Experimental lifestyle simulation for validating energy-saving techniques

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ABSTRACT

The evaluation of the effectiveness of cogenerations in energy saving is dependent on the profile of electricity demand and heat demand as many experts know. Those demands depend on the use and the energy efficiency of appliances, on the envelope performance reflecting upon the heating/cooling loads, on the climatic conditions such as outdoor temperature and city water temperature, etc. The cogeneration system is not the only one energy-saving technological element, whose effectiveness depends on those conditions. Although such dependency makes the evaluation of the effectiveness in energy saving more difficult, there is a necessity for developing a method, by which the effectiveness of various kinds of technological elements can be estimated very clearly. As methods for that purpose, 1) field survey under real occupancy, 2) experiment in research houses, 3) computer simulation and 4) laboratory experiment, have been used in researches. These methods have merits and demerits. To overcome demerits of these methods, especially to produce easily understandable information in terms of assumptions for the evaluation, this research project is focused on the mechanically simulated occupancy implemented in research houses. The simulated occupancy has ever been applied sometimes in the experiment, but overall simulation of occupants' behavior and operation of almost all kinds of equipment is applied in this research project.

This paper introduces the background of the research project and the framework of the experimental method, and describes an example of the experimental result and the theoretical framework on how to utilize the experimental results for developing regulations and design methods.

1. INTRODUCTION

The engineering for the energy saving in buildings has been relied on by the society to offer convenient tools, which can be adopted as a part of regulations and design methods. The expectation for such contribution is becoming stronger and stronger, because more radical regulations and policies for the global warming issue are being applied to the buildings in some countries and areas. The micro cogeneration is one of the promising energy-saving technological elements, and the fuel cell technology is a key toward so called hydrogen society in the future, which is less dependent on fossil fuels. However, in order to proceed in that direction, it seems that more honest and steady approach is needed so that the actual energy performance of buildings and the effectiveness of each energy-saving technological element can be evaluated more accurately. The building as a system is much more complicated than other industrial products, such as the automobile, in that the way of usage is much more varied and the performance is heavily dependent on various conditions.

2. METHODOLOGY

2.1 Theoretical framework

The structure of energy consumption in residential buildings has been studied mainly by 1) field survey, 2) experiment in research houses, 3) computer simulation and 4) laboratory experiment. In order to compensate for disadvantages of these major methodologies, this research is intended to fully develop and apply the simulated occupancy, which is for reproducing realistic occupants' behavior in relation to energy consumption and indoor environment, to the experiment in research houses (Fisk & Morrison, 1979). The concept of the design of the experiment is as follows.

1) By utilizing plural dwelling units in the same site, the energy consumption and indoor environment of target dwelling unit(s) shall be compared with a reference dwelling unit during the experiment. In the experiment, prospective technological elements, which are expected to be effective on energy saving, are installed usually in the target unit(s), while a set of standard specifications is applied to the reference unit. The ratio of the energy consumption of the target dwelling unit to that of the reference dwelling unit is defined as the energy consumption ratio, which is used in the design method.
2) However, it is not indispensable to utilize the plural dwelling units at the same time, and it is still possible to use only one unit, which is changed its specifications or occupants' behavioral conditions in turn, and the results are to be adjusted according to outdoor climatic conditions, so that data for different conditions can be compared.
3) The groups of factors, which are focused upon and tested in this series of experiments, are (a) building equipment including co-generation systems, (b) building envelope and (c) human behavior (lifestyle). Each group contains various items, as shown in Table 1.

3. Experimental method

3.1 Experimental house

Four dwelling units situated in the corners of a three storied research apartment house constructed by reinforced concrete are used so far (Figure 1). The floor area of each unit is 73 m^2, and other specifications are summarized in Table 2. The building faces due south, and its has no windows on the gable walls facing due east and west to keep the conditions of units on the east and west side similar to each other.

3.2 Family type and their use of time and occupancy

It is known that energy use by a family is dependent on the number of the family member, its life stage, income, etc. However, quantitative understanding of how multiple aspects of the family lifestyle determine the energy use is not complete at all. This experimental method is to be applied to simulate variety of family types and lifestyle of occupants, so that the effect of such human behavior on the energy use can be clarified.

