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The relationship between indoor and outdoor temperature in two types of residence

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Abstract

Residential thermal conditions are important because people spend the majority of their time in the home environment. Indoor temperature and relative humidity (RH) were measured continuously over 1 year in 14 residences in Seoul, Korea. The relationship between residential indoor and outdoor conditions were determined by four meteorological parameters—temperature, apparent temperature (AT), RH, and absolute humidity (AH). Outdoor and indoor temperature, and AT and AH were closely correlated, but RH was not. While indoor temperatures, AT, and AH were significantly higher than the corresponding outdoor levels, indoor RH was significantly lower than outdoor RH. Regression models between indoor and outdoor temperature detected a heating threshold at 15.0°C for outdoor daily temperature, but not cooling point. Cooling point of hourly temperature was observed only in 2 PM at apartment with air conditioning. Indoor temperatures in apartments were lower in summer and higher in winter than those in detached houses. However, indoor RHs in apartments were lower than in detached houses.

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Keywords: Indoor temperature; Indoor relative humidity; Residential type; Air conditioning; heating point; coolingpoint;

1. Introduction

Outdoor thermal conditions are associated with various health effects [1], and studies on these health outcomes have used outdoor monitoring data as indicators of personal exposure. However, the indirect assessment approach

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may result in a misclassification of exposure due to individual differences in time-activity patterns and microenvironmental conditions [2]. Indoor thermal conditions are considered to be a critical component of personal exposure, as most people in industrialized countries stay in indoor environments for over 90% of the day [3]. The relationship between indoor and outdoor thermal conditions in residences can be critical when considering thermal conditions in epidemiological studies [4].

Residential thermal conditions affect the comfort of occupants and possibly their susceptibility to illness. Poor thermal conditions in residences are recognized as potential risks to health [5]. High relative humidity (RH) has been associated with respiratory and allergic disease [6], and low temperatures have been linked with an excess in winter deaths [7-8]. Improving the thermal condition of a cold house has clearly observable health benefits once dampness and mold are eliminated [9].

Maintaining the optimal thermal condition in residences is critical for comfort and health. Complaints about the indoor environment are often associated with temperature and humidity. Moreover, the residential environment can have a major role in providing shelter from extreme weather conditions. With potential changes in ambient temperature and humidity due to climate change, a better understanding of residential thermal conditions is necessary. Despite this fact, extensive monitoring of residential temperature and humidity has not been undertaken.

The purpose of this study was to investigate residential thermal conditions in two types of residence over a 1-year period in Seoul, Korea, where weather had distinctive seasonal variations. The relationship between residential indoor and outdoor conditions were determined by four meteorological parameters—temperature, apparent temperature (AT), RH, and absolute humidity (AH).

2. Methods

Year-long measurements were conducted in 14 residences from March 2010 to February 2011, in Seoul, Korea. Seven apartments and seven detached houses were selected to participate. A short questionnaire was used to collect information about the residential structure and the heating and cooling systems. The average number of family members was just under four per residence. All residences had an individual gas heating system, except for two apartments, which relied on a central heating system that served the entire building. Nine residences had air-conditioning (AC; five apartments and four detached houses). These residences had a single standing AC unit in the living room, except for two detached houses in which a standing AC unit was fitted in the living room and a window type AC unit was also fitted in the bedroom.

Temperature and RH measurements were made using a U10 Temperature and Relative Humidity Data Logger (Onset, Cape Cod, MA, USA). The data logger had a temperature accuracy of ±0.4°C from 0 to 40°C and a RH accuracy of ±3.5% from 25 to 85%. The data logger was set up to record temperature and RH every 30 min during the 12-month period. A data logger was placed in the living room of all 14 residences. In six residences (three apartments and three detached houses), an additional data logger was placed in a bedroom. Each sampling location was chosen to be representative in the room. The position selected was away from the immediate influence of the AC system, humidifier, gas stove, heater, doors, windows, and direct sunlight. One data logger placed in the living room of an apartment did not save the data due to an equipment malfunction.

The data loggers were set to provide hourly, daily, and monthly data. Temperature and RH in the living rooms were used for determining the indoor thermal conditions, except for the one apartment with missing data due to the equipment malfunction. AT and AH were calculated from the indoor temperature and RH. AT combines the mean temperature and dew-point temperature and was calculated according to the following equation [10] :

$$AT = -2.653 + (0.994 \times T) + (0.0153 \times T_d^2) \quad (1)$$

where T is the mean temperature and T_d is the dew-point temperature.

