STOCHASTIC CHARACTERISTICS OF THERMAL LOAD IN A SINGLE DWELLING IN A RESIDENTIAL BUILDING BASED ON BUILDING ENERGY SIMULATION COUPLED WITH A SUB-MODEL FOR CONSIDERING VARIATION IN BEHAVIOR SCHEDULES OF RESIDENTS

Aya Hagishima[1], Jun Tanimoto[1], Naoki Ikegaya[1], and Seijiro Mitsuyasu[2]
[1]Kyushu University, Fukuoka, Japan
[2]Sasebo National College of Technology, Nagasaki, Japan

ABSTRACT

The stochastic characteristics of the heating/cooling load of a dwelling in a residential building were investigated using time-series data estimated by Total Utility Demand Prediction System TUD-PS which can predict utility demand such as air-conditioning loads considering the time-varying behavior schedule of residents. The simulation results for 16 cases of different conditions of family type and dwelling indicates the universality of the probability density functions of heating/cooling load.

INTRODUCTION

Accurate prediction of the air-conditioning load of buildings has been one of important issues in the research field of building physics for past decades.

In the early stage of the period, particular types of weather data, which is statistically aggregated from original time-series data with fluctuations of various time scales such as TAC (statistically disposed outdoor temperature for a design calculation proposed by the Technical Advisory Committee of ASHVE ,Takeda (1990)), have been developed to estimate the statistically representative thermal load for designing HVAC system under the limited computational resources. Some of them represent only diurnal variations of summer and winter for estimating maximum load of heating/cooling, subsequently, weather datasets represent an annual variation for a typical year, such as TMY (Hall et al 1978a, 1978b, Siurna et al 1984), have become popular for the calculation of unsteady building energy simulation.

In contrast, analytical approaches for estimating statistical characteristics of air-conditioning load by using stochastically modelled meteorological data have also presented. For example, Yoshida and Terai (1990/91) separated time series weather data into the deterministic components of annual and diurnal variations and stochastic components, and modelled them by using Fourier series and normal distribution, respectively as input data for building energy simulation, and presented theoretically that the thermal load derived from the weather data is normally-distributed. Hokoi et al (1990) presented an analytical method to derive probability distribution of building thermal load under the assumption that time-series variation of weather data can be modelled by normal distributions.

Moreover, recent years, both remarkable improvement of computer performance and increased availability of meteorological data have enabled to simulate time-series building thermal load as well as temperature of room air and building envelops for a long time period more than 10 years. It indicates that we can predict various statistics of building thermal load, which accurately reflects the stochastic characteristics of long term meteorological data. However, the stochastic effect on building thermal load caused by the probabilistic occupants' behavior has not been well considered in building energy simulation compared to that caused by the weather conditions except for limited work (e.g., Virote and Neves-Silva, 2012, de Meester et al 2013).

Meanwhile, the authors performed a field survey on the usage of air-conditioners in residence, and revealed that the stochastic features of on/off behavior of air-conditioners can be modelled by using state transition probability functions (Tanimoto et al. 2005). In addition, the authors have constructed a holistic numerical model to predict total utility demand including thermal requirement, various energies, domestic hot water, as well as city water of a residential house (Tanimoto et al 2008a). The system, which we call Total Utility Demand Prediction System (TUD-PS), is based on the methodology for generating actual occupants' behavior schedules with 15 minutes time-resolution and a dynamic heating/cooling load calculation. The latter part of the model is coupled with the previously mentioned probabilistic model for HVAC turning on/off events which reproduce probabilistic thermal requirement determined by occupants' on/off behaviour. TUD-PS has been validated by comparing field survey data (Tanimoto et al 2008b), furthermore a series of numerical experiment using TUD-PS has revealed that the stochastic behavior schedule of occupants strongly affects the estimation of maximum load of cooling/heating (Tanimoto and Hagishima 2010). Moreover, we modified TUD-PS for estimating utility demand of multi-dwelling sites (Tanimoto et al 2010).