In this paper, an example for a four-member family as a representative case is introduced. The representative number of family member is determined according to the existing demographic data, and is assumed to be four. The ages of householder, housewife and children are determined by the statistics as the most average combination, as shown in Table 3. The use of time and occupancy for week days and holidays are determined by referring to the result of surveys carried out by a major Japanese broadcasting company. For the holidays, two different schedules are determined both for "going out" and "staying at home". The heat and moisture emission from the occupants are simulated with originally designed instruments, of which total heat emission is set at 125W including latent heat of 38W (60g/h) in winter/medium seasons or 44W (70g/h) in summer (Architectural Institute of Japan, 1988). Heat and moisture dissipation to indoor space by cooking with a range hood in operation is estimated to be 74g/day and 377kJ/day as a total for breakfast, lunch and dinner, according to the original experiment with subjects. The dissipation by cooking is simulated with an instrument, which is situated in the living/dining room (LD) and emits at 140W and 100g/h.

3.3 Use of space heating and cooling equipment

It is still not easy to predict the actual energy consumption of heating and cooling equipment, which is used in buildings. Although there are standards to evaluate energy efficiency of such equipment, their rating conditions do not necessarily reflect the actual conditions, which are usually too complicated to be reproduced in the laboratory tests of products. For example, the COP of room air-conditioners is commonly tested under operation at the rating output and at 7 degree Celsius outdoor condition for heating. Therefore, the accurate prediction of electricity consumption is not possible only with heat load and the usual COP, so far (Miura et al. 2008, Habara et al., 2008). For hot water radiant heating systems, the efficiency of its boiler is commonly tested until now also at a rating condition, while the boiler can change its output and be in intermittent operation, which can influence heavily upon its energy efficiency.

For the above reasons, the actual use of the heating and cooling equipment shall be simulated, so that its actual energy efficiency as well as performance to create comfortable thermal environment can be evaluated. It means that the logic, according to which the occupants operate the heating and cooling equipment, is programmed and controlled.

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3.4 Use of building equipment and other appliances

The uses of other electric appliances such as local exhaust ventilator, light, TV, refrigerator, warm toilet bench, laundry machine, PC, hair dryer, TV-game, etc., which are selected according to the existing surveys on the spread of consumer electronics, are reproduced with real appliances or electric resistances of the equivalent electricity consumption. To check the equivalence of illuminance in both dwelling units, the measurement was done and the result

Table 1: Factors and methods, which seem to be influential on the energy performance of the house and its indoor environment, and are dealt with in the research project

	Group name	Factors to be observed and validated
Building equipment and electric appliances	Heating & cooling	- Actual COP of room air conditioners - System efficiency of hot water heating systems such as floor heating - Appropriateness of capacity selection - IAQ and humidity when using open burning type appliances
	Domestic hot water	Effectiveness of the following methods on energy-saving - micro cogenerations (to be tested also of its utilization for space heating) - latent heat recovery boilers and heat pump water heaters - Systems with solar heat collectors - Insulated piping systems and bathtubs
	Ventilation	- Energy saving by energy efficient fans including DC motor fans - Energy saving by heat recovery ventilators - Change of ventilation rate and electricity use with dust accumulation - Moisture controllability of whole house and local exhaust ventilation
	Lighting	- Influence of efficient lamps and lighting design methods on energy and lighting environment
	Electric appliances	- Energy-saving electric appliances - Influence of newly introduced electric appliances on total energy use, etc.
Building envelope	Insulation	- Influence on indoor thermal environment quality expressed as distribution inside heated/cooled space, temperature when or where un-heated/un-cooled - Influence on condensation
	Solar shading	- Effectiveness on cooling energy reduction
	Natural ventilation	- Effectiveness on cooling energy reduction
	Day lighting	- Energy saving and improvement of visual environment
Life style	Operation of heating & cooling equipment	- Influence of condition for switching on and off equipment, settings, area and duration, on energy use and indoor thermal environment
	Operation of openings	- Influence of condition for window opening on energy use and indoor environment
	Quantity and temperature of hot water	- Influence of hot water use, quantity and time on energy use
	Lighting quality and quantity	- Influence of illuminance requirement
	Family structure and Use of time	- Influence of family number, daily activities, appliance usage and time of staying at home
	Variety of lifestyle needs	- Influence of hobbies, work at home with necessary appliances