AH was calculated from the temperature and RH. The daily outdoor temperature, RH, and dew-point temperature were obtained from the Korea Meteorological Administration. Outdoor AT and AH were calculated in the same way as indoor AT and AH.

A Student's *t*-test was used to compare the monthly temperature, RH, AT, and AH of indoor and outdoor environments for each month. An association between the temperature and the RH, AT, and AH in the bedroom and living room was determined by a linear regression analysis. The Student's *t*-test was used to compare daily temperature, RH, AT, and AH by residence type for each month. Pearson correlation coefficients (*r*) between the indoor and outdoor daily average values were determined. Piecewise linear regression models were used to further investigate the relationship. To detect the threshold point where the values were significantly changed, the piecewise linear regression model was based on the significant zero crossing method (SiZer) [11].

All statistical analyses were performed using Predictive Analytics Software (PASW) Statistics (version 21.0; SPSS Inc., Chicago, IL, USA), and R version 3.0.2 (R Foundation for Statistical Computing, Vienna, Austria) was used for piecewise regression modeling and drawing scatterplots. SigmaPlot 10.0 (Systat Software Inc., San Jose, CA, USA) was used to draw graphs and plots.

3. Results

Indoor and outdoor temperature, AT, and AH displayed a seasonal pattern with highs during the summer months and lows during the winter months, as shown in Figure 1. The lowest and highest monthly average indoor temperatures were 21.3°C in January and 29.7°C in August, respectively, and the respective lowest and highest monthly outdoor temperatures were –7.2°C in January and 26.5°C in August. The lowest and highest monthly average indoor ATs were 19.7°C in January and 35.8°C in August, respectively, while the respective lowest and highest monthly outdoor ATs were –5.9°C in January and 31.1°C in August. Indoor temperatures and ATs were significantly higher than the corresponding outdoor levels in every month ($P < 0.0001$).

The lowest and highest outdoor AHs were 1.6 g/m^3 in January and 19.4 g/m^3 in August, respectively, and the respective lowest and highest monthly average indoor AHs were 5.9 g/m^3 in January and 20.3 g/m^3 in August. Indoor AHs were significantly higher than outdoor AHs in every month ($P < 0.0001$). Unlike temperature, AT, and AH, indoor RH was significantly lower than the corresponding outdoor level in every month except March ($P <$ 0.0001). The lowest and highest monthly average indoor RHs, across all homes, were 32% in January and 68% in August, respectively, while the respective lowest and highest outdoor RHs were 54% in January and 78% in August.

(a) Temperature **(b) Relative humidity**

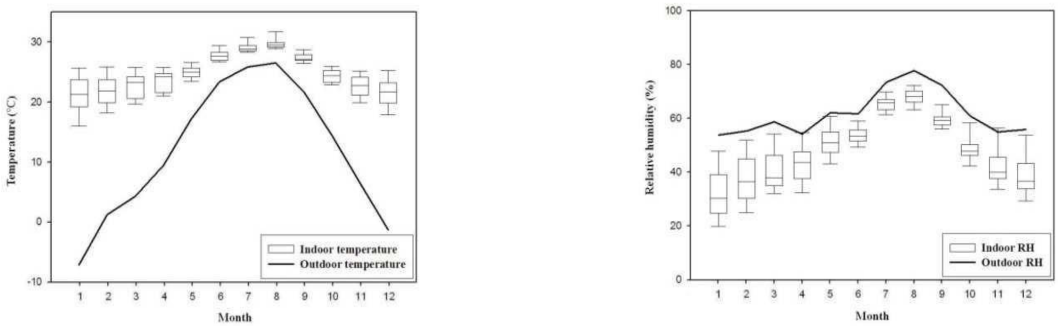
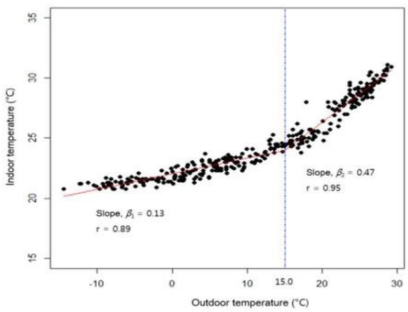


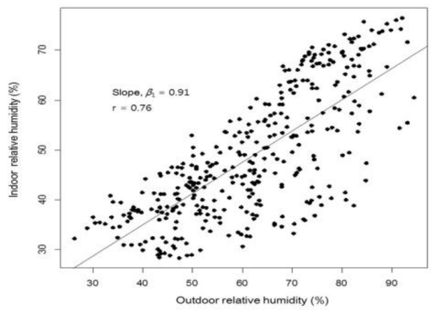
Fig. 1: Distribution of monthly averages of indoor and outdoor (a) temperature and (b) relative humidity (RH) in 14 residences.

