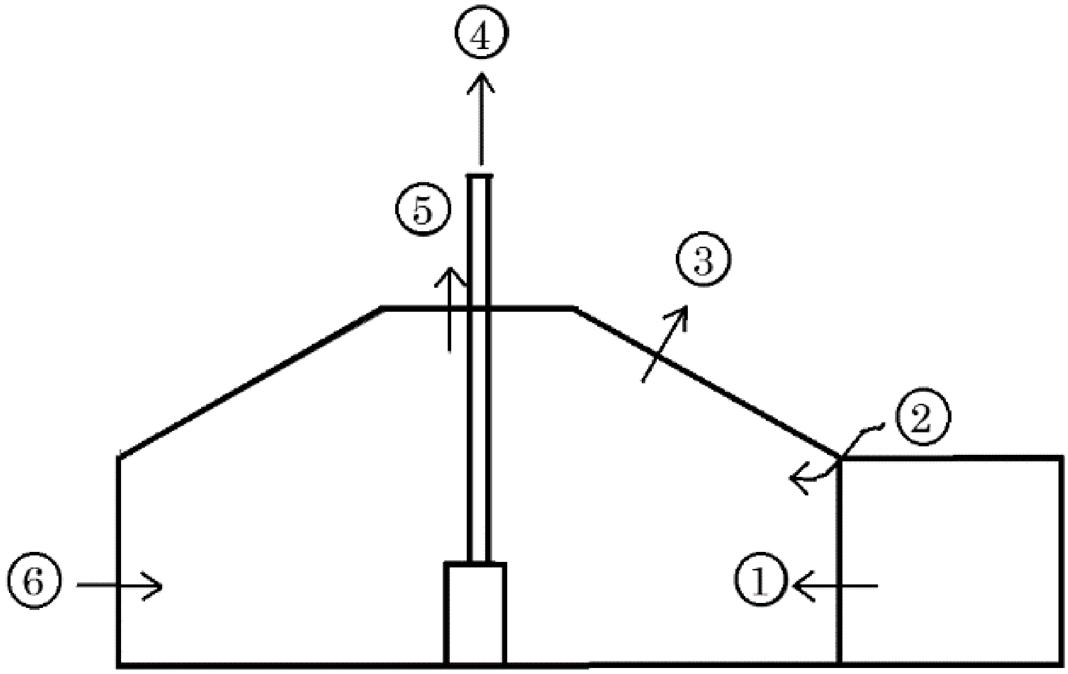
4.5.1 Ventilation rate

Air flows through the walls, roofs and gaps in the door, the top glass window, and the chimney. Air also penetrates through the felt insulation as shown in Fig.4.15.

The door of the Ger has direct contact with outdoor air and whenever the door opens, CO_2 is exhausted outside. The ventilation rate during daytime is difficult to estimate because of the uncertainty of those coming and leaving. CO_2 concentration during 4:00 - 6:00 when residents are sleeping is the most stable throughout a day for the Gers. CO_2 concentration during this period is used to estimate the ventilation rate with Equation (4.1) [33].

$$\mathrm{V} = \frac{m}{(p-p_0)\cdot 10^{-6}} \qquad (4.1)$$

When estimating the ventilation rate, CO_2 emitted from the coal burning is assumed to be exhausted to the outdoors through the chimney without affecting the inside air. Results of the ventilation rate for the nine Gers are shown in Fig.4.16.



1 Cold air flowing in through a gap of the door
2 Cold air flowing in a gap between the wall and the roof
3 Hot air flowing out through the roof
4 Hot air flowing out through the chimney
5 Hot air flowing through the top opening
6 Cold air flowing in through the wall

Fig.4.15 Air flow path of the Ger

As mentioned in section 3.2.5, Ger-2 is excluded from the estimation because of the absence of the household. The highest average ventilation rate is 118 m^3/h ($4.6h^{-1}$) for Ger-1 while the lowest is 40 m^3/h ($1.8h^{-1}$) for Ger-8. As seen in Fig.4.16 the ventilation rate differs significantly among the Gers but this difference is not related to the number of insulation layers. The reason for this is because Gers are handmade through different technologies resulting an uneven thermal resistance. The ventilation rate during 4:00 - 6:00 is the lowest throughout the day because the door rarely opens during that time. However, the air change rate of the Gers is much higher than that of apartments, it is at a reasonable level from the viewpoint of indoor CO_2 concentration and heat loss.

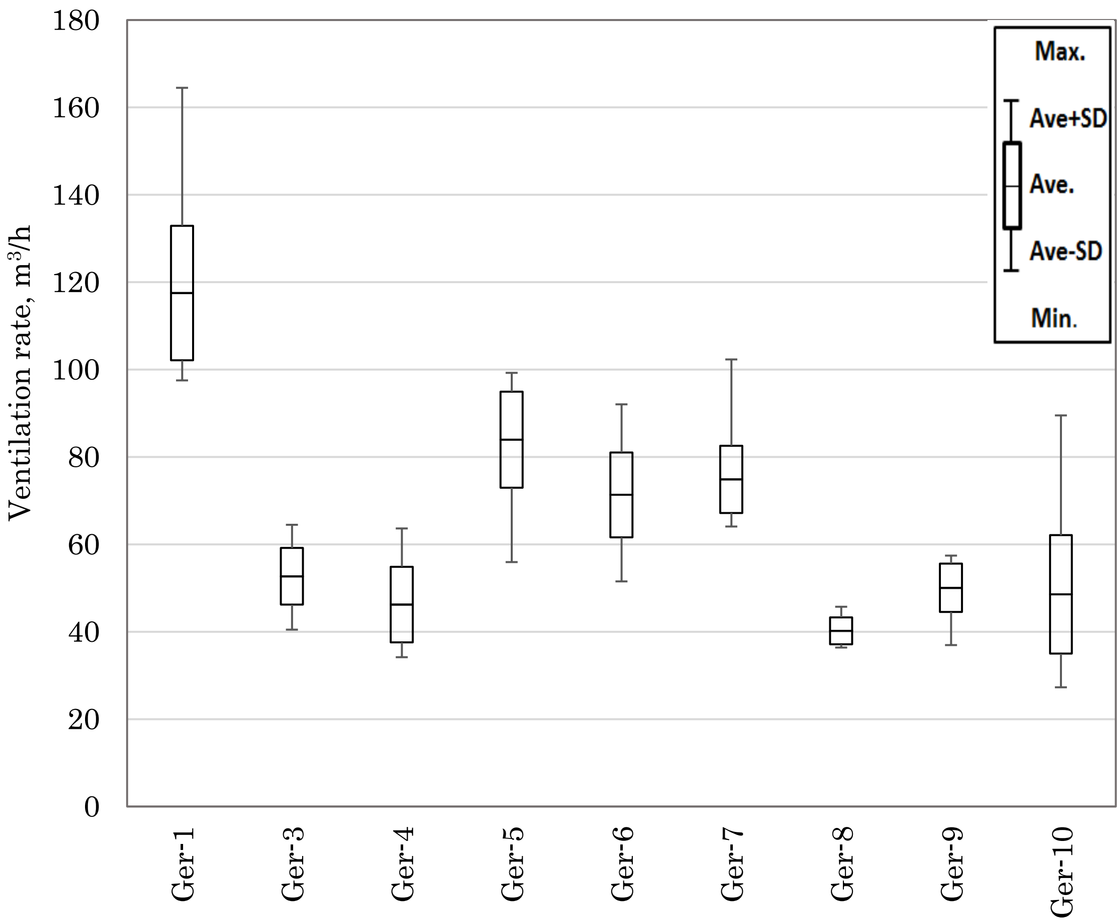


Fig.4.16 The ventilation rate of the Gers during 4:00AM to 6:00AM

4.5.2 Heat loss coefficient

The heat loss coefficient is estimated based on the coal consumed throughout measuring period using Equation (4.2) [42].

$$Q = \frac{H_g}{\Delta\theta \cdot A_f} = \frac{m_c \cdot \varepsilon \cdot c}{\Delta\theta \cdot A_f \cdot d \cdot 24 \cdot 3600} \quad (4.2)$$

Internal heat gains from the home electric devices, lighting and human bodies were miniscule in comparison to the heat gain from the coal burning. Therefore, they are neglected in Equation (4.2). Residents living in the Gers consume Nalaikh coal which comes from the closest coal mine for Ulaanbaatar. Nalaikh coal is lignite with a specific heat capacity of 14.6 MJ/kg [44].

The heat loss coefficient of the ten Gers is compared in Fig.4.17. The minimum heat loss coefficient is 1.31 W/(m^2K) whereas the maximum is 3.96 W/(m^2K). The heat loss coefficient is different among the Gers because of the difference in the ventilation rate and heat transfer loss through the felt insulation. There is no direct relationship identified between the heat loss coefficient and the ventilation rate. Because the heat loss coefficient is not only decided by the ventilation rate but also the heat transfer through the felt. Felt insulation is produced by different manufacturers with different technologies without any standard. Therefore, air flow coming in through a gap between walls and the floor is significantly large [38] which varies among the Gers depending on whether it is covered with earth or other air resistant materials.

The average heat loss coefficients for existing dwellings in Ulaanbaatar were compared in Fig.4.18. Though the average annual heating consumption of the Ger is small related to its floor area, the heat loss coefficient per square meter area is about 135% and 237% higher than the non-insulated and insulated apartments, respectively.

