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DEVELOPMENT OF RESIDENTIAL ENERGY END-USE SIMULATION MODEL AT CITY SCALE

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ABSTRACT

This paper describes a simulation model for predicting end-use energy in residential sectors of a city or region. In this model, the annual energy consumption of a dwelling is simulated from the occupants' schedule of living activities, weather data and energy efficiencies of appliances and dwellings. By summing up the simulation results for various household categories, total energy consumption for the residential sector in a region can be estimated.

In this paper, the energy consumption for Osaka City is simulated by this model. The result is compared with statistical data. The effects of energy efficiency standards and urban heat island phenomena are also examined.

INTRODUCTION

Energy consumption in Japanese residential sector is increasing continuously along with the change of life-style, increase of home electric appliances, tendency to increase the number of families with small members, enlargement of dwellings, improvement in indoor thermal environment and so on. To accomplish national energy and carbon dioxide reduction targets, various kinds of measures, such as improvement in thermal insulation of dwellings, improvement in energy efficiency of home electric appliances, introduction of renewable energy system and introduction of residential combined heat and power generation system have been proposed. However, city-scale effects of these measures are not clear since energy consumption of each household differs considerably depending on household type, dwelling type and other factors. Therefore, simulated effects of these energy saving measures for a 'standard type of household' is not applicable. This is especially true with intermittent air-conditioning which is common in Japan, as the different schedules in living activities of occupants affect the amount of energy consumption greatly.

In addition, since an increase in the number of elderly people and changes in the composition of household type are expected in the near future, a consideration for the composition of households is essential to simulating city-scale energy consumption in the future residential sector. Energy efficiency of the stock of dwellings and appliances is also important to estimate precisely present and future energy consumption.

Jones et. al. (2001) estimated city-scale energy use considering the difference of house characteristics, but energy consumption by each appliances are not calculated. Michalik et. al. (1997) developed structure model of energy demand in the residential sector of a region by summing up each appliances operation schedule. However, this method does not include heat load calculation.

In this paper, we developed a model which simulates city-level energy consumption in the residential sector considering the composition of household type and dwelling type. By applying this model for Osaka City (Population: 2,600 thousand, 1,058 thousand households), the present amount of energy consumption in the residential sector is estimated and compared with statistics. In this calculation, all of the households in Osaka City are classified by household type and dwelling type. After that, hourly energy consumption is simulated for each household category. This simulation model consists of appliances' operation schedule model, hot water supply model, heat load calculation model and heating/cooling equipment performance model. By adding the scenario of how the dwelling and appliance stock will be changed and how the population and the composition of household will be changed, the model is able to quantify the impact of each scenario on total energy consumption in Osaka City's residential sector.

This paper evaluates the impact of new energy efficiency standard for thermal insulation of dwelling and room air conditioner on total energy consumption in Osaka City. The influence of urban heat island phenomena is also evaluated.

SIMULATION METHOD

Simulation Procedures

Figure 1 shows the flowchart for the simulation. In this simulation, energy use of dwellings is calculated iteratively for 23 household types and 20 dwelling