Under these circumstances, the aim of this paper is to highlight the probabilistic nature of the heating/

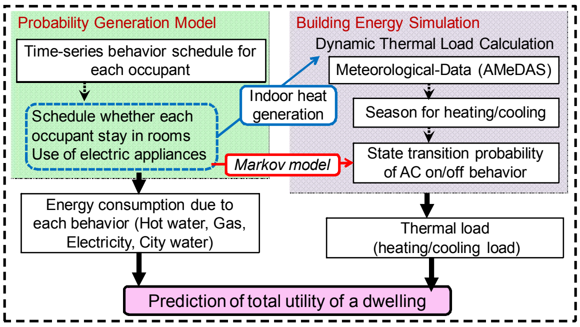

Figure 1 Schematic chart of TUD-PS

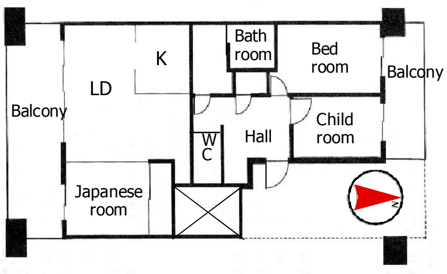

Figure 2 A house used for the simulation

Table 1 Standard condition for the simulation.

Room layout	A room for living room, dining, and kitchen (LDK) +3 rooms 80.4m^2 , LDK is south-facing.
Location of a house	Intermediate story
Insulation of envelops	Compliance with energy-saving standard of Japan (insulation thickness 50mm)

Table 2 Factors and levels for the simulation.

Location of a house	A; Intermediate story B; Top story
Insulation of envelops	A; Compliance with energy-saving standard of Japan (insulation thickness 50mm) B; non-insulation
Family configuration	A; A male worker + a full time housewife + a middle school child + a primary school child B; A male and a female 70years or more of age C; A male worker D; A male worker + a female worker

cooling load of a dwelling in a residential building by effectively utilizing the features of TUD-PS, namely, which can consider various stochastic effects of not only meteorological conditions but also occupants' behavior schedule as well as operation schedule of air-conditioners. A long-term building energy simulation using TUD-PS can be indeed positioned as a complete enumeration which reflects the diversity and interdiurnal variation of occupants' behavior. In this paper, we investigate several statistics and histograms of cooling/heating load of a dwelling in a residence building. In addition, the similarity of probability density functions of cooling/heating load under various conditions of housing and family type is discussed. Considering the fact that the efficiency of air-conditioners strongly depends on the amount of load, such analysis is effective for predicting the realistic annual thermal load as well as for designing various new high-efficient facilities for residence, such as fuel-cell cogeneration units.

MODEL DESCRIPTION

TUD-PS (Total Utility Demand Prediction System)

To accurately estimate heating/cooling demand in residential, TUD-PS considers probabilistic variations in occupant behavior, which consists of two key features as shown in figure 1. The first is an algorithm that generates every 15 min activities of occupants (Tanimoto and Hagishima 2005) derived from database of a field survey of Japanese occupant behavior (NHK Laboratory, 2000), which provides statistics of various occupant demographic under conditions of a day of the week. Therefore, generated behavior schedule can consider the difference due to occupant demographic, such as a primary school child, a fulltime housewife, a male or female worker, elderly adult, and so on, and it determines the time-series data of internal heat generated by various home electrical appliances and gas stoves, which are treated as source terms of unsteady energy conservation equations of room air and a building envelop in the so-called building energy simulation. The second key feature is a stochastic model of HVAC operation based on a Markov chain. In this model, we assume that the probability of on/off events of an air-conditioner during at least one occupant stay in a room can be defined by logistic distribution as a function of indoor globe temperature/ outdoor air temperature, which can reproduce likely behavior of occupants according to their thermal comfort condition. The event occurrence of on/off behavior of air-conditioners stochastically estimated for each time step is used to switch between 2 modes of the building energy simulation, namely calculations of heating/cooling load and room air.