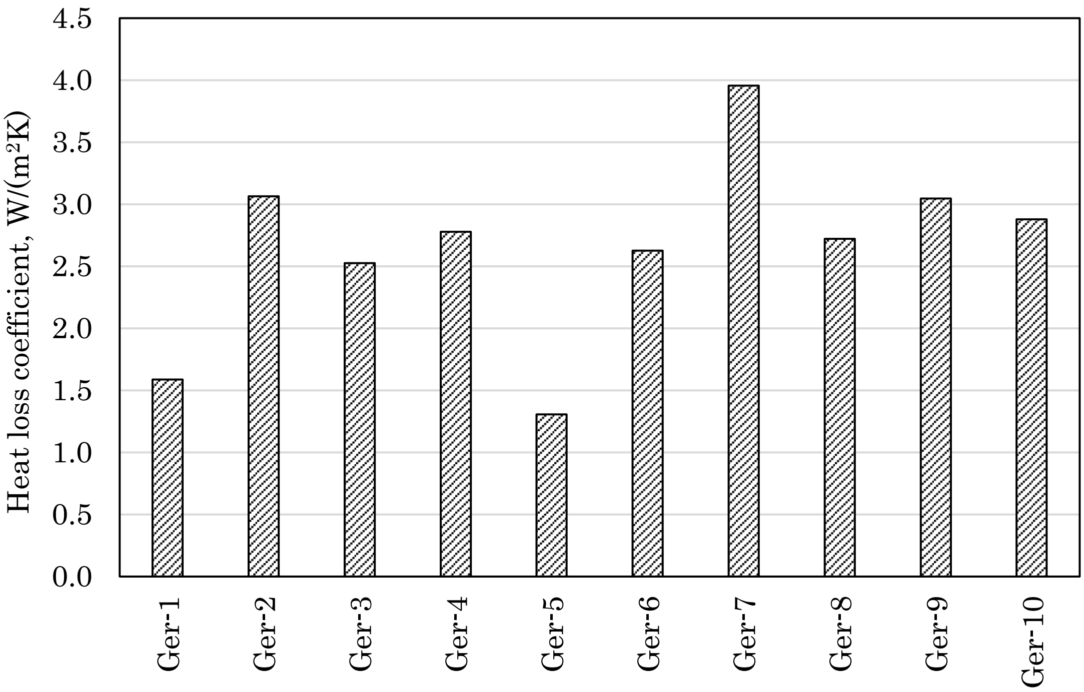


Fig.4.17 The heat loss coefficient of the Gers

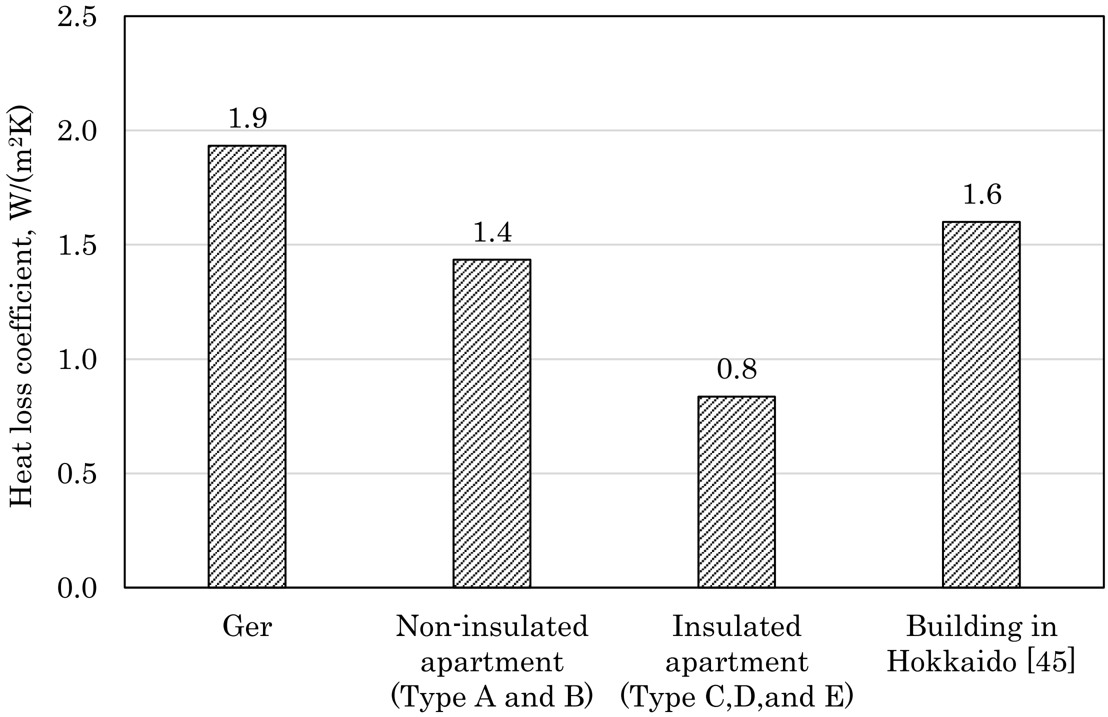


Fig.4.18 Comparison of the average heat loss coefficients for the apartments and the Ger

4.6 Summary

In this chapter, 59 Gers were investigated, 10 of which were selected for measuring the indoor environment. The main findings from this chapter are:

- The indoor environment of the Gers is not thermally comfortable compared with that of apartment buildings due to the large temperature change and low relative humidity throughout a day. The average of the maximum temperatures during daytime is 41.4 ^{0}C whereas the average of the minimum temperatures during nighttime is 8.0 ^{0}C;
- Indoor CO and CO_2 concentrations are within acceptable level;
- The ventilation rate during 4:00-6:00 is between 40 m^3/h and 118m^3/h which is equivalent to 1.8 h^{-1} and 4.6 h^{-1};
- The heat loss coefficient of the Gers is highest between 1.31 W/(m^2K) and 3.96 W/(m^2K) among surveyed dwelling types.

CHAPTER 5
Parametric analyses of the heating load for apartment building

5.1 Introduction

Relating to the population growth of Ulaanbaatar, the number of dwellings, especially apartments has been increasing as a result of the effective housing policy taken by the government. Along with enlarging number of dwellings the energy consumption for residences has been increasing, which contributes to severe air pollution and energy shortages in recent years.

The number of residential buildings account for 27% of the district heating energy consumers in Ulaanbaatar as of 2014 [46]. There are still many residential buildings with non-insulated structures in Ulaanbaatar. Therefore, potential of energy saving for residential buildings is high by thermal retrofitting and energy saving design.

The purposes of this chapter are to clarify the potential of reducing energy consumption for existing non-insulated residential buildings in Ulaanbaatar by thermal retrofitting and to make suggestions for the thermal design of newly constructed buildings through computer simulations.

So far very few studies have been carried out on the thermal environment and energy consumption of the residential buildings in Mongolia. The energy consumption and thermal environment in apartment buildings were investigated in Chapter 3 with questionnaire survey and field measurements [47]. During the previous investigation we identified that it is necessary to make clear the influence of each parameters to the heating load of apartment buildings by simulations.

In this chapter, the typical floor model of residential building was created, and dynamic simulations were carried out for each considered structure type with energy simulations to analyze the impact of the parameters such as orientation, insulation thickness, indoor temperature, window type and air change rate. A regression equation was developed to estimate the heating load of the typical floor with seven parameters.

Abbreviations:

S_{index} Sensitivity index;

D_{max} Maximum output value of annual heating load [GJ];

D_{min} Minimum output value of annual heating load [GJ];

Q Annual heating load [GJ];

K Weighted average heat transfer coefficient of the building envelope [W/(m²K];

A_{ext} Sum of the exterior envelope surface areas [m²];

HDD Heating degree-day at actual room temperature [K.day];

V Ventilation rate [m³/h];

g Solar heat gain coefficient [-];

I_r Global solar radiation on the south facing surface of the building [W/m²];

A_{wind} Area of the south oriented windows [m²];

N Numbers of households on the same floor [-].

5.2 Methodology

In this chapter thermal performance of the buildings is analyzed dynamically with building energy simulation program TRNSYS ver.18 [48]. The weather data required by the program, the Typical Meteorological Year (TMY) for Ulaanbaatar was developed in Chapter 2 using observational weather data in 2006-2015 [49]. The TMY contains 11 elements of the outdoor air for 8,760 hours throughout a year.

The monthly averages of the outdoor air temperature and relative humidity of the TMY are shown in Fig.5.1. The annual average outdoor temperature is 0.5 ^{0}C while the average for heating season is -5.5 ^{0}C. The heating season lasts 245 days, from 15th September to 15th May in Ulaanbaatar. Figure 2 shows the annual global horizontal solar radiation. Solar radiation is the strongest in June and the weakest in December.

The simulation program requires an apartment model which should be typical according to floor area, type of apartment plan, household structure and activity schedules of the residents. A typical apartment model was developed in this chapter that will be described in section 5.3.2.

To accomplish our purposes parametric analyses were carried out. Orientation, insulation thickness, window type, indoor temperature and air change rate are selected as parameters for the analyses. Parameters and their changing intervals are shown in Table 5.1. Input parameters were changed once for each run while other parameters remain unchanged as the reference case shown in Table 5.2. The exterior wall structures shown in the table are from outside to inside. In the case of insulation of the Type A the outer ceramic tile will be replaced with EPS covered with plastering. There were 48 simulation runs for each type in total.

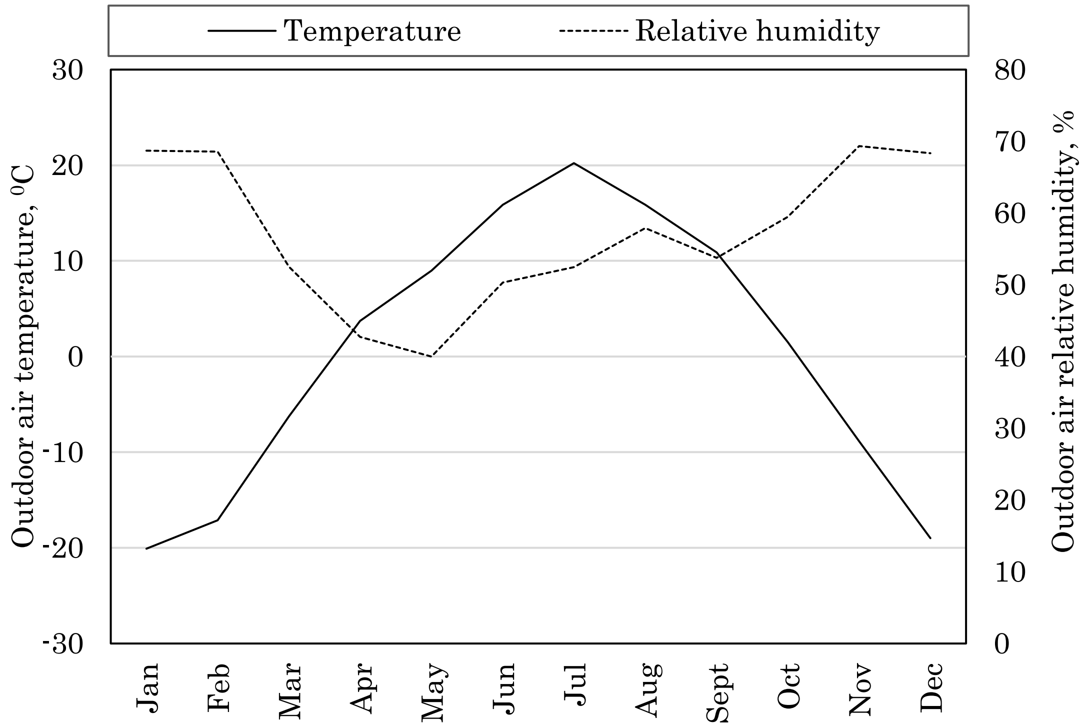


Fig.5.1 Monthly average air temperature and relative humidity during heating season

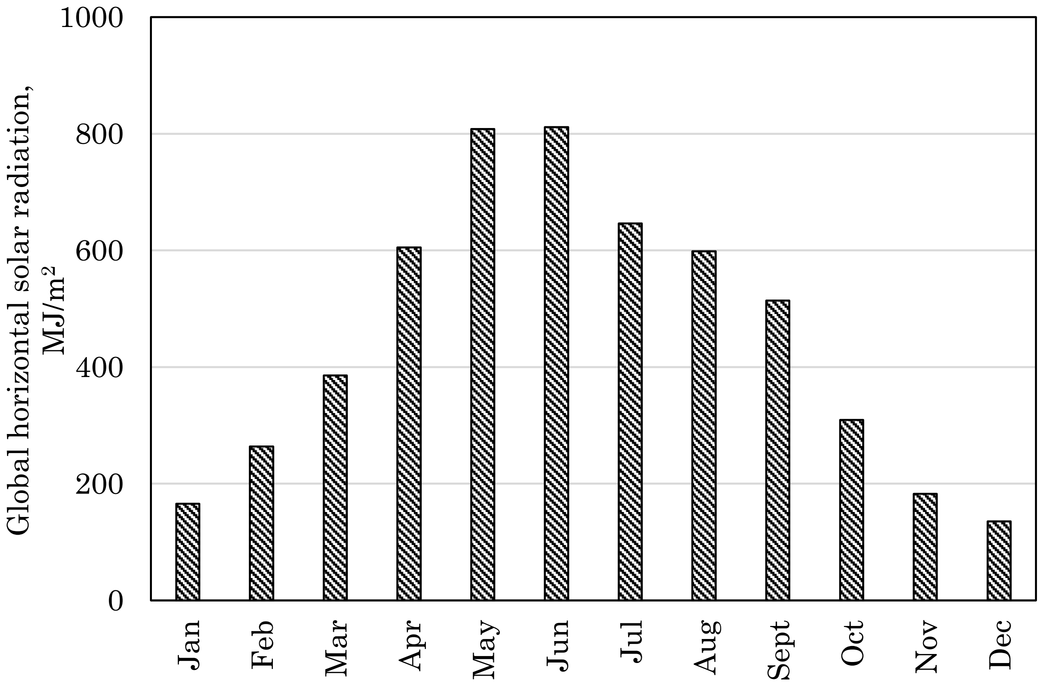


Fig.5.2 Monthly global horizontal radiation per square meter area

Table 5.1. A summary of the input parameters.

Parameters	Unit	Interval	Range
Orientation	^{0}	45	(-90) to (90)
Insulation thickness	cm	5	0 to 50
Window type	-	-	• Double glazing • Triple glazing • Triple glazing with krypton filled, Low-E
Air change rate	$\frac{1}{h}$	0.1	0.1 to 1.5
Indoor air temperature	^0C	1	18 to 28

Table 5.2. Reference case parameters.