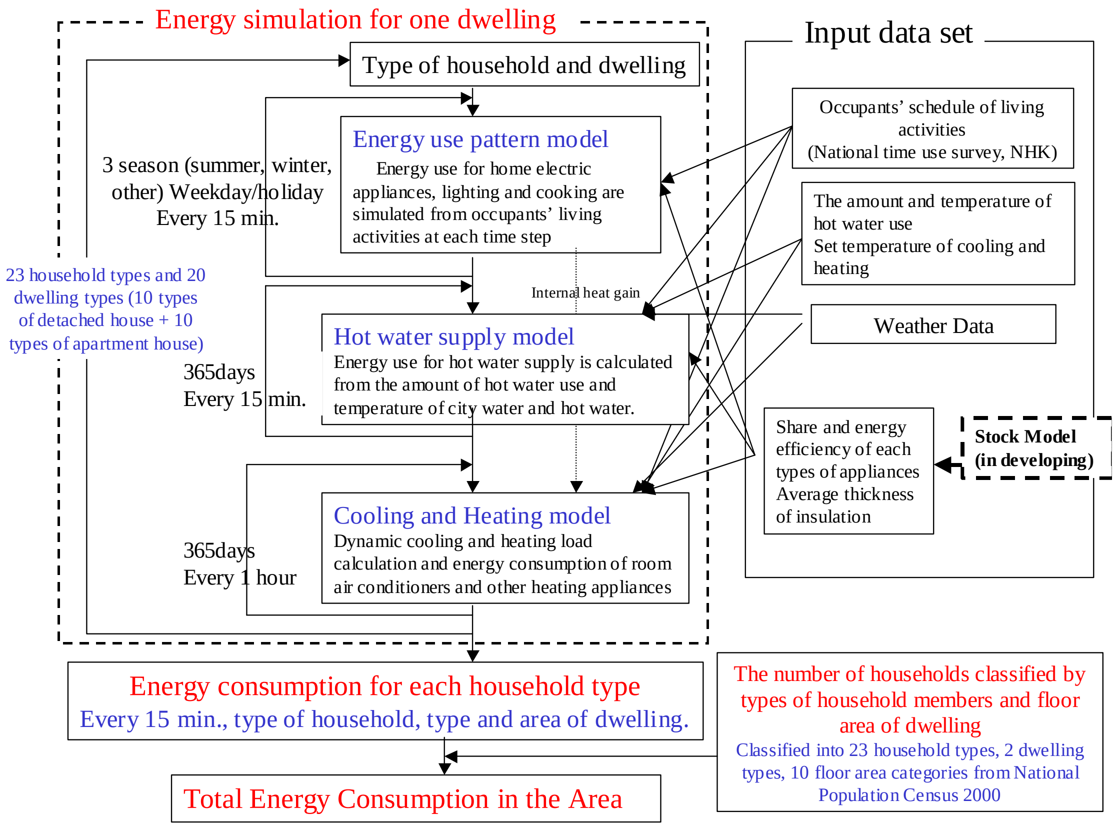

Figure 1. Flowchart of the simulation.

types (10 types for detached house and 10 types for apartment house). Then annual energy consumption for every one hour for 460 types of dwellings is calculated. Occupants schedule of living activities, amount and temperature of hot water supply, set temperature of cooling and heating, weather data, appliances' energy performance properties and dwellings' thermal properties are provided as input data for this simulation.

By multiplying simulated energy consumption and the number of households for each category and then summing them up, total energy consumption for the residential sector in object region (Osaka City) is estimated.

The authors are developing the 'stock model', which estimates average value or distribution of appliance's energy efficiency and dwelling's thermal properties in the object region.

Schedule of Living Activities

To determine the occupants' schedule of living activities, the result of national time use survey by Broadcasting Culture Research Institute, NHK (Japan Broadcasting Corporation) is applied.

This data describes the probability distribution of each living activity, such as sleep, meal, work etc. at 15 minutes time steps on weekdays, Saturday and Sunday for each family member's category. The family member's category is classified by gender, age and occupation. The authors summed up these data into 'gender', 'age groups' and 'employed or not' as shown in table 1.

Linking Between Living Activities and Energy Use

SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan)(2000) developed the simulation software 'SCHEDULE' which generate the schedule of heating and cooling, lighting and other energy use in dwellings by the NHK national time use survey. By referring to this model, each living activity is linked with heating and cooling, lighting, hot water use and other energy use. The room where these energy uses occur is also identified by the links between each family member and room provided as input data. Home electric appliances are classified into two categories: One is the appliance where its operation is linked with the occupant's living activities. The other is the appliance whose operation is not linked with living activities such as a fax, a telephone, a refrigerator and a shower toilet. Table 2 shows the power consumption and standby power of home electric appliances used in this simulation.

Table 1 Household types and number of households in Osaka City.