Simulation settings

A typical residence house of a multifamily building shown in figure 2 and Table 1 is adopted for the simulation. The room layout of the house which consists of a room used for living room, dining and kitchen (hereafter LDK) and 3 rooms is standard one in Japan. We assume that LDK and 3 rooms equip air-conditioners and the preset temperatures for heating and cooling are 20 $^{\circ}$C and 26°C.

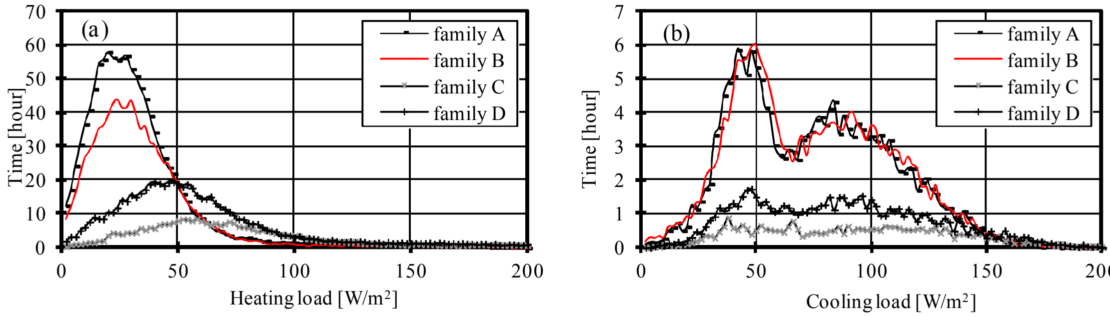

Figure 3 Histograms of (a) heating and (b) cooling load per year.

Table 3 Statistics of heating/cooling load.

	Family type	Average [W/m^2]	Median [W/m^2]	Standard deviation [W/m^2]	TAC2.5 [W/m^2]	Skewness	Kurtosis
Heating	A	31.7	26.9	24.0	101.8	2.40	11.97
	B	37.8	33.1	26.4	111.9	2.34	12.19
	C	81.9	67.5	55.5	238.3	1.50	5.24
	D	61.1	51.0	42.9	188.7	1.67	6.37
Cooling	A	73.6	71.8	33.0	140.9	0.41	2.39
	B	73.9	71.7	33.3	140.4	0.39	2.38
	C	91.5	91.0	42.0	173.1	0.29	2.23
	D	84.9	83.0	38.4	164.8	0.40	2.43

As boundary conditions, weather data observed by Automated Meteorological Data Acquisition System (AMeDAS) in Tokyo, Japan for 15 years from 1981 to 1995 are used. To evaluate the effect of family configuration on heating/cooling load, the simulation was done for 4 contrasting conditions of family configuration as shown in Table 2. In addition, we selected 2 factors, location of a house and the level of building insulation for the numerical experiment.

SIMULATION RESULT

Histograms of heating/cooling load

Figure 3 and Table 3 show histograms and statistics of heating/cooling load of LDK for different family configurations under standard conditions derived from the simulation for 15 years period.

The histogram of heating load shown in Figure 3 (a) indicates that the peak value of the family of four (family A) is the highest among 4 cases, and that of the senior couple (family B) is the second. The distributions of these two cases are biased toward low heating load. In contrast, the peaks of dink (double income couple with no kid, family C) and the single male household (family D) are relatively gentle and exhibit under larger heating load compared with the others. It is caused by the facts that the time period when someone stay in LDK tends to be long for families A and B compared to the others, thus, the frequency of large heating load events, most of which occur immediately after switching on due to heat storage effect, is low compared with dink or single household. We can find similar tendency from the data of skewness shown in Table 2. Videlicet, the larger skewness of families A and B implies that the frequency of extremely large heating load events is lower compared to families C and D.