	Type A	Type D	Type E
Wall structure	• Ceramic tile • Ceramsite concrete • Plastering	• Plastering • EPS • Light weight concrete • Plastering	• Plastering • EPS • Reinforced concrete • Plastering
Orientation	180^0	180^0	180^0
Window	Double glazing	Double glazing	Double glazing
Air change rate	$0.5\,\frac{1}{h}$	$0.5\,\frac{1}{h}$	$0.5\,\frac{1}{h}$
Indoor air temperature	20 ^0C	20 ^0C	20 ^0C

5.3 Development of the typical floor model

5.3.1 Survey on residents and buildings

A survey conducted in 2016 during investigation of the indoor environment and energy consumption of apartment as described in Chapter 3 was used to develop a typical model for building simulations.

The type of the surveyed apartments is shown in Fig.5.3 regarding to the number of rooms. Most of the households live in the apartments with one or two bedrooms. Fifty three percent of the surveyed households live in 1BHK apartments, which means one bedroom, a living room and a kitchen.

The floor area for each apartment is shown in Fig.3.11. The floor area is classified into three categories: under 51 m^2 (56%), 51-80 m^2 (40%) and above 81 m^2 (4%). According to 2013 statistics households with four members live in the apartment which has above 40 m^2 floor area [4].

Structures of the surveyed households are composed of couples with their children, couples with their parents, households with their relatives, couple without children and single persons. The households of couple with their children were the largest of all groups as shown in Fig.3.5.

The number of residents for each household can be seen in Fig.3.6 and households that have four to five residents account for the largest portion.

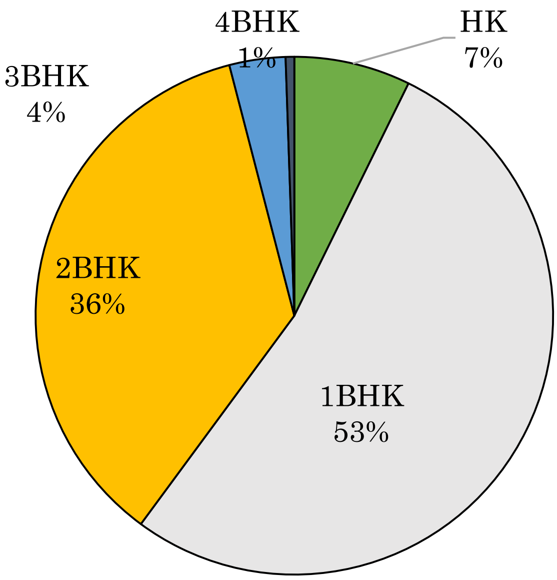


Fig.5.3 The type of apartments

5.3.2 The typical floor

In order to analyze the heating load of apartment buildings with a simulation program a typical floor including four apartments was developed based on the survey results and requirements of the Mongolian national standards. Usually a typical apartment rather than a typical floor is used for building simulations in Japan [50]. In this chapter, however, a typical floor is suggested for the simulation because orientations and floor area are different among apartments on the same floor due to the middle corridor plans. As seen in Fig.5.3 the most common type is a 1BHK apartment. Therefore, there are four 1BHK apartments with the floor area of 53-56 m^2 on the typical floor as shown in Fig.5.4. Window area is selected within the accepted limit of window to wall ratio stated in the National standard [34]. The developed model is assumed locating in the middle floor of the building. The number of residents, usage of electric appliances and lighting behavior influence the internal heat gain. According to Fig.3.8 and Fig.3.9 four people comprising a couple with two children are assumed for each household.

Occupancy fraction of the typical household is created based on the household structure and daily activities of each member. It is assumed that parents work during the day and children go to high and elementary schools in this study. One of them attends the morning session whereas another attends the afternoon session due to a lack of class rooms in Ulaanbaatar.

We estimated lighting and electric appliance power density as 4 W/m^2 and 46 W/m^2, respectively from the survey, which agrees with measured value of the electricity consumption of households [51]. Lighting and electric appliance usages are shown in Fig.5.5 and Fig.5.6, respectively. Fractions of electric appliances during weekdays and weekend are different in some hours related to the activities of residents.

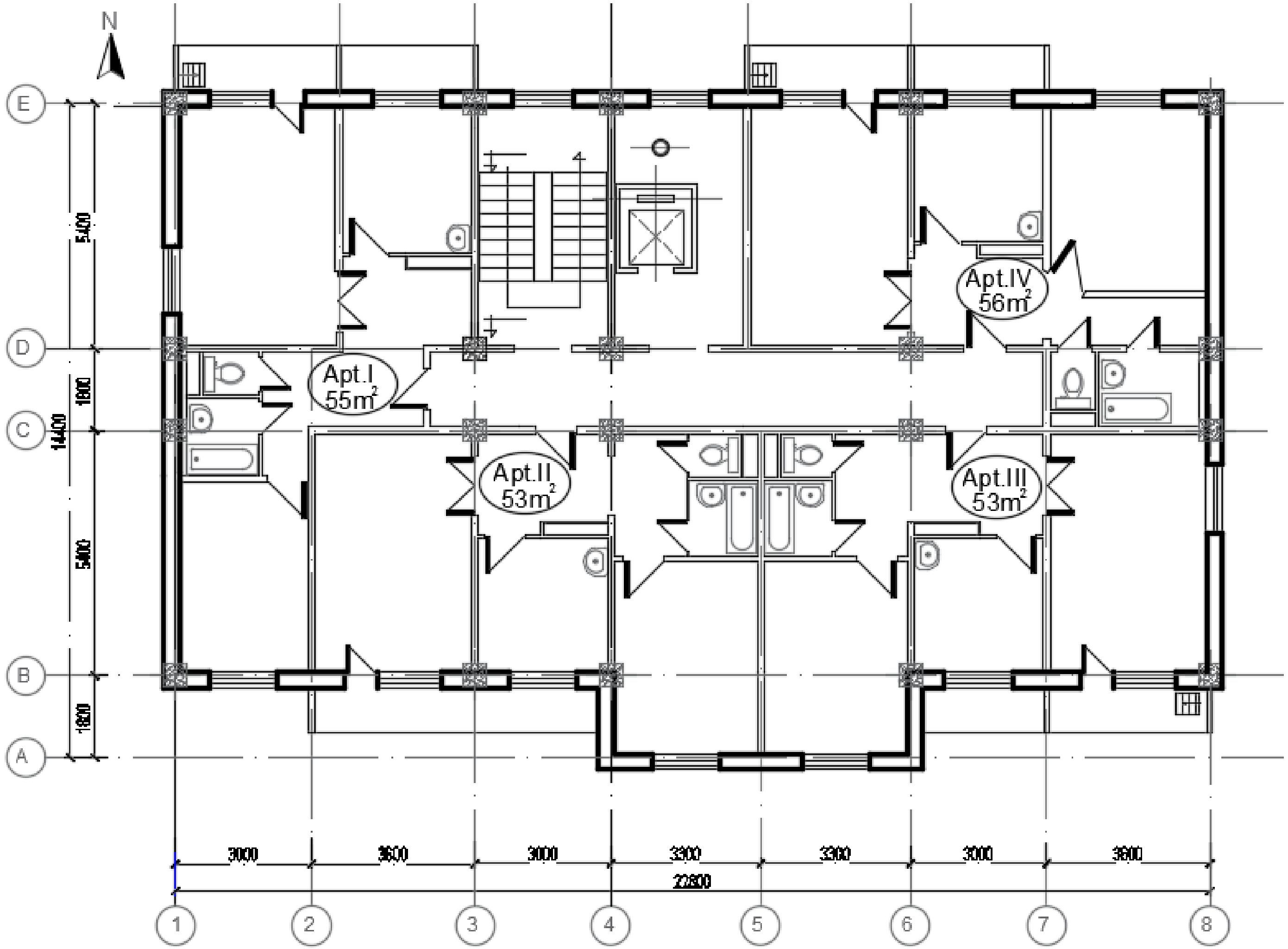


Fig.5.4 The typical floor plan

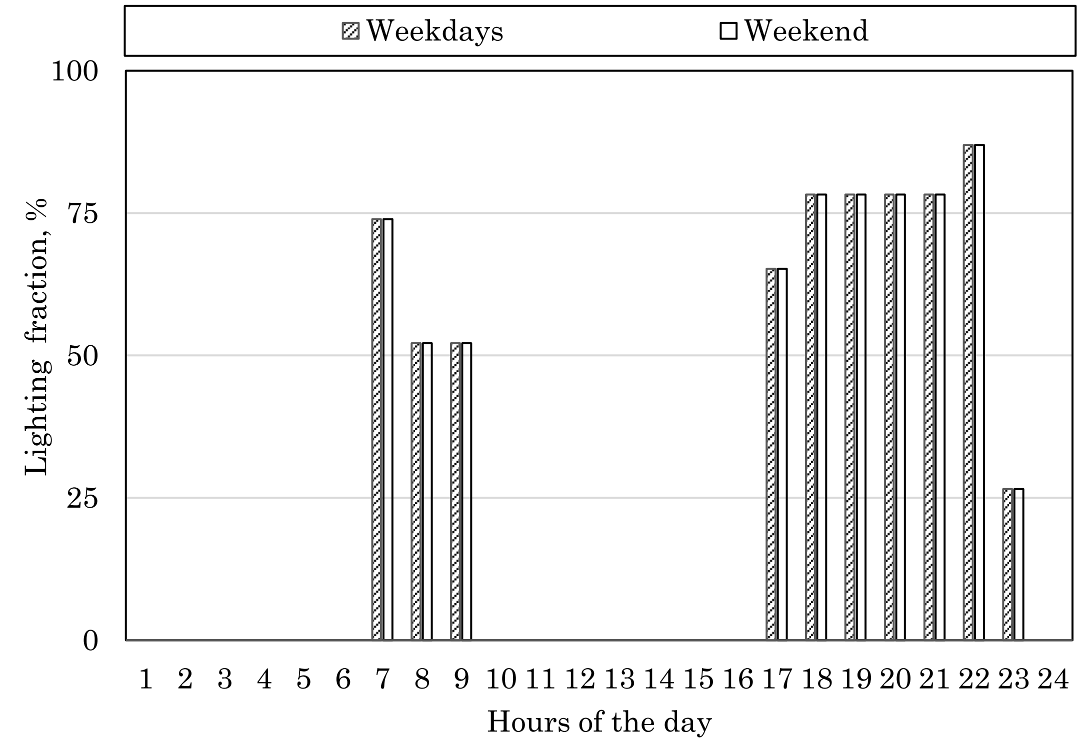
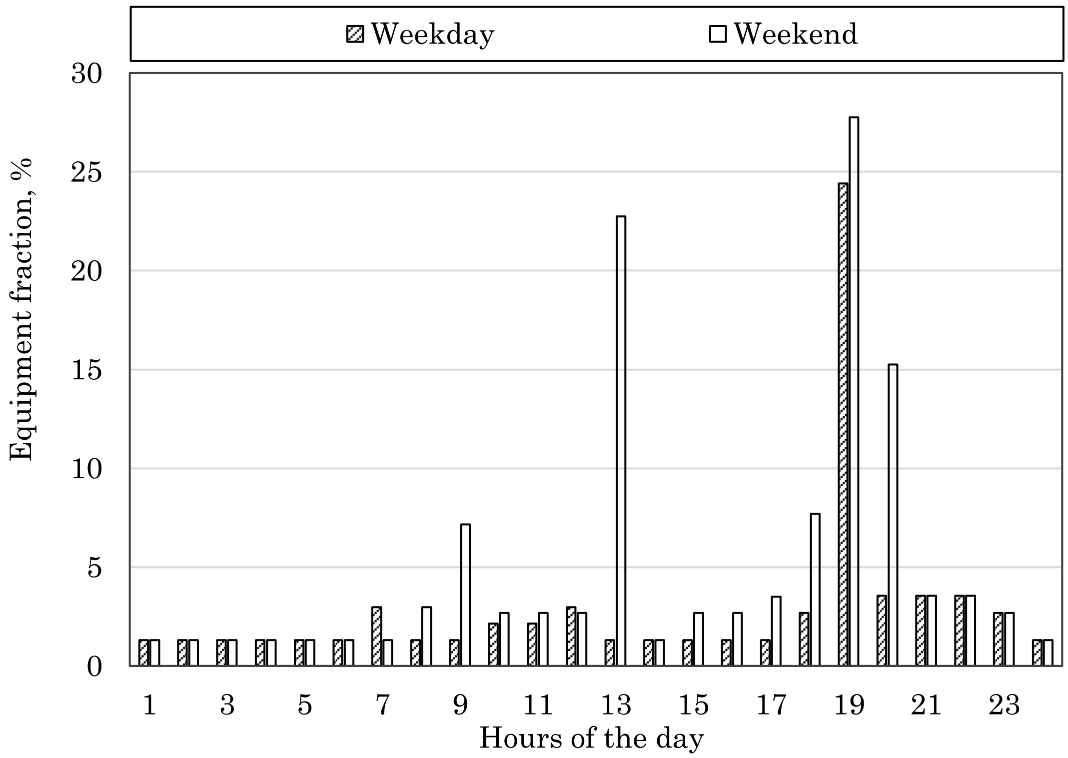