The relationships between indoor and outdoor temperature, and AT, RH, and AH are shown in Figure 2. A piecewise linear regression model detected a threshold for outdoor daily temperature at 15.0°C and for outdoor daily AT at15.9°C. When the outdoor temperature was above the threshold of 15.0°C, a strong linear correlation was detected between the average indoor and outdoor temperature (r = 0.95, b = 0.47, standard error (b) = 0.12). When outdoor temperatures were below the threshold, the correlation was relatively weak (r = 0.89, b = 0.13, standard error (b) = 0.05). When the outdoor AT was above the threshold of 15.9°C, the linear correlation between the average indoor and outdoor AT displayed a strong correlation (r = 0.97, b = 0.66 standard error (b) = 0.15). When the outdoor AT was below the threshold, the correlation was relatively weak (r = 0.94, b = 0.28, standard error (b) = 0.07), and the linear correlation between indoor and outdoor RH was also relatively weak (r = 0.76, b = 0.91, standard error (b) = 0.42). A very strong linear correlation was noted between the indoor and outdoor AH (r = 0.99, b = 1.27, standard error (b) = 0.07)

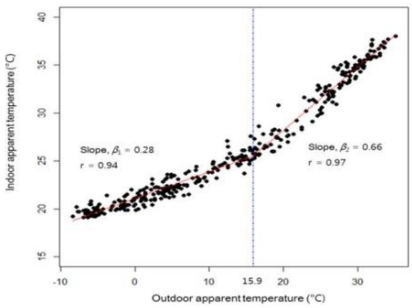
(a) Temperature



(c) Relative humidity



(b) Apparent temperature



(d) Absolute humidity

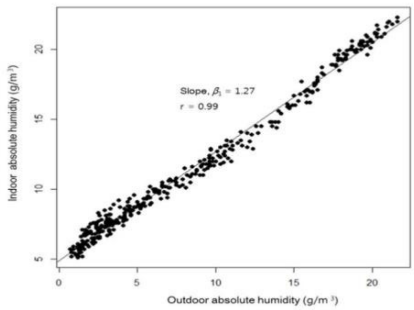
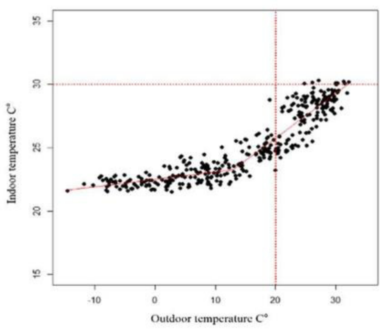
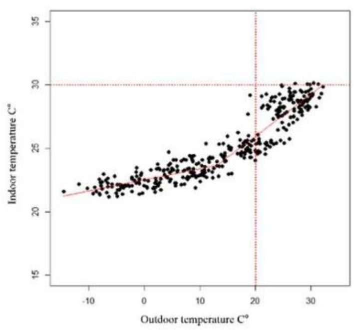


Fig. 2: Scatterplot and regression results for the indoor and outdoor relations for (a) temperature, (b) apparent temperature (AT), (c) relative humidity (RH), and (d) absolute humidity (AH) from March 2010 to February 2011. Piecewise linear regression was undertaken for temperature and apparent temperature, and linear regression was performed for relative humidity (RH) and absolute humidity (AH).

(a) Apartments with AC



(b) Detached houses with AC



(c) Detached houses without AC

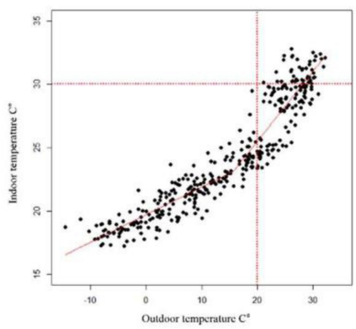


Fig 3: Temporal profiles of indoor and outdoor temperature in apartments and detached houses with AC or not during one year (11AM-12PM).