Unlike in the case of heating load, the histograms for cooling show bimodal distributions. The peaks observed in the larger cooling load are mainly attributed to turning-on events happen when residents return to their sun-heated house. It is consistent with the fact that the peaks of higher cooling load for families A and B with relatively long period of stay in the house is small than the peaks of lower cooling load.

Such stochastic difference of heating/cooling load among family configurations is exactly what TUD-PS can reproduce.

Probability density functions of heating/cooling load

Figure 4 shows probability density functions (PDFs) of heating/cooling load normalized by the average for 4 types of family configuration under standard conditions. In addition, the PDFs for 16 cases with different conditions of family configurations, insulation and floor number are shown in figure 5.

We can find that the scattering of plots observed in figure 3 is greatly reduced in the data of figure4, and figure 5 still shows small scattering despite the various housing conditions. Such a tendency is more remarkable in the result of heating load, which might be caused by the fact that temperature difference between a preset value and outside air is large in

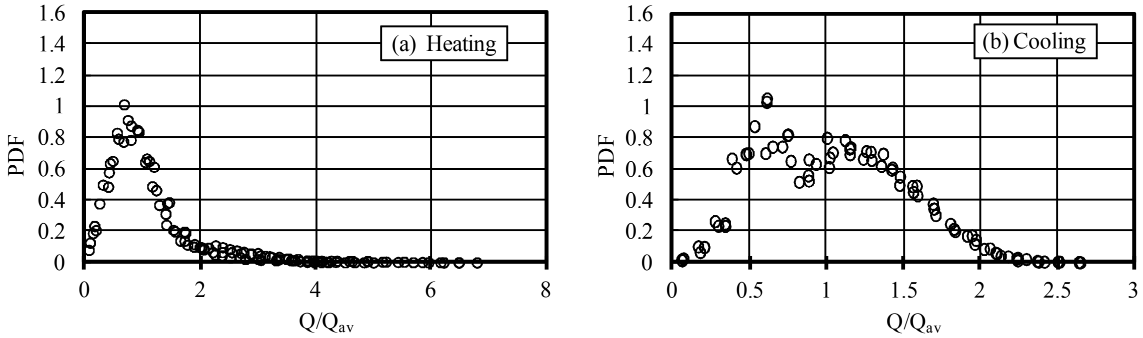

Figure 4 Probability Density Functions (PDF) of (a) heating and (b) cooling load for different family configurations (A, B, C and D) under standard conditions.

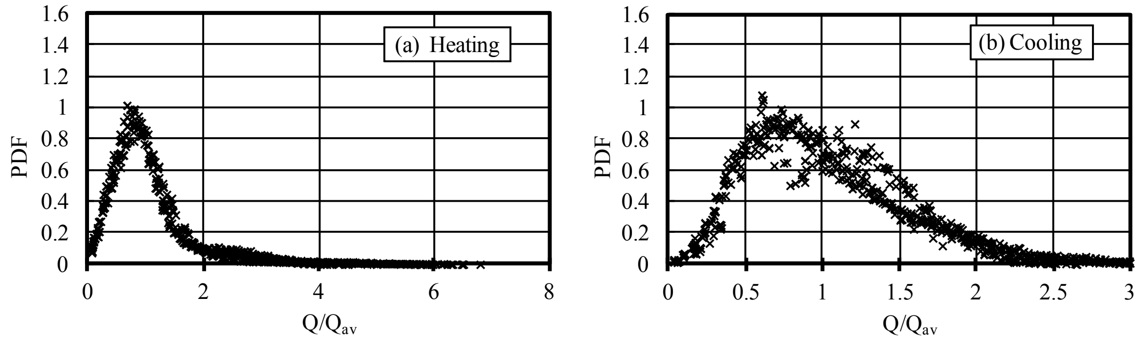

Figure 5 Probability Density Functions (PDF) of (a) heating and (b) cooling load for 16 cases with different conditions of family configurations (A, B, C and D), insulation (with/without) and floor number (intermediate story and top story).

winter, thus, heating system is more continuously operated compared with cooling system, resulting in the small effect of large-load-events happen immediately after switching on.