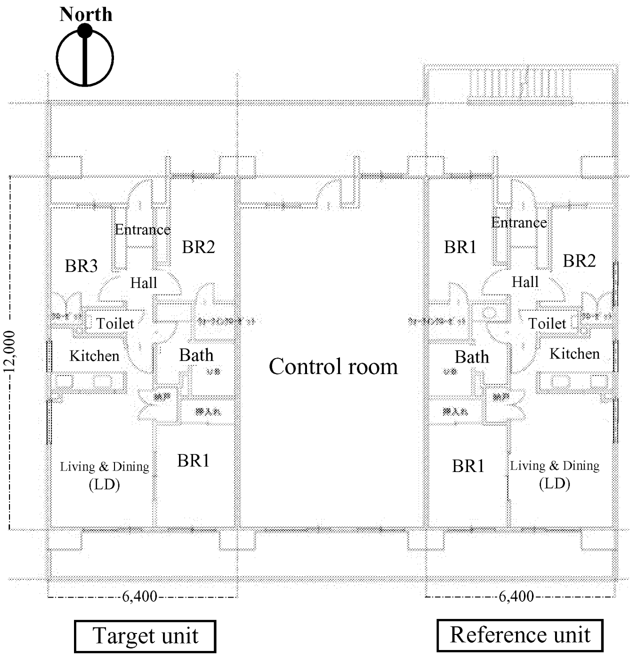

Figure-1 Plan of the three storied research apartment house (third floor)

is shown with electric power consumption in Table 4. In both units, whole house continuous ventilation is installed with an identical balanced ventilation system with heat recovery, of which electric power and ventilation rate are shown in Table 5. The intermittent local exhaust ventilations are installed at the kitchen, bath and toilet, but fans, which were assumed to be more efficient judging from the power consumption at the rating condition, are used for the kitchen and toilet only of the target dwelling unit. Figure 2 shows electricity consumption for appliances except for heating/air-conditioning and lighting, and that for lighting on week days in winter.

Both conditions have base electricity consumption during midnight, which is one fourth or one fifth of 1kW, the capacity of the most common micro cogeneration units in Japan. If one wishes to use those units for longer time during the day, they should have an ability to adjust power output to partial load, or should be applied selectively to building use conditions of higher base electricity consumption, which is inevitable for any reasons, such as due to inevitable usage of special electric appliances (workstation at SOHO, second refrigerator, wine cooler, etc.).

3.5 Hot water usage

Table 2: Specifications of the research apartment house

Site	City of Tsukuba, Ibaraki prefecture, Japan. $DD_{18\text{-}18}$ is in the range 1500-2500 (Region IV)
Floor area	Total 72.8 m^2 (LD+K:24.8 m^2, BR1:11.9 m^2, BR2: 12.6 m^2, BR3: 9.0 m^2, Hall: 6.5 m^2, Bath: 6.7 m^2, Toilet: 1.3 m^2, Balcony: 10.9 m^2 (area by center line of wall)
Height	Story height: 2,900 mm, Ceiling height: 2,500 mm
Structure	Thickness: slab 250 mm, separation or gable wall 225 mm, south or north facing 180 mm
Insulation, etc.	Roof and Floor (Ground floor only): polystyrene foam 70 mm (R=2.5 m^2K/W) and 30 mm (R=0.9 m^2K/W), respectively. Wall (Unit 301): polyurethane foam (water) 65mm (R=2.0 m^2K/W), Wall (other units): polyurethane foam (CFC gas) 35 mm (R=1.3 m^2K/W) Windows: double glazed and normal aluminum sash Partition walls inside each unit: carefully sealed to avoid unidentified airflow among rooms.

Table 3: Fundamental assumption for family member

Family with four members (2 adults and 2 children): Householder (male 46 years old, businessman), Spouse (female 44 years old, housewife), First child (female, 16 years old, high school student), Second child (male, 14 years old, junior high school student)

In the evaluation of energy performance of buildings, energy for domestic hot water has a large influence not only on the evaluation of cogeneration, but also on that of conventional equipment. In this research, referring to existing results of field surveys on hot water usage in residential buildings, the quantity and the time of the hot water usage in 42 degree Celsius hot water equivalence has been assumed as shown in Table 6.