Fig.5.5 Lighting fraction of the apartment



Fi.5.6 Equipment usage fraction of the apartment

5.4 Results and analyses

Influences of the parameters such as orientation, insulation thickness, window type, indoor air temperature and air change rate are examined in this chapter. Fig.5.7 shows the impact of the building orientations on the heating load. The typical model is facing south in the reference case and it is changed by 45^0. There were five orientations for each type. As the result shown in Fig.5.7 the heating load is the smallest for all three types when they are facing South. This is because more solar gain is achieved through windows when the building is facing South. The difference of heating load among orientations is within 7.6% for all types.

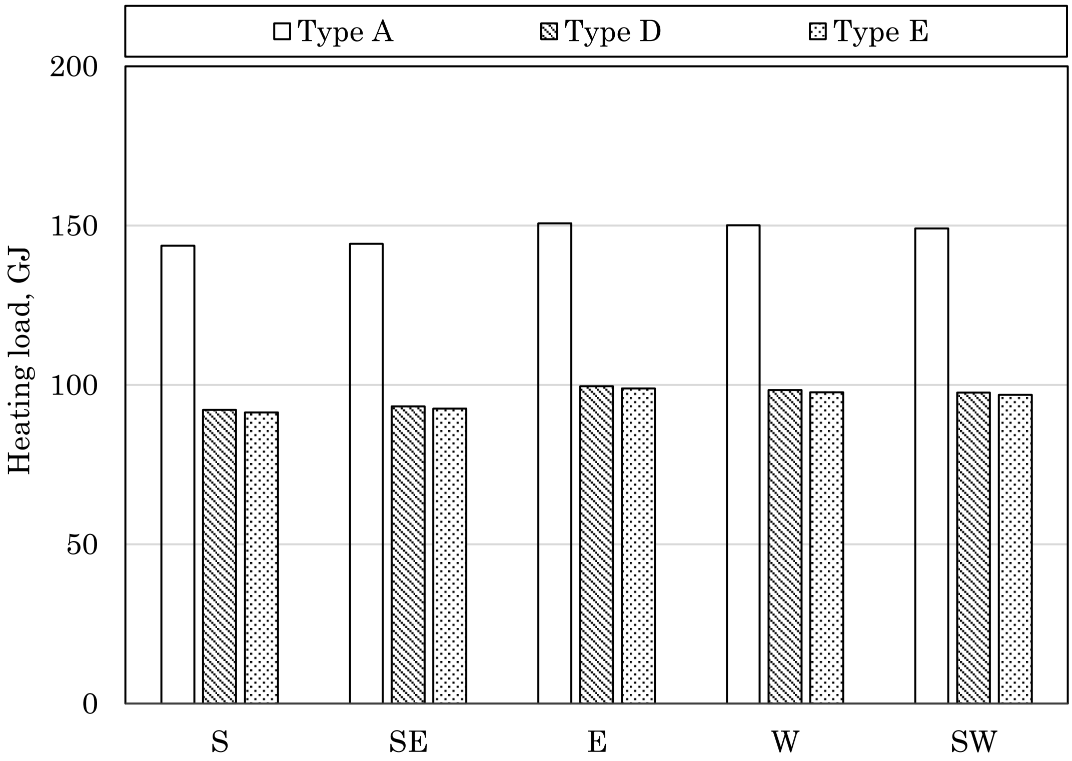


Fig.5.7 Effect of orientation on the annual heating load of the typical floor

The impact of orientation for each apartment is shown in Fig.5.8. The apartment with the largest heating load is Apartment IV and that with the smallest heating load is the Apartment II because of different solar gains between these two apartments.

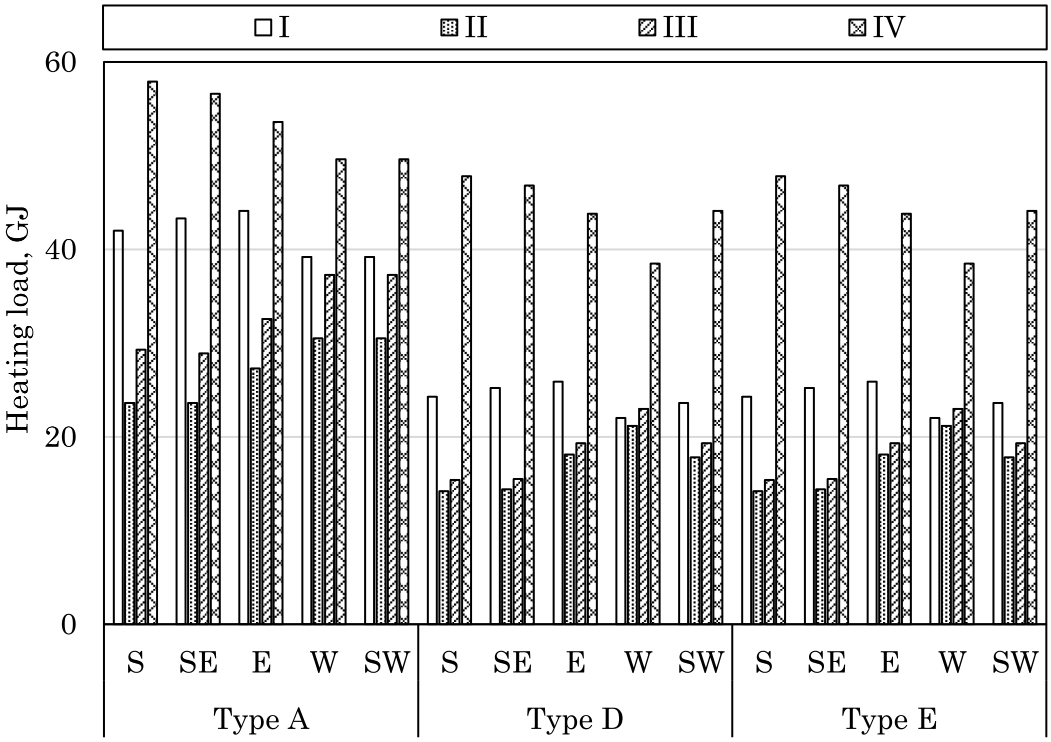


Fig.5.8 Effect of orientation for each apartment

Figure 5.9 shows the impact of insulation thickness of the exterior walls on the heating load. Heating load with non-insulated structure of the Type E is much larger because of the high thermal conductivity of the reinforced concrete. The maximum heating load reductions found 25% for Type A, 22% for Type D, and 63% for Type E when non-insulated structures are insulated with 5cm EPS board. The effect of additional thickness of the insulation is lower for all the structure types because the insulation thickness affects the heating load non-linearly. Moreover, an additional thickness of the insulation after 30 cm has weak impact on the heating load for all types of structures. Appropriate thickness of the insulation could be selected based on the cost and thermal resistance analysis for all types of buildings.

As shown in Fig.5.10, windows of the existing apartment buildings in Ulaanbaatar are double glazing ones with the PVC frames. The impact of a window with double glazing, triple glazing and krypton filled triple glazing with Low-E coating is compared. Window types have small impact for all the three types of structures because window to wall ratio is less than 18% in this paper. The heating load can be reduced by 6%-13% by triple glass and krypton filled triple glass with Low E.