Number of household members	Family type of household	Activities of husband and wife	Category	Detached house	Apartment house
1	male		1a	26,166	188,118
	female		1b	19,774	142,160
	Aged male		1c	7,221	12,578
	Aged female		1d	31,400	27,292
2	couple	A	2a	21,239	49,088
		B	2b	19,291	44,584
		C		3,045	7,037
		D		3,369	7,787
	Aged couple		2c	37,600	23,358
	Mother and child	C	2d	12,571	19,868
		D	2e	8,822	13,943
	Aged mother and child			3,606	5,699
3	Couple and child	A	3a	25,676	33,615
		B	3b	29,818	39,038
		C		1,892	2,477
		D		2,784	3,645
	Aged couple and child			3,180	4,163
	Mother and children	C	3c	6,156	9,729
		D	3d	4,320	6,827
	Aged mother and children			1,766	2,791
4	Couple and children	A	4a	23,478	30,737
		B	4b	27,266	35,696
		C		1,730	2,265
		D		2,546	3,333
	Aged couple and children			2,907	3,806
	Couple, child and Parent	A	4a	5,332	1,450
		B	4b	6,192	1,683
		C		393	107
		D		578	157
5	Couple and children	A	5a	6,287	8,231
		B	5b	7,301	9,559
		C		463	607
		D		682	893
	Aged couple and children			779	1,019
	Couple, children and Parent	A	5a	3,998	1,087
		B	5b	4,644	1,262
		C		295	80
		D		434	118
6	Couple and children	A	6a	846	1,108
		B	6b	983	1,286
		C		62	82
		D		92	120
	Aged couple and children			105	137
	Couple, children and parents	A	6c	1,415	140
		B	6d	1,643	163
		C		104	10
		D		153	15
	Couple, children and parent	A	6c	1,431	389
		B	6d	1,662	452
		C		105	29
		D		155	42
7~	Couple, children and parents	A	7a	1,654	164
		B	7b	1,920	190
		C		122	12
		D		179	18

* Activities of husband and wife
A: Both husband and wife employed.
B: Husband employed, wife not employed.
C: Husband not employed, wife employed.
D: Neither husband nor wife employed.

Approximate dissemination ratios of home electric appliances are also considered in this model. Table 3 shows the dissemination ratio and the average number per household of home electric appliances used in this study. It is assumed that TV sets are installed in the living room and all of the bedrooms in order to set the average number per household to 2.0. However, for the other appliances that average number per household are larger than 1.0, the value is approximated to 1.0.

Energy consumption of refrigerators is modeled as a

Table 2 Power consumption and standby power of home electric appliances used in this simulation [W]

	Appliance	Room	Power Consumption ON	Power Consumption Stand-by
a.	Rice cooker	Kitchen	225	31
b.	Microwave	Kitchen	200	-
c.	Thermos	Kitchen	-	66
d.	Fan	Kitchen	20	-
e.	Washing machine	Bathroom	126	-
f.	Tumble dryer	Bathroom	1300	-
g.	Hair dryer	Bathroom	450	-
h.	Desk lamp	Bedroom	30	-
i.	Vacuum	Living room	200	-
j.	Iron	Living room	500	-
k.	Television	Living &bedroom	120	2
l.	VCR	Living &bedroom	20	11
m.	Radio	Living &bedroom	100	14
n.	PC	Bedroom	300	1.5
o.	Stereo	Bedroom	100	14
p.	Kotatsu *(foot warmer)*	Living room	500	-
q.	Electric carpet	Living room	580	-
r.	Fax	Living room	-	20
s.	Telephone	Living room	-	5
t.	Refrigerator	Kitchen	-	60*
u.	Shower toilet	Toilet	-	35

*: Modeled as a function of outdoor air temperature.

Table 3 Dissemination ratios of home electric appliances

Appliance	Dissemination ratio [%]	Average number per household
Rice cooker	81.2	0.882
Microwave	96.4	1.011
Washing machine	99.4	1.066
Tumble dryer	28.1	0.287
Vacuum	97.5	1.489
Television	99.5	2.273
Radio	48.8	0.571
Stereo	78.9	1.420
PC	38.1	0.481
Kotatsu *(foot warmer)*	84.8	1.171
Electric carpet	73.3	1.102
Fax	39.2	0.399
VCR	81.0	1.271
Telephone	92.6	2.485
Refrigerator	99.2	1.231
Shower toilet	43.2	0.494