3.6 Control and measurement

Real electric appliances and lighting fittings, electric resistances simulating some electric appliances, instruments simulating heat/moisture dissipation by occupants/cooking and space heating/air-conditioning equipment are automatically switched on and off according to the schedule. Discharge of hot water through faucets for kitchen, shower, etc. and for bathtub, which is automatically pumped out later, is controlled with electromagnetic valves.

A water tank is installed inside the refrigerator and the water is exchanged by a pump periodically to simulate the change of the food to be cooled. The windows and curtains are also opened and closed by motors automatically controlled. As for the measurement, outdoor and indoor environmental factors, flow rate and the temperature of city water and hot water, electricity, gas and oil consumption are measured and recorded. The electric consumption is measured for each appliance. The heating and air-conditioning equipments, lighting fittings, window and curtain can be controlled by referring to the environmental factor(s) such as room temperature, outdoor wind, illuminance, etc.

Table 4: Measured illuminance in rooms of the target dwelling unit (A) and the reference dwelling unit (B)

	Electric Power (W)		Room Mean (Lx)		Room Max. (Lx)		Room Min. (Lx)	
Unit→	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
LD	79.1	84.1	175	176	308	311	55	56
BR1	79.1	84.1	265	291	358	390	194	215
BR2	79.1	84.1	301	284	452	435	188	94
BR3	79.1	84.1	196	149	270	215	126	61
Hall	36.9	172.8	39	37	43	44	30	29
Ent.			36	44	41	50	30	37

Note: the measurement of the illuminance was done at the lattice points of the 0.5 m grid on the table level in each room.

Table 5: Ventilation rate (L/s) and electric power consumption (W) of mechanical ventilation

Function or room	Mode	Target dwelling unit		Reference dwelling unit	
		Flow rate (L/s)	Power (W)	Flow rate (L/s)	Power (W)
Whole house	High	30.3	70.8	28.6	73.2
Range hood	High	107.8	58.8	100.6	66.6
Toilet	-	13.9	8.4	8.3	14.0
Bath	High	39.4	26.8	29.2	30.6

Table 6: Total daily hot water usage for different uses in 4-member family (Mae et al., 2008)

L/day (42°C)	kitchen	bathtub	shower	wash up	total
Week days (large)	120	150	140	60	470
Week days (small)	100	150	80	50	380
Weekend, stay at home (large)	200	150	200	100	650
Weekend, stay at home (small)	160	150	140	100	550
Weekend, outgo (large)	10	150	200	20	380
Weekend, outgo (small)	10	0	200	30	240

4. EXAMPLES OF THE RESULTS

Each minimum round of the experiment is six days long, and contains six different hot water usages shown in Table 6. For each of the combinations of specifications for the target dwelling unit, at least one round in each season

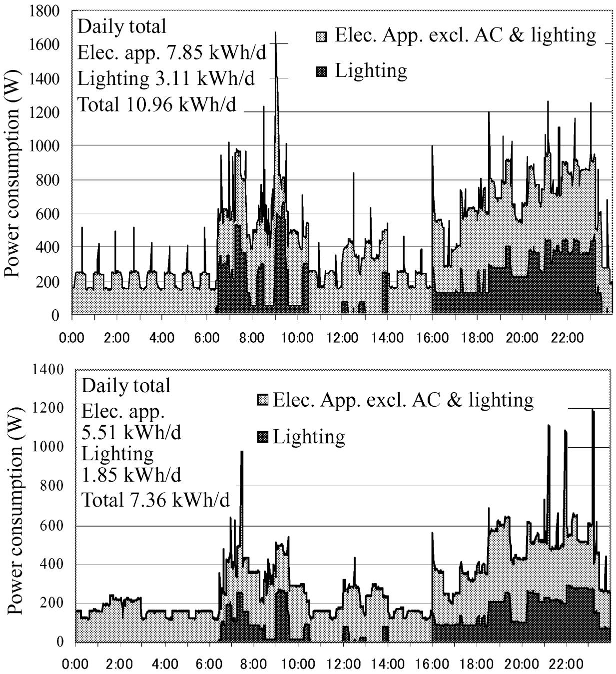

Figure 2 Electricity consumption for "electric appliances excluding heating/air-conditioning and lighting" and for "lighting" on week days in winter (top: reference dwelling unit, bottom: target dwelling unit, which is planned to be more energy efficient.)