In general, the results can be interpreted that the PDF of heating load of a LDK space of a residence has universal nature regardless of family configuration, insulation condition, and the location of a house.

CONCLUSION

The stochastic characteristics of the heating/cooling load of a dwelling in a residential building were investigated using time-series data estimated by TUD-PS, which can predict air-conditioning load on the basis of the time-varying behavior schedule of residents. Histograms of heating/cooling load for 4 types of families show contrasting tendencies because of the different time schedule when residents stay in a house. However, the PDFs of heating/cooling load normalized by the average shows interestingly a similar tendency regardless of conditions of not only family types but also dwelling conditions.

ACKNOWLEDGEMENT

This research was financially supported by a Grant-in Aid for Scientific Research (No. 24560716) from the Ministry of Education, Science and Culture of Japan.

REFERENCES

Hall,I.J., Prairie,R.R., Anderson,H.E., Boes,E.C. 1978a Generation of a typical meteorological year. Proc. of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, pp.669-671, Denver, Colorado.

Hall,I.J., Prairie,R.R., Anderson,H.E., Boes,E.C. 1978b Generation of a typical meteorological year for 26 SOLMET stations. Sandia Laboratories Report SAND 78-1601, Albuquerque, New Mexico.

Hokoi,S., Niwa,K., Matsumoto,M. 1990 An Analysis of Stochastic Properties of the Cooling Load in an Intermittently Air-conditioning Building: Analysis of Discrete-Time Systems, ASHRAE Transactions Vol.95 Part 2, 3322.

de Meester,T., Marique A-F., Herde, A.D., Reiter,S. 2013 Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe, Energy and Buildings, Vol.57, pp.313-323.

NHK Broadcast & Cultural Laboratory, 2000 National survey on living time schedule

Siurna,D.L., D'Andrea,L.J., Hollands,K.G.T. 1984 A Canadian representative meteorological year for solar system simulation. Proc. 10th Annual National Meeting of Solar Energy Society of Canada, pp. 85- 88, Calgary, Alberta.

Takeda, H. 1990 Tokyo weather data for air-conditioning: outdoor design conditions for heating and cooling loads by the TAC Method. Energy and Buildings Vol.15, pp.263–9.

Tanimoto,J., Hagishima,A. 2005 State transition probability for the Markov Model dealing with on/off cooling schedule in dwellings, Energy and Buildings Vol.37, pp.181-187.

Tanimoto,J., Hagishima,A. Sagara, H., 2008a A methodology for peak energy requirement considering actual variation of occupants' behavior schedules, Building and Environment Vol.43, pp.610-619.

Tanimoto,J., Hagishima,A. Sagara, H., 2008b Validation of probabilistic methodology for generating actual inhabitants' behavior schedules for accurate prediction of maximum energy requirements, Energy and Buildings Vol.40, pp.316-322.

Tanimoto,J., Hagishima,A. 2010 Total utility demand prediction system for dwellings based on stochastic processes of actual inhabitants, Journal of Building Performance Simulation, Vol.3(2) pp. 155-167.

Tanimoto,J., Hagishima,A., Iwai,T., Ikegaya,N. 2010 Total utility demand prediction for multi-dwelling sites by a bottom-up approach considering variations of inhabitants' behaviour schedules, Journal of Building Performance Simulation Vol.6(1) pp.53-64.

Virote,J., Neves-Silva,R. 2012 Stochastic models for building energy prediction based on occupant behavior assessment, Energy and Buildings Vol.53, pp.183-193.

Yoshida,H., Terai,T. 1990/91 An ARMA type weather model for air-conditioning, heating and cooling load calculation, Energy and Buildings Vol.15-16, pp.625-634