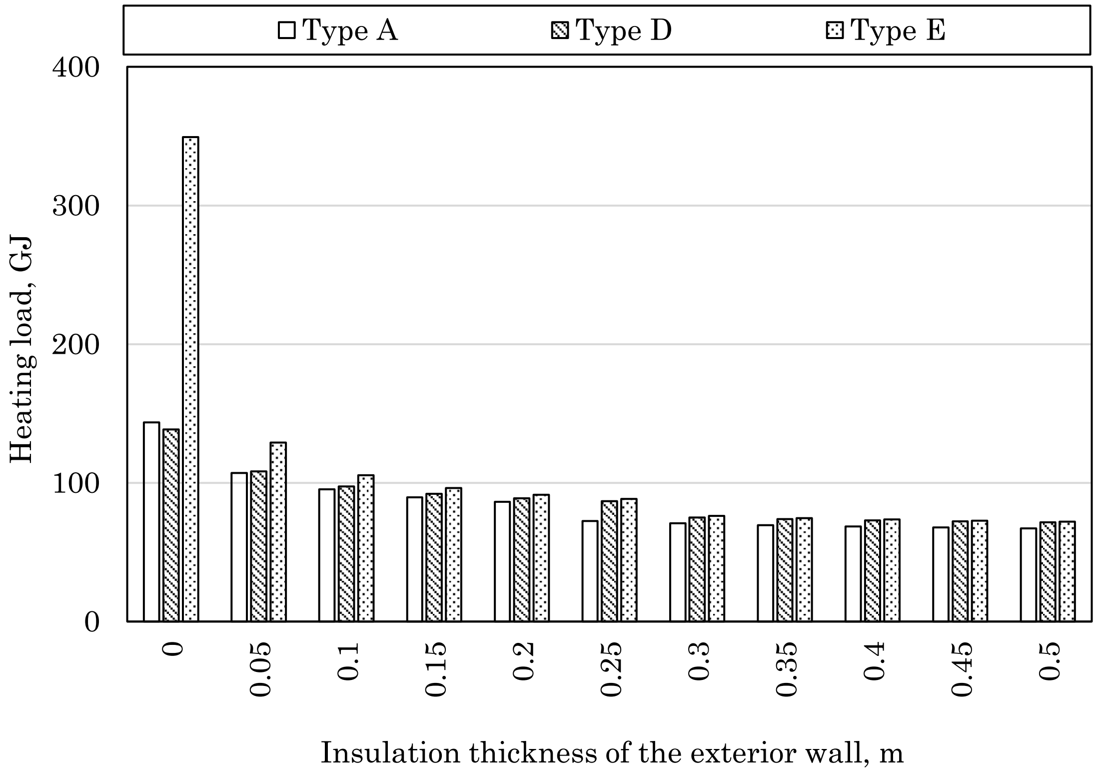


Fig.5.9 Effect of insulation thickness on the annual heating load

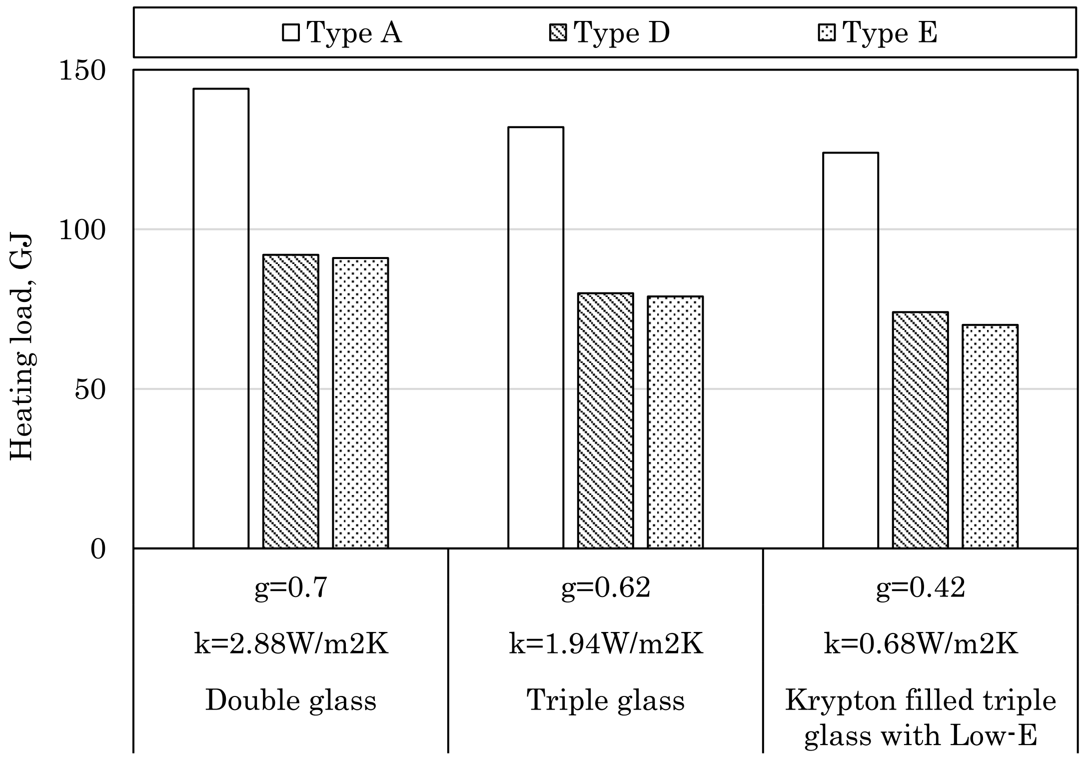


Fig.5.10 Effect of window types on the annual heating load of the typical floor

In the reference case air change rate is set at 0.5 times per hour for all the apartments excluding the staircase, elevator hall and corridor. Figure 5.11 shows the impact of air change rate on the heating load of the typical floor. The air change rate correlates with the heating load linearly. The heating load is increased by 11% for the Type A, 18% for the Type D and 19% for the Type E respectively, when the air change rate is increased by 0.1 times per hour. The significant reduction of heat loss could be expected from the reduction of the air change rate, but the required ventilation rate shall be maintained.

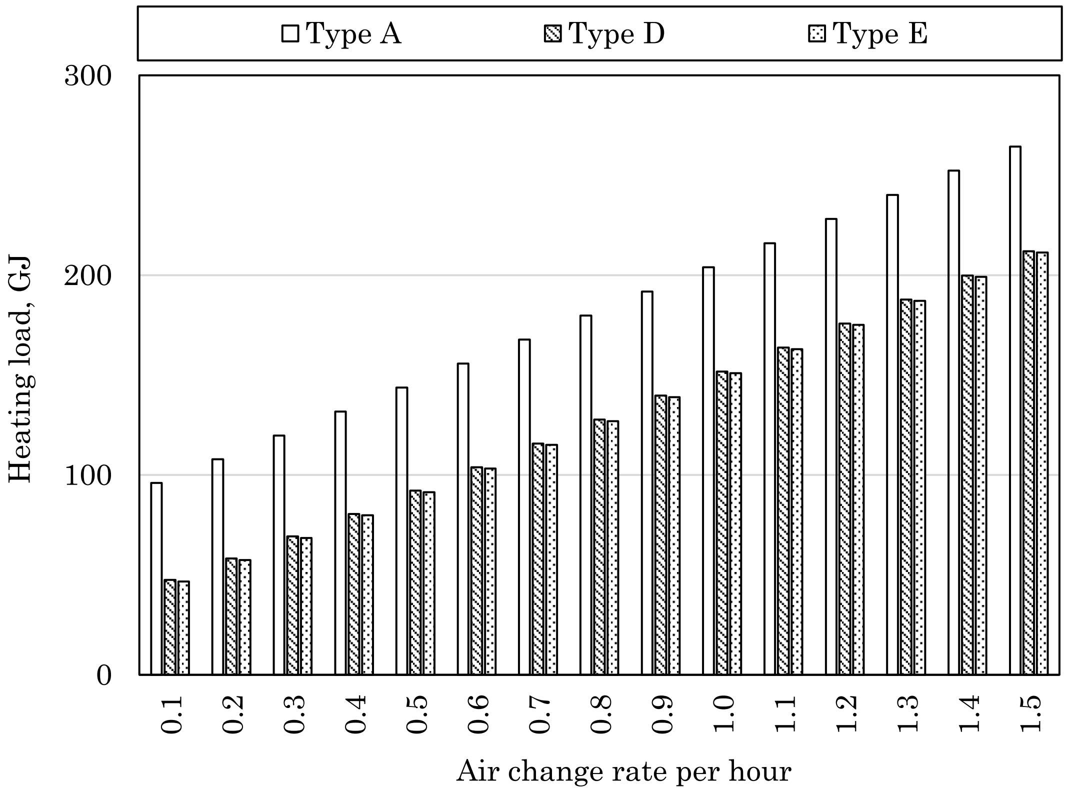


Fig.5.11 Effect of air change rate on the heating load of the typical floor

The impact of indoor air temperature is shown in Fig.5.12. Indoor air temperature has strong relationship to the heating load. There would be 5% to 6% of energy savings for every 1 ^{0}C drop in indoor air temperature. This shows that overheating of the building enlarges the heating load significantly. Therefore, indoor air temperature should not exceed values recommended by the national standard on the indoor environment [30].

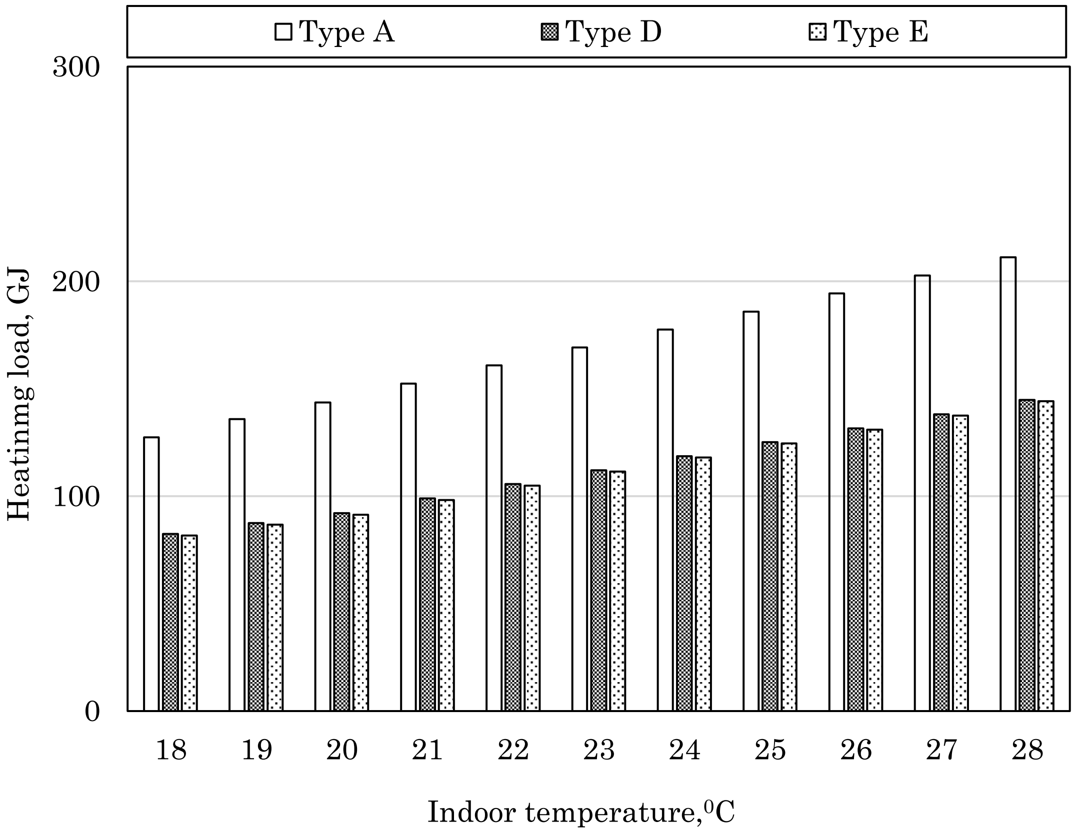


Fig.5.12 Effect of indoor air temperature on the annual heating load of the typical floor

Above mentioned five parameters influence the heating load differently. Therefore, it is needed to identify influential parameters which could have significant benefit to save energy. Each parameter's degree of effect on the heating load was identified by the sensitivity analysis. Sensitivity index of the parameter was estimated the output difference when varying one input parameter from its minimum value to maximum value as given in Equation (5.1)[52].

$$S_{index} = \frac{D_{max} - D_{min}}{D_{max}} \qquad (5.1)$$

Sensitivity analyses results are shown in Fig.5.13. Effects of the building orientation and the type of window are small on the annual heating load however effects of insulation thickness, indoor temperature, and air change rate are significant.