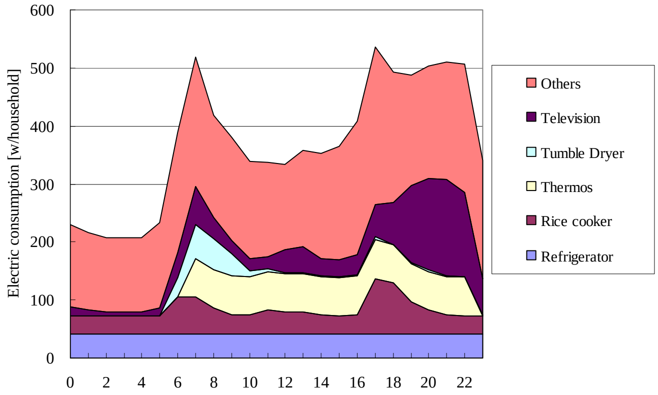

Figure 2. Hourly electricity consumption of appliances (a couple and two children, weekday)

function of outdoor air temperature.

Figure 2 shows the simulated hourly electricity consumption of appliances in the family of a couple and two children on weekday.

Hot Water Supply

Heat load for hot water supply is calculated from the amount of hot water at each time step, hot water temperature and city water temperature. City water temperature is calculated from outdoor air temperature as follows (Nabeshima, 1998).

$$T_W = 1.28 + 0.19T_{a1} + 0.72T_{a2} \quad (1)$$

T_W : City water temperature [°C]

T_{a1} : Daily average outdoor air temperature on the same day [°C]

T_{a2} :Average outdoor air temperature for past seven days[°C].

Energy consumption for hot water supply is calculated from dissemination ratio of gas boiler (96.8%) and electric water heater (3.2%) and their assumed efficiencies (Gas boiler : 0.90, Electric water heater : 0.75). Figure 3 shows the simulated hourly energy consumption for hot water supply in the family of a couple and two children on weekday in winter.

Heat Load Calculation and HVAC Energy Use

After classifying all dwellings in Osaka City into 20 categories by dwelling type and floor area and setting representative floor plan of each category, heating and cooling loads of these dwellings are simulated. Table 4 shows the categories and ratio of dwellings belonging to each category for detached houses and apartment houses in Osaka City.

The algorithm of the simulation is based on HASP/ACLD Program and the response-factor method is used to calculate heat conduction. Ventilation among rooms is not considered in this simulation. The degree of thermal insulation is set as the estimated average thickness of thermal insulation materials in 1997 (Jukankyo Research Institute, 1999) for detached house and apartment house respectively.

For heating and cooling by room air conditioner (RAC), its COP is modeled as the function of outdoor air temperature. This function is derived

Table 4 Dwellings floor area groups and ratio in Osaka City.

Scale	Detached house	Apartment house
~19m^2		16.76%
20~29m^2	17.81%	16.43%
30~39m^2		14.20%
40~49m^2	11.88%	12.63%
50~59m^2	10.05%	13.69%
60~69m^2	11.45%	13.96%
70~79m^2	6.90%	7.15%
80~89m^2	6.58%	3.76%
90~99m^2	8.08%	
100~119m^2	8.37%	0.68%
120~149m^2	8.36%	0.74%
150m^2~	10.53%	

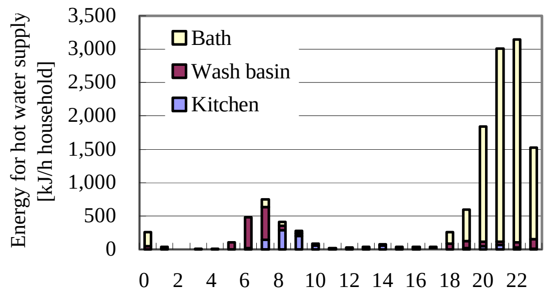

Figure 3. Hourly energy consumption for hot water supply (a couple and two children, weekday in winter)