is necessary to estimate the annual energy consumption. It is still better to do the experiment for more than a single round for each season, in order to obtain data for a wide range of outdoor conditions. In order to estimate the annual energy consumption, the experimental result (especially energy consumption) for each appliance is analyzed of its dependency on the climatic conditions, such as daily mean outdoor temperature and city water temperature so on. If a control logic of any appliance can learn the energy consumption pattern of the family in preceding days as the case of a Japanese fuel cell system or CO_2 heat pump systems, longer experiment (20 days for the fuel cell system and 30 days for the CO_2 heat pump systems) is necessary as described in the reference (Miura et al., 2008), which also contains the result on the effectiveness of the fuel cell system on energy saving. Figure-4 shows an example of the comparison between predicted annual energy consumptions for five different combinations of specifications for equipment. It can be said that the electricity consumption can be reduced from 49.2 GJ to 33.0 GJ, by choosing efficient electric appliances and lighting fittings. As for the

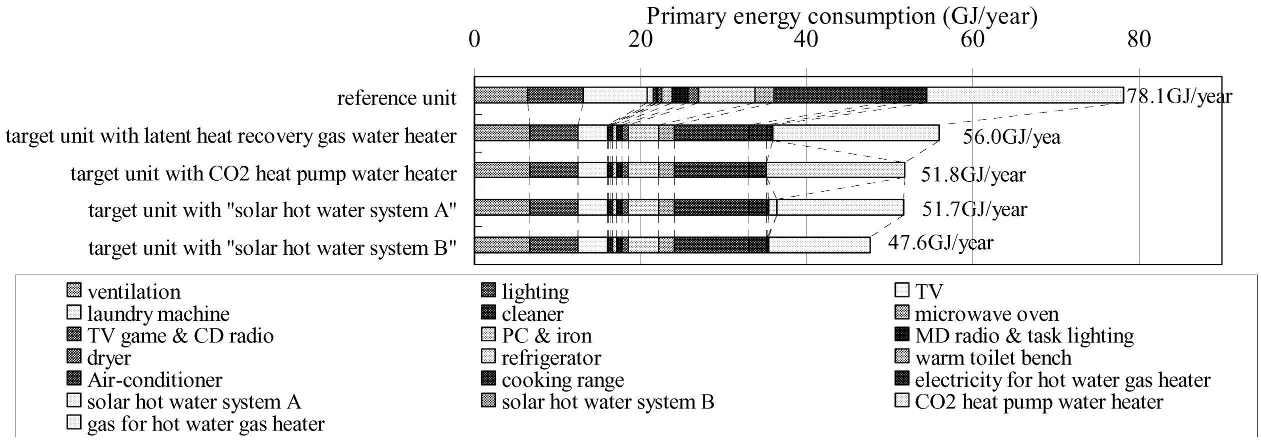

Figure 3: Prediction of annual energy consumption (conversion coefficient: 9.83MJ/kWh$_e$) for the reference dwelling unit equipped with a standard hot water gas heater and that for the target dwelling unit equipped with four different hot water systems (latent heat recovery gas water heater, CO_2 heat pump water heater, solar hot water systems A [with forced antifreeze circulation between vacuum solar collector and independent tank] and B [vacuum solar collector unified with tank in which water is circulated by convection]) and more energy efficient electric appliances

heating and cooling energy, by improving the COP of the room air-conditioners roughly from 3 to 6, the energy consumption decreases from 13.1 GJ to 8.9 GJ. Among electric appliances, the energy consumption of the refrigerator and the TV were influential in these experiments, and as shown in Figure-4 the careful selections of those appliances reduced the energy consumption from 14.5 GJ to 7.2 GJ. The largest saving was obtained by the change of the domestic hot water system from the most common gas instant hot water heater (26.8 GJ) to the solar hot water system B combined with a gas instant latent heat recovery hot water heater (12.5 GJ). In the most energy efficient case, the estimated annual energy consumption is 47.6 GJ, which is about 60% of the reference case.

5. CONCLUSIONS

The expectation by the society for convenient and accurate tools to evaluate the building energy performance is becoming stronger and stronger. In order to answer the expectation, it seems that more honest and steady approach is needed so that the actual energy performance of the building and each energy-saving technological element can be evaluated more accurately. In this paper, as one of the solutions to realize the more accurate evaluation, the experimental evaluation with simulated occupancy is proposed with the utilization of the results for developing regulations and design methods.

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