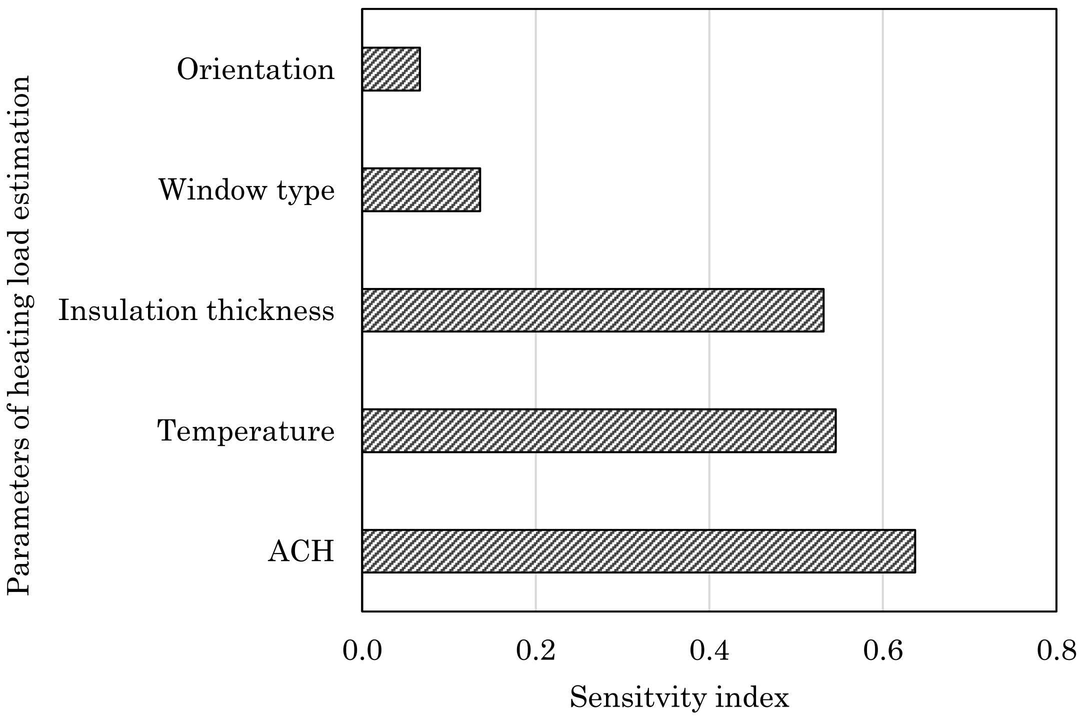


Fig.5.13 Sensitivity analyze of the parameters

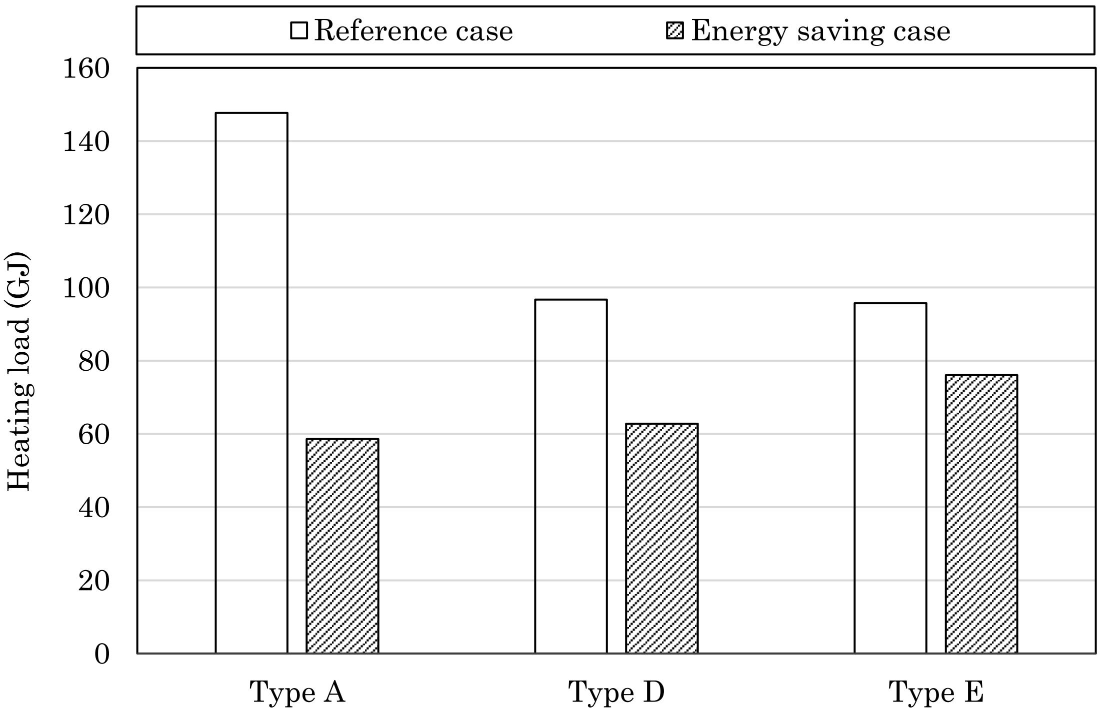


Fig.5.14 Comparison of heating load between the reference and the energy saving cases

Indoor temperature was higher than the acceptable value according to the standard for most of the apartments as shown in Fig.3.13 and air change rate was high too for some apartments of Type A as shown in Fig.3.24. Therefore, there could be some potential to save energy for all type of existing buildings in Ulaanbaatar. In order to clarify the potential of energy savings for existing non-insulated buildings (Type A) and insulated buildings (Type D and E) the energy saving model is proposed and possible parameters are selected based on related standards. In this study cost is not considered for optimization of parameters due to time frame. Parameters of the proposed model is shown in Table 5.3.

Table 5.3. Parameters of the proposed energy saving model

Parameters	Unit	Value	Reference
Orientation	^{0}	0	
Window type	-	Triple glazing	
Insulation thickness	cm	30	
Indoor temperature	^0C	20	MNS4585:2007
Air change rate	h-1	0.5	ASHRAE: Handbook of fundamentals [23]

Figure 5.14 shows comparison of heating load between proposed energy saving model and reference cases. Energy savings is 60% for Type A, 35% for Type D and 21% for Type E. The energy saving potential is the largest for Type A since it is non-insulated structure in the reference case.

5.5 Estimation of the annual heating load

Energy analyses of buildings by the simulations require a lot of efforts and knowledge about computer programming. Therefore, it will be meaningful if it is possible to find some equations to estimate the annual heating load without simulations. In this chapter, a simple equation to estimate annual heating load based on the simulated results was developed. We assumed that heat loss is determined by a combination of transmission and ventilation heat losses on the other hand it is gained from the sun throughout the heating season. Equation (5.2) is created to estimate the annual heating load for the typical floor of apartment buildings in Ulaanbaatar using the least square method.

$$Q = (4.41 \cdot 10^{-5} + 91.439 \cdot K \cdot A_{ext} \cdot HDD + 27.477 \cdot V \cdot HDD$$

$$-3.876 \cdot g \cdot I_r \cdot A_{wind})\frac{N}{4} \tag{5.2}$$

In this chapter a typical floor with four apartments was suggested for simulations. However, real number of apartments on each floor can be different from four. In that case, the annual heating load of the actual buildings can be modified by substituting real number of apartments on each floor for N in Equation (5.1). Figure 5.15 shows the correlation between values of the annual heating load from simulation and estimation with Equation (5.1). The root mean square error is 5.5 GJ which implies that the Equation (5.1) could be used to estimate annual heating load of any type of apartment buildings in Ulaanbaatar with limited errors.

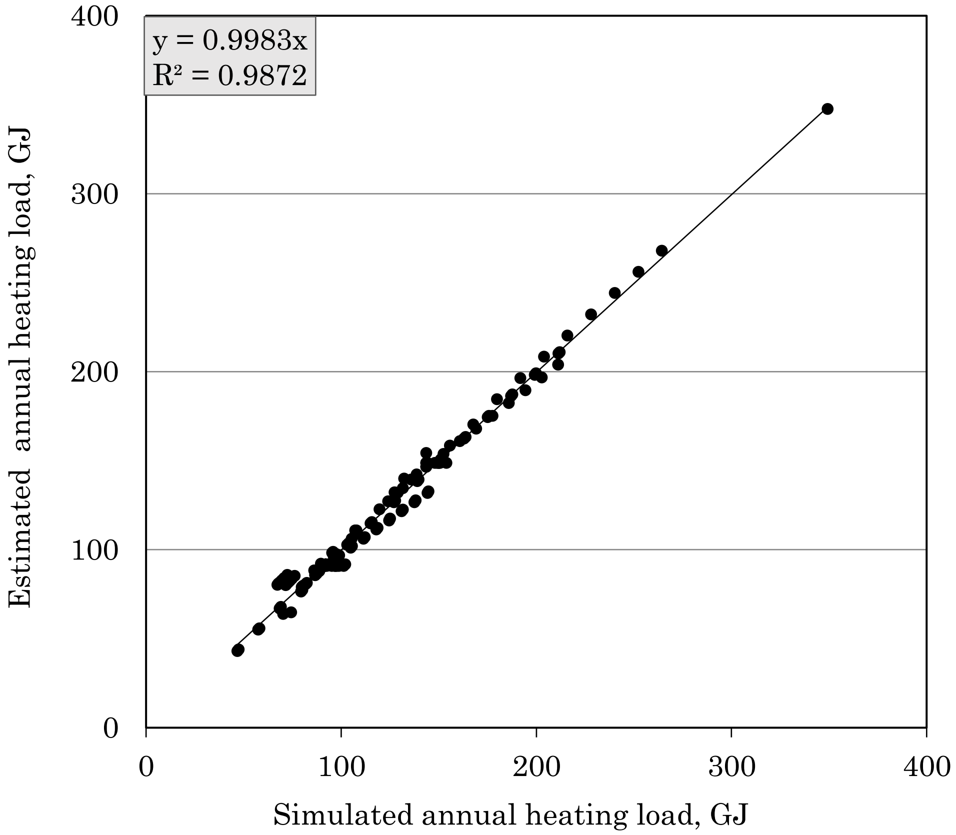


Fig.5.15 Comparison of estimated and simulated value of annual heating load of the typical floor

5.6 Summary

In this chapter, the typical floor model of apartment buildings was created according to survey results, and parametric analyses were carried out for three types of structures existing in Ulaanbaatar. The main findings from this study are:

- The impacts of insulation thickness, air change rate and indoor air temperature are large and that of orientation and window type are small;
- The energy saving potential was clarified by comparing the heating load between the energy saving and the reference models. The potential of energy saving is 60% for Type A, 35% for Type D, 21% for Type E, respectively;
- An estimation equation was developed with which annual heating load of apartment buildings in Ulaanbaatar could be estimated with limited errors.

Chapter 6
Conclusions and Suggestions

6.1 Conclusions

The energy consumption in Mongolia has increased due to improvement of people's living standard and growth of population, which contributes to severe air pollution and energy shortages in recent years.

The purposes of this study are to make clear the energy consumption and the indoor environment of residences including residential buildings, Gers and to give suggestions about energy saving measures based on surveying, measurement and simulations. To fulfill those purposes several consecutive studies were conducted: developing Typical Meteorological Year for Ulaanbaatar Mongolia, clarifying the indoor environment and energy consumption of apartment buildings and the Gers, identifying the potential of energy saving for apartment buildings and giving suggestions.

The background purposes and literature reviews were stated in Chapter 1.

In Chapter 2, a solar model to estimate global solar radiation on the horizontal surface was developed for Ulaanbaatar. Estimated global solar radiation using the developed model was validated with the observational data of Ulaanbaatar for the year of 2015. Using the solar radiation estimated with the developed model and observational data of other air elements, the Typical Meteorological Year was developed for Ulaanbaatar which enables a process of building simulation. The main conclusions from this chapter are:

- The solar radiation on the horizontal surface was modeled as equation (2.6) for Ulaanbaatar using observational data obtained from the NCDC and IRIMHE. Errors caused by the solar model developed in this study are smaller than those of the Beijing model by 6.5%;
- Using the dry bulb temperature, dew point temperature, wind speed and global horizontal solar radiation the TMY weather data was developed for Ulaanbaatar from a 10-years data period of 2006-2015. The TMY consists of 8760 hourly data of main air elements. Further, the TMY is uploaded into the building energy simulation program for dynamic analyses.

In Chapter 3 the energy consumption and the indoor environment of apartments were made clear through surveying and measurement. Apartment buildings in

Ulaanbaatar with different types of structure are focused on and the indoor environment and the heat loss coefficient are clarified by questionnaire survey and measurement. The questionnaire survey was conducted for 374 apartments with different structure types: Type A (non-insulated precast ceramsite), Type B (non-insulated brick structures), Type C (insulated brick), Type D (insulated lightweight block) and Type E (insulated concrete), and 18 apartments were selected for measuring indoor environment elements such as air temperature, relative humidity and CO_2 concentration. The ventilation rate was calculated using CO_2 concentration data to estimate heat loss through ventilation. Finally, the heat loss coefficients of the apartment buildings with different structure types were compared with each other. The main findings from Chapter 3 are:

- The indoor air temperature of the apartment building is higher while relative humidity is lower than the Mongolian standard as well as ISO 7730 standard for most hours;
- Energy savings can be achieved by lowering the temperature in Hot - Dry and Hot zones to adequate level. In order to realize this, extension of radiators by the residents should be prohibited by rules;
- Average indoor CO_2 concentration is between 624 ppm and 1,835 ppm which is nearly within the Mongolian standard;
- The ventilation rate by the natural ventilation system is between 34 m^3/h - 105 m^3/h;
- The heat loss coefficient is between 0.74 W/m^2 K and 1.53 W/m^2 K for apartment buildings. Significant energy savings can be expected for Type A and B by thermal retrofitting;

The following conclusions can be drawn for the insulated Type D and Type E only:

- The average district heating consumption throughout the year is 56.8 GJ including hot water supply for insulated structures (Type D and Type E). Among this 44.1 GJ energy is used for space heating system and 12.7 GJ is used for hot water supply;
- The average electricity consumption throughout the year is 7.1 GJ per household. Electricity consumption does not differ significantly from month to month;
- The average unit energy consumption of the insulated buildings is 63.8 GJ.