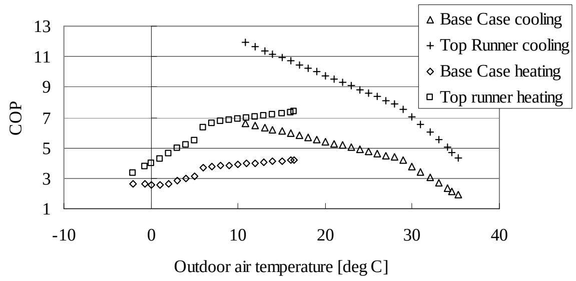

Figure 4 Relationships between air temperature and COP of room air conditioner.

from the measured electricity input and heat output for five conditions defined by The Japan Refrigeration and Air-Conditioning Industry Association (1999). COP at standard condition is set to the average value of present stock of RAC estimated by Jukankyo Research Institute (1999). Figure 4 shows the relationships between outdoor air temperature and COP. The amount of energy used for heating by appliances other than RAC such as gas/oil heater is estimated by setting the share and efficiencies of these appliances.

Classification of all Families in Osaka City

Using the result of National Population Census 2000(Statistics Bureau and Statistics Center 2000), all households in Osaka City (Total : 1,128 thousand households) are classified into 55 household types, 2 dwelling types (detached house or apartment house) and 10 dwelling floor area groups. Table 1 also shows the household types and number of households in Osaka City.

Annual energy consumption simulations are calculated for all 460 categories of household for every 15 minutes (appliances and hot water supply) or for every 1 hour (cooling and heating). These results are multiplied by household numbers of each category and aggregated into the annual energy consumption for Osaka City's residential sector.

SIMULATION RESULTS

Simulation Results of each Household Category

Figure 5 shows the annual electricity consumption by home electric appliances for various household types and floor area groups in detached houses. In the household types which have a large number of household members, energy consumption increases with floor area since the number of some appliances increases with number of rooms.

Figure 6 shows the simulation result for annual electricity consumption for lighting. Electricity consumption for lighting depends strongly on floor area.

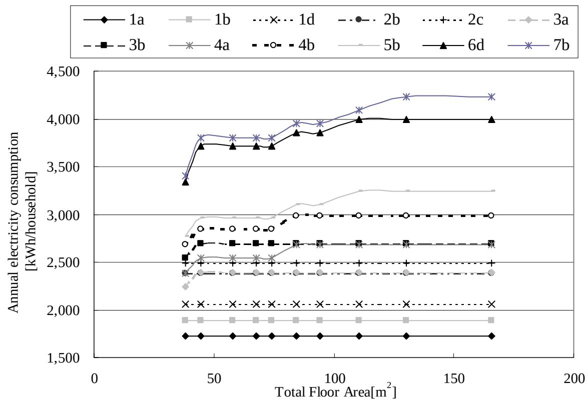

Figure 5 Electricity for appliances [detached house] (symbols in the legend are correspond to Table 1)

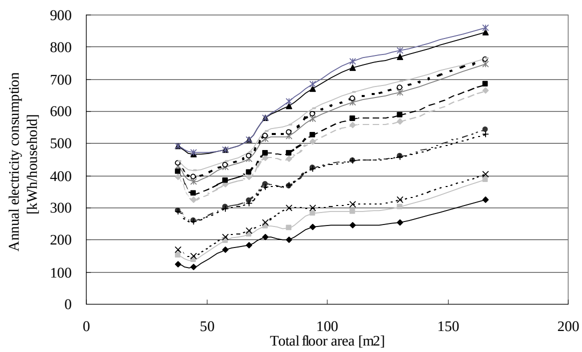

Figure 6 Electricity for lighting [detached house]

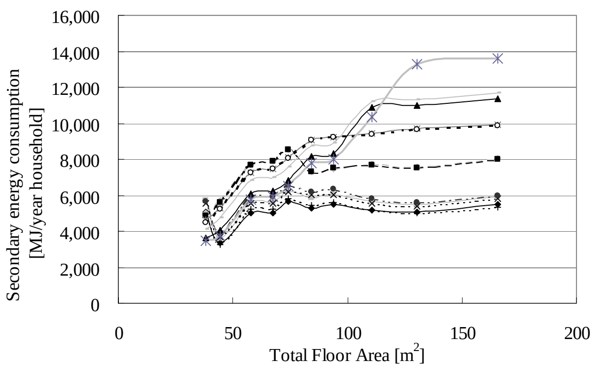

Figure 7 Electricity for heating [detached house]