Although no cooling point was observed for daily temperature, hourly temperature at 12PM (11AM-12PM) showed presence of air conditioning operation in both types of residence with air conditioner. Residences without air conditioner did not show cooling point. Slope of regression between outdoor and indoor temperatures in the houses at 12 PM (11AM-12PM) was significantly lower than other hours, as shown in Fig 3. Since 11AM-12 PM was when outdoor temperature was increasing, cooling point for hourly temperature was observed at that time. Although no obvious cooling points was not observed at hours other than 11AM-12PM, it did not indicate that air conditioning was not used in other hours. Lack of cooling point in other hours might explain that Korean used air conditioning for rather shorter time.

4. Discussion

Seoul has four distinctive seasons with monthly outdoor temperatures ranging from –7.2 to 26.5°C. The summer monsoon season experiences heavy rainfall. Outdoor temperatures were similar to those of Zone 5 in the United States, as defined by the International Energy Conservation Code (IECC) [12], although they were slightly lower in the summer months. Monthly outdoor RH ranged from 53.8 to 77.7%, with the highest RH being observed in August. The outdoor RH levels were lower than the US Zone 5 levels.

Residential temperature, AT, and AH were significantly higher than outdoor levels, while indoor RH was lower than the outdoor level. The ranges of monthly average residential temperature and humidity were narrower than the corresponding outdoor values. The ranges of monthly average indoor temperature and AT were 8.4°C and 16.1°C, respectively, while the corresponding outdoor ranges were 33.7°C and 37.0°C. The range of monthly average indoor AH was 14.4g/m^3, while the corresponding outdoor range was 17.8 g/m^3. When indoor temperature and RH were measured for 1 year in a house in the United States, indoor temperature ranged from 21 to 27°C and RH ranged from 25 to 63% [13]. When apartments in Seoul were measured over short time-periods, temperatures in winter and summer were 23.9°C and 27.5°C, respectively, and RHs in winter and summer were 31.6% and 59.5%, respectively [14].

Indoor AH was strongly correlated with outdoor AH in Seoul, suggesting that outdoor AH can be a good indicator of personal exposure to AH. A similar correlation was observed in homes in eastern Massachusetts, USA [4]. Indoor temperature and AT were strongly correlated with outdoor levels only during warm outdoor conditions. Outdoor temperature and AT can be a good indicator of personal exposure in summer. Various heat-related risks were determined using outdoor temperature conditions [15]. However, the use of outdoor temperatures may cause a high degree of measurement error for personal exposure under cold conditions. Further studies are needed to determine an indicator for cold conditions. The correlation between indoor and outdoor RH was weak and outdoor RH was not a good indicator of indoor RH.

The relationship between indoor and outdoor temperature was described by two distinctive regression models. When the outdoor temperature was over 15°C, the relationship was linear and the indoor temperature was higher than the outdoor temperature. When the outdoor temperature was lower than 15°C, the indoor temperature was maintained between 20 and 25°C, which suggests that occupants may use their heating systems when the daily outdoor temperature is below 15°C. The heating point in this study was higher than the level observed in eastern Massachusetts [4]. In addition, the residential temperature in cold weather was slightly higher in Seoul than in Massachusetts. Energy consumption per capita in Seoul is increasing, and energy savings from heating may be needed.

This study has some limitations. . This small study only measured indoor thermal conditions in 14 houses that were selected according to the type of residence. The small number of houses might not be enough to represent each house type. However, this data could provide basic information of annual tendency in each house type. Previous measurements of thermal conditions have mainly focused on commercial buildings and measurements undertaken in residential buildings have been of a short duration. Behavioral information was not collected on a daily basis, and a simple data collection method may be beneficial for such long measurement periods. Understanding the thermal environment of residences in response to ambient temperature extremes, particularly during heat waves, is relevant to house design, energy management strategies, and public health programs.

5. Conclusion

The indoor temperature and humidity were measured over a period of approximately 1 year to determine indoor thermal conditions in two types of residence. The findings showed that outdoor temperature, apparent temperature, and absolute humidity could be good indicators of indoor conditions, but outdoor relative humidity was not useful for determining the indoor level. Indoor temperature and humidity differed between the types of residence. The indoor thermal conditions may be useful for understanding personal thermal exposure in the two types of residence studied here.

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