In Chapter 4 the energy consumption and the indoor environment of the Gers were made clear through surveying and measurement. Fifty-nine households living in the Gers were surveyed and 10 of them were selected for measuring indoor air temperature, relative humidity, CO and CO_2 concentrations. The ventilation rate was estimated from the indoor CO_2 concentration and the heat loss coefficient of the measured Gers was estimated based on the coal consumed throughout the measurement period. The main findings from Chapter 4 are:

- The indoor environment of the Gers is not thermally comfortable compared with that of apartment buildings due to the large temperature change and low relative humidity throughout a day. The average of the maximum temperatures during daytime is 41.4 ^{0}C whereas the average of the minimum temperatures during nighttime is 8.0 ^{0}C;
- Indoor CO and CO_2 concentrations are within acceptable level;
- The ventilation rate during 4:00-6:00 is between 40 m^3/h and 118m^3/h which is equivalent to 1.8 h-1 and 4.6 h-1;
- The heat loss coefficient of the Gers is highest between 1.31 W/(m^2K) and 3.96 W/(m^2K) among surveyed dwelling types.

In Chapter 5 the potential of reducing energy consumption for existing non-insulated residential buildings in Ulaanbaatar by thermal retrofitting were clarified and suggestions for the thermal design of newly constructed buildings were made through computer simulations. In this chapter, the typical floor model of residential building was created, and dynamic simulations were carried out for each considered structure type with energy simulations to analyze the impact of the parameters such as orientation, insulation thickness, indoor temperature, window type and air change rate. The Typical Meteorological Year data for Ulaanbaatar, Mongolia which developed in Chapter 2 was uploaded into the simulation program TRNSYS18. The main findings of Chapter 5 are:

- The impacts of insulation thickness, air change rate and indoor air temperature are large and that of orientation and window type are small;
- The energy saving potential was clarified by comparing the heating load between the energy saving and the reference models. The potential of energy saving is 60% for Type A, 35% for Type D, 21% for Type E, respectively;

- An estimation equation was developed with which annual heating load of apartment buildings in Ulaanbaatar could be estimated with limited errors.

In Chapter 6 this study is summarized, and suggestions are given for energy conservation and improvement of the living environment.

6.2 Suggestions

After having conducted this study, the following suggestions are derived for policy makers, building designers, and heating and ventilation engineers and researchers:

- The hourly weather data for building simulations, Typical Meteorological Year should be developed for other locations in Mongolia following the method stated in Chapter 2 because the weather condition is different from location to location;
- The indoor air temperature should be monitored to avoid overheating which results in an increase of energy consumption for apartments. The following measures can be enforced: prohibiting extension of radiators by rules; replacing the one-pipe vertical hydronic heating system installed in non-insulated apartments with the two-pipe vertical system which enables independent monitoring for every apartment located as series vertically; installing thermostat valves on the heating devices that are adjusted automatically depending on the signals received from the room thermometers;
- The apartments with non-insulated structure should be thermally renovated urgently. Increasing the insulation thickness more than 30cm is not effective. The air change rate should be controlled at $0.5h^{-1}$.
- The Gers should be replaced with the insulated detached houses or apartments in the long run as part of the urban planning in Ulaanbaatar due to its high energy consumption, poor indoor air quality and pollution emitted from the coal-fired stoves. In the short run the Gers could exist for a certain period. Therefore, the Gers should be constructed on the insulated foundation and to reduce the ventilation rate by covering the lower part of the walls with the airtight materials;

- Orienting long side of the buildings into the south is more beneficial compared to other options. Further studies are necessary on solar control, heat transition among different apartments, the optimum design of windows, and so on;
- Payment of space heating should be based on the energy consumed instead of floor area. Further studies should be carried out on strategies of implementation.

PUBLICATIONS

Journal Articles:

[1] Bilguun Buyantogtokh, Qingyuan Zhang: Development of solar model and typical meteorological year for Ulaanbaatar, Mongolia, J.Environ.Eng., AIJ, Vol.82, No.736, pp561-568, 2017

[2] Bilguun Buyantogtokh, Qingyuan Zhang:. Investigation on indoor environments of residential buildings in Ulaanbaatar during winter, Studies on environments and energy consumption of dwellings in Mongolia, Part 1, J.Environ.Eng., AIJ, Vol 83, No. 747, pp.443-451, 2018

[3] Bilguun Buyantogtokh, Qingyuan Zhang: Investigation on indoor environments of the Gers in Ulaanbaatar during winter, Studies on environments and energy consumption of dwellings in Mongolia, Part 2, J.Environ.Eng., AIJ, Vol 84, No. 757, 2019

Pier Reviewed Article:

[1] Bilguun Buyantogtokh, Qingyuan Zhang: Heating load analyses of the residential buildings in Ulaanbaatar, Mongolia through computer simulations

Conference Proceedings:

[1] Bilguun Buyantogtokh, Qingyuan Zhang: Development of typical meteorological year for Ulaanbaatar, Mongolia, Annual meeting proceedings, AIJ, 2017

[2] Bilguun Buyantogtokh, Qingyuan Zhang: Investigation of the unit energy consumption for insulated residential buildings in Ulaanbaatar, Mongolia, Grand Renewable Energy 2018 Proceedings, 2018

[3] Bilguun Buyantogtokh, Qingyuan Zhang: A study on indoor thermal environment of the Gers in Mongolia during winter, Annual meeting proceedings, AIJ, 2018

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Appendix A

Qustionnaire on Energy Consumption of the Households

Personal information

Name

Address

Telephone

Q1. Please indicate your age from the following list

Card	Under 20	1
	20-29	2
	30-39	3
	40-49	4
	50-59	5
	60-64	6
	Above 65	7

Q2. Fill the gender of respondent

Card	Male	1
	Female	2

Q3. Please indicate your occupation

Card	Public officer	1
	Company employee	2
	Self employed	3
	Part time worker	4
	Housewife	5
	Student	6
	Unemployed/Retired	7

Q4. Please indicate the number of people living in your home. Please do not include those who have been away from home for more than 6 months for reasons such as work, study.

Card	1	1
	2	2
	3	3
	4	4
	5	5
	Above 6	6

Q5. Please indicate the members living in your home. These should be the same people you answered a moment ago as living in your home at least 5 days a week.

Card	Single	1
	Couple wtihout a child	2
	Household with a child	3
	Household with children	4
	Household with relatives	5

Q6. Please indicate the number of members in your household who have job.

Card	1	1
	2	2
	3	3
	4	4
	Above 5	5

Q7. Please indicate your monthly household income.

Card	Up to 210$	1
	211-420$	2
	421-840$	3
	Above 841$	4
	Would rather not answer/Do not know	6

Q8A Please indicate if you know total floor space of your home.

	m^2

Q8B. Please give approximate total floor space of your home. /If Q9A is not answered/

Card	Less than 50 m^2	1
	50 - 99 m^2	2
	100 - 149 m^2	3
	150 - 199 m^2	4
	200 m^2 or more	5
	Do not know	6

Q9. Please indicate the year in which your home was built.

Card	Before 1970	1
	1980	2
	1990	3
	2000-2004	4
	2005-2009	5
	2010 or after	6
	Do not know	7

Q10. Please indicate structure of the building

Card	Pre-cast 5 storeys	1
	Pre-cast 9 stpreys	2
	Pre-cast 12 storeys	3
	Old brick	4
	Insulated brick	5
	Insulated light weight block or insulated reinforced concrete	6

Q11. Please indicate whether the house you live in is owned or rent.

Card	Self owned	1
	Rent	2
	Other ( ):	3

Q12. Please indicate the number of rooms there are for each type.

		Yes		Quantity	
Card	Room with living and kitchen	1	⇒		rooms
	Kitchen	2	⇒		rooms
	Living	3	⇒		rooms

	Bedroom	4	⇒		rooms
	Bath	5	⇒		rooms
	Toilet	6	⇒		rooms
	Room with bath and toilet	7	⇒		rooms

Q13. Please answer about the amount of electricity use and its cost for last one year.

*If you have your electricity payment receipt, please look at that before answering;

* If you are unable to answer about your use for each month, please give the monthly average of your amount used or cost.

	Months	kWh	Cost in Riel
2016	Jan		
	Feb		
	Mar		
	Apr		
	May		
	Jun		
	Jul		
	Aug		
	Sept		
	Oct		
	Nov		
	Dec		
Monthly average			

Q14. Additional heating device /Answer Q15 if there is no any additonal heating device/.

* Fill out following if the household used an additonal heater in 2016;

* In case production date and capacity is unknown write down when the heater is purchased;

* Rather no answer or do not know "9999."

Type	Quantity	Produced year (Purchased year)							Capacity									How many hours used in a day, day/hour	Setting
		Before 1990	1991-1995	1996-2000	2001-2005	2006-2010	After 2011	Do not know	Less than	2.2-2.4 kW	2.5-2.7 kW	2.8-3.5 kW	3.6-3.9 kW	4.0-5.1 kW	Above 5.2 kW	Do not know		
Electric heater	1st unit	1	2	3	4	5	6	7										1 Strong 2 Medium 3 Weak
	2nd unit	1	2	3	4	5	6	7										1Strong 2 Medium 3 Weak

Q15. Please indicate months which you used a heater.

* in case of existing several heaters, consider the most frequent used one.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec

Q16. Please indictate hours of usage.

(Weekdays)

0 3 6 9 12 15 18 21 24 (h)

(Weekends)

0 3 6 9 12 15 18 21 24 (h)

Q18. Information about TV sets.

* Consider January to December 2016;

* In case the produced year is unknown write down the purchased year;

* Rather no answer or do not know “9999”.

Type	Whtether exist	Which unit	Screen size (inches)	Produced year (Purchased year)							Electricity consumpiton								How many hours in a day (h/day)	
				Before 1990	1991-1995	1996-2000	2001-2005	2006-2010	2011 after	Do not know	Less than	40-59 W	60-79 W	80-99 W	100-119 W	120-139 W	Above 140 W	Do not know	Weekdays -	Weekends-
Flat-screen (LCD, Plasma)	1 Yes	1st unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		
	2 No	2nd unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		
CRT (traditional type)	1 Yes	1st unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		
	2 No	2nd unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		

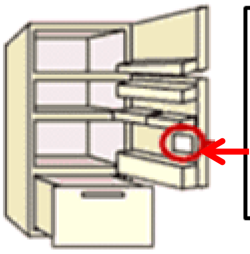
Q19. Information about a refrigerator.

* If you don’t know the cubic capacity, please check the cubic capacity in the illustration and fill it in;

* If the time of manufacture cannot be confirmed, fill in the time of purchase;

* For items that cannot be answered, please fill in “9999”.

Type	Whether exist	Which unit	Capacity (l)	Produced year (Purchased year)						
				Before 1990	1991-1995	1996-2000	2001-2005	2006-2010	After 2011	Do not know
Refrigerator 	1 Yes 2 No	1st unit		1	2	3	4	5	6	7
		2nd unit		1	2	3	4	5	6	7
Freezer 	1 Yes 2 No	1st unit		1	2	3	4	5	6	7



比較的新しい冷蔵庫の 場合

品名及び型番
〇〇ノンフロン冷凍冷蔵庫 XX-1234X (X)型
定格内容積 全定格内容積 210L
冷凍室 40L
冷蔵室 170L
消費電力量 50Hz 350kWh/年
60Hz 350kWh/年
外形寸法 幅 600mm
奥行 600mm
高さ 1,800mm

2012年製

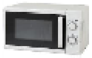
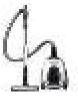
古い冷蔵庫の 場合

品名及び型番
〇〇電気冷蔵庫 XX-117X(X)型
有効内容積 全有効内容積 210L
冷凍室 40L
冷蔵室 170L
消費電力量 50Hz 52kWh/月
60Hz 52kWh/月
外形寸法 幅 600mm
奥行 600mm
高さ 1,800mm

1987年製

Q20. Information about other electronic appliances.

Type	Whether exist	Quantity	How many times in a week (times/week)	Type	Whether exist	Quantity	How many times in a week (times/week)
Washing machine 	1 Yes 2 No			Water kettle 	1 Yes 2 No		
Rice cooker 	1 Yes 2 No			Water kettle 	1 Yes 2 No		
Do you use the keep-warm function?	1 Yes 2 No			Do you use the keep-warm function?	1 Yes 2 No		

Kitchen exhaust 	1 Yes 2 Ugui			Microwave 	1 Yes 2 No		
PC 	1 Yes 2 No			Cooking stove 	1 Yes 2 No		
Gaming 	1 Yes 2 No			Water filter 	1 Yes 2 No		
DVD player 	1 Yes 2 No			Mobile charger 	1 Yes 2 No		
Iron 	1 Yes 2 No			Baking stove 	1 Yes 2 No		
Vacuum 	1 Yes 2 No			Hair dryer 	1 Yes 2 No		

Q21. Information about lighting.

* Desk lighting is not considered;

* When answering about the time used, please fill in the average time of use of each lighting device for each room.

Incandescent light bulb	Fluorescent	LED
		

If shape is not clarified check the color. (Incandescent: yellow, fluorescent: white, LED: very white).

Room	Type						Quantity			Average time of usage h/day		
	Incandescent		Fluorescent		LED		Incandescent	Fluorescent	LED	Incandescent	Fluorescent	LED
	Yes	No	Yes	No	Yes	No						
Room with a living and kitchen	1	2	1	2	1	2						
Kitchen	1	2	1	2	1	2						
living	1	2	1	2	1	2						
Bedrooms	1	2	1	2	1	2						
Bath	1	2	1	2	1	2						
Toilet	1	2	1	2	1	2						
Room with a bath and a toilet	1	2	1	2	1	2						

Q22. Information about hot water usage (Shower).

* Is shower is not used “0”;

* Please indicate by each member;

* do not know “9999”.

	Member									
	1st	2	3rd	4th	5th	6th	7th	8th	9th	
How many times do you have a shower? (day/week)										
How many minutes per time? (min/time)										

Q23. Information about hot water usage (Bathing).

* If no bathing “0”;

* Please indicate by each member;

* do not know “9999”.

	Member									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	

How many times do you have a bath? (day/week)										

Q24. Please indicate your level of satisfaction with the indoor temperature.

Card	Very satisfied	1
	Satisfied	2
	Do not know	3
	Unsatisfied	4

Q25A. What is your consideration for purchasing electronic devices. Choose from Q25A.

Q25B. What problem is facing when you consider energy savings for purchasing electronic devices.

	Q25A (Card)							Q25B (Card)			
	Price	Brand	Energy saving	Basic performance (Size, capacity.)	Value added functions (controllability, usability.)	Others ( )	Q25a is answered go to Q25B	Energy efficient products are costly	Do not know which one is energy-efficient	Others:	Not any problem
Refrigerator/Freezer	1	2	3	4	5	6	⇒	1	2	3	4
TV	1	2	3	4	5	6	⇒	1	2	3	4
Lighting	1	2	3	4	5	6	⇒	1	2	3	4
PC	1	2	3	4	5	6	⇒	1	2	3	4

Q26. Please select the answers that best describe your household's attitudes and actions regarding energy consumption. If you are unable to answer because you do not own the particular home electronic or for another reason, please answer "not applicable."

			Card		
			Yes	No	Not applicable
TV sets	(a)	Reduce the brightness of the television	1	2	3
	(b)	Switch off the power of the television when not using	1	2	3
Refrigerator	(c)	Do not leave the refrigerator door open	1	2	3
	(d)	Try not to put too many things in the refrigerator	1	2	3
Lighting	(e)	Try to turn lights off when leaving a location, even for a short time	1	2	3
Shower	(f)	Use a water saving shower head	1	2	3
	(g)	Shorten the time of using showers	1	2	3
	(h)	Try to take cold instead of hot showers	1	2	3
Electronic appliances	(i)	Reduce the number of times to run the washing machines	1	2	3
	(j)	Try not to use the keep-warm function of the electric rice cooker	1	2	3
	(k)	Turn off power of PC or switch to low-power mode when not in use	1	2	3
Cooking	(l)	Fill pots and kettles with the optimal amount of water when boiling	1	2	3

THANK YOU.

Appendix B

Qustionnaire on Energy Consumption of the Households (Ger)

Personal information

Name

Address

Telephone

Q1. Please indicate your age from the following list

Card	Under 20	1
	20-29	2
	30-39	3
	40-49	4
	50-59	5
	60-64	6
	Above 65	7

Q2. Fill the gender of respondent

Card	Male	1
	Female	2

Q3. Please indicate your occupation

Card	Public officer	1
	Company employee	2
	Self employed	3
	Part time worker	4
	Housewife	5
	Student	6
	Unemployed/Retired	7

Q4. Please indicate the number of people living in your home. Please do not include those who have been away from home for more than 6 months for reasons such as work, study.

Card	1	1
	2	2
	3	3
	4	4
	5	5
	Above 6	6

Q5. Please indicate the members living in your home. These should be the same people you answered a moment ago as living in your home at least 5 days a week.

Card	Single	1
	Couple wtihout a child	2
	Household with a child	3
	Household with children	4
	Household with relatives	5

Q6. Please indicate the number of members in your household who have job.

Card	1	1
	2	2
	3	3
	4	4
	Above 5	5

Q7. Please indicate your monthly household income.

Card	Up to 210$	1
	211-420$	2
	421-840$	3
	Above 841$	4
	Would rather not answer/Do not know	6

Q8 Existence of the family member during daytime of the weekdays

Card	Everyday	1
	3-4 days	2
	1-2 days	3

	No one	4

Q9. How many years do you live in this Ger?

Card	Less than 3 years	1
	3-5 year	2
	More than 5 years	3
	Do not know	4

Q10. Please indicate whether the Ger you live in is owned or rent.

Card	Self owned	1
	Rent	2
	Other ( ):	3

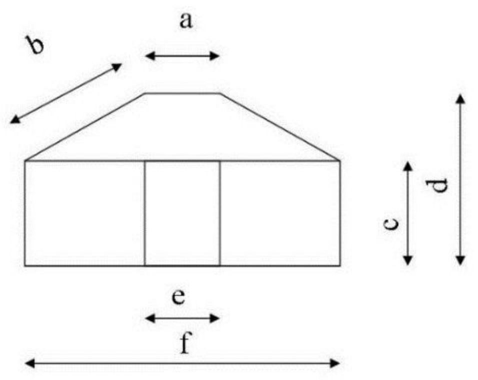
Q11. Please indicate the number of insulating felt layers.

Number of layer	1. 1	2. 2	3. More than 3

Q 12. Please write down the material type of the felt insulation.

	1st layer	2nd layer	3rd layer
Material type			

Q13. Dimensions of the Ger.

<table>
<tr><td rowspan="8">
</td><td>Number of wall sections</td><td colspan="2"></td></tr>
<tr><td>a</td><td colspan="2"></td></tr>
<tr><td>b</td><td colspan="2"></td></tr>
<tr><td>c</td><td colspan="2"></td></tr>
<tr><td>d</td><td colspan="2"></td></tr>
<tr><td>e</td><td colspan="2"></td></tr>
<tr><td>f</td><td colspan="2"></td></tr>
<tr><td>Existence of the wind break room</td><td>1. Yes</td><td>2.No</td></tr>
</table>

Q 14. Please indicate type of the stove.

1. Traditional	2. Turkish	3. Other ( )

Q 15. Please answer about the amount of electricity use and its cost for last one year.

* If you are unable to answer about your use for each month, please give the monthly average of your amount used or cost.

	Months	kWh	Cost in Riel
2016	Jan		
	Feb		
	Mar		
	Apr		
	May		
	Jun		
	Jul		
	Aug		
	Sept		
	Oct		
	Nov		
	Dec		
Monthly average			

Q16. Information about TV sets.

* Consider January to December 2016;

* In case the produced year is unknown write down the purchased year;

* Rather no answer or do not know "9999".

Type	Whtether exist	Which unit	Screen size	Produced year (Purchased year)	Electricity consumpiton	How many hours in a day

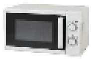
				Before 1990	1991-1995	1996-2000	2001-2005	2006-2010	2011 after	Do not know	Less than	40-59 W	60-79 W	80-99 W	100-119 W	120-139 W	Above 140 W	Do not know	Weekdays -	Weekends-
Flat-screen (LCD, Plasma)	1 Yes 2 No	1st unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		
		2nd unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		
CRT (traditional type)	1 Yes 2 No	1st unit		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8		
		2nd unit		1	8	3	4	5	6	7	1	2	3	4	5	6	7			

Q17. Information about a refrigerator.

* If you don't know the cubic capacity, please check the cubic capacity in the illustration and fill it in;
* If the time of manufacture cannot be confirmed, fill in the time of purchase;
* For items that cannot be answered, please fill in "9999".

Type	Whether exist	Which unit	Capacity (l)	Produced year (Purchased year)						
				Before 1990	1991-1995	1996-2000	2001-2005	2006-2010	After 2011	Do not know
Refrigerator 	1 Yes 2 No	1st unit		1	2	3	4	5	6	7
		2nd unit		1	2	3	4	5	6	7
Freezer 	1 Yes 2 No	1st unit		1	2	3	4	5	6	7

Q18. Information about other electronic appliances.

Type	Whether exist	Quantity	How many times in a week (times/week)	Type	Whether exist	Quantity	How many times in a week (times/week)
Washing machine 	1 Yes 2 No			Water kettle 	1 Yes 2 No		
Rice cooker 	1 Yes 2 No			Microwave 	1 Yes 2 No		
PC 	1 Yes 2 No			Iron 	1 Yes 2 No		
Gaming 	1 Yes 2 No			Vacuum 	1 Yes 2 No		
DVD player 	1 Yes 2 No			Mobile charger 	1 Yes 2 No		

Hair dryer 	1 Yes 2 No						

Q19. Information about lighting.

* Desk lighting is not considered;

* When answering about the time used, please fill in the average time of use of each lighting device for each room.

Incandescent light bulb	Fluorescent	LED
		

If shape is not clarified check the color. (Incandescent: yellow, fluorescent: white, LED: very white).

Part of the Ger	Type						Quantity			Average time of usage (h/day)		
	Incandescent		Fluorescent		LED		Incandescent	Fluorescent	LED	Incandescent	Fluorescent	LED
	Yes	No	Yes	No	Yes	No						
North center	1	2	1	2	1	2						
South center	1	2	1	2	1	2						
Wind break room	1	2	1	2	1	2						

Q20. Information about electric heater.

Type	Unit	Produced year (Purchased year)							Capacity								How many hours used in a day (day/hour)	Setting
		Before 1990	1991-1995	1996-2000	2001-2005	2006-2010	After 2011	Do not know	Less than 2.2kW	2.2-2.4 kW	2.5-2.7 kW	2.8-3.5 kW	3.6-3.9kW	4.0-5.1kW	Above 5.2 kW	Do not know		
Electric heater	1st unit	1	2	3	4	5	6	7										1 Strong 2 Medium 3 Weak
	2nd unit	1	2	3	4	5	6	7										2 Strong 2 Medium 4 Weak

Q21. Please indicate months which you used a heater.

* in case of existing several heaters, consider the most frequent used one.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec

Q22. Please indictate hours of usage

(Weekdays)

0 3 6 9 12 15 18 21 24 (h)

(Weekends)

0 3 6 9 12 15 18 21 24 (h)

Q23. Please indicate coal consumption.

Period	Unit	Quantity
For heating season		
Monthly		

Daily		
Per time		

Q24. How many times put the coal into the stove.

Q25. Please indicate wood consumption.

Period	Unit	Quantity
For heating season		
Monthly		
Daily		
Per time		

Q26. Please indicate cooking method and daily usage.

1. Stove	2. Electric stove	3. Electric pot	4. Others
…………times	……………times	……………times	……………times

Q27. Please indicate water consumption.

Per time	l	
How many days do you use	days	
How many liters per day	l/day	

Q28. Please indicate your level of satisfaction with the indoor temperature.

Card	Very satisfied	1
	Satisfied	2
	Do not know	3
	Unsatisfied	4

Q29. Please indicate symptom identified during coal firing if you have.

Card	Dizziness	1

	Throat pain	2
	Eye irritation	3
	Other ( )	4

Q30. Does anyone have following symptoms when the stove is fired?

	Type of symptoms	Yes	No	How many people
Card	Nose running	1	2	
	Coughing	1	2	
	Allergy	1	2	

THANK YOU.

Appendix C

Heading load model of the TRNSYS