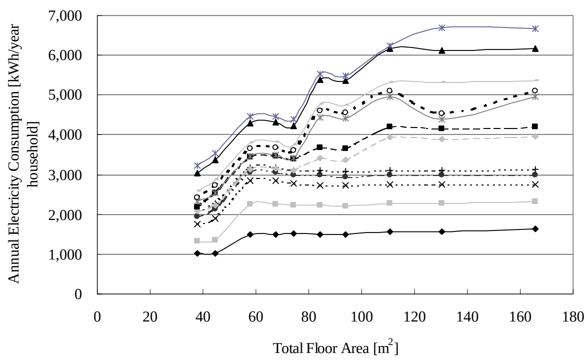

Figure 8 Electricity for cooling [detached house]

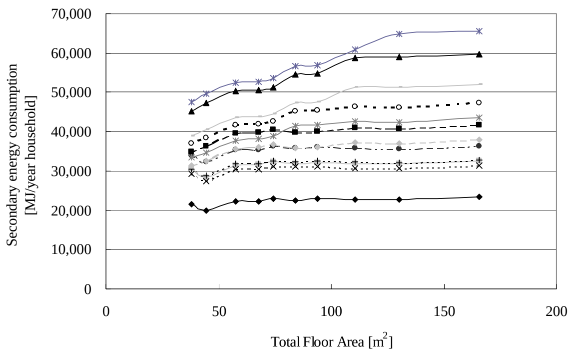

Figure 9 Total energy consumption [detached house] (Symbols are same as figure 5)

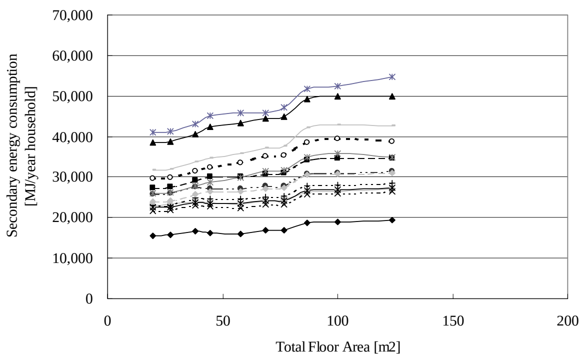

Figure 10 Total energy consumption [apartment house] (Symbols are same as figure 5)

Figure 7 and 8 shows annual energy consumption for heating and cooling respectively. Energy consumption for heating and cooling also depends on floor area. However, in the case of the households with a small number of members, energy consumption for heating and cooling no longer increases with floor area for large floor areas since the number of rooms heated or cooled does not increase.

Figure 9 and 10 shows the simulation result of total annual energy consumption per household in detached house and apartment house respectively. In the same category, energy consumption in apartment house is smaller than detached house.

Total Energy Consumption of Residential Sector in Osaka City

Total energy consumption of residential sector in Osaka City that is calculated from the simulation results is shown in figure 11. The statistic value in the FY 1999 and the estimated values derived by multiplying total number of households in Osaka City with unit energy consumption per household estimated from field survey (Jukankyo Research Institute, 1999) are also shown in figure 11.

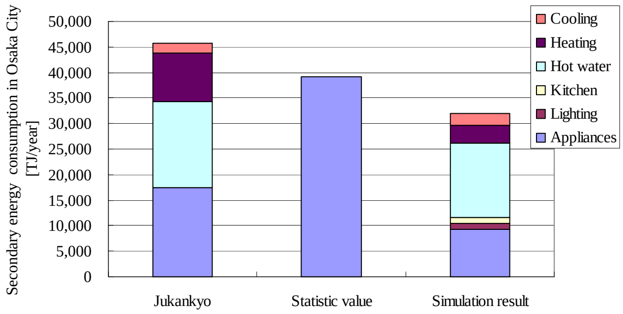

Figure 11 Comparison among simulation result, statistic value and estimation from field survey

Total energy consumption calculated from the simulation result is 32,018TJ/year, and it is smaller than the statistic value by 18%. In addition to the errors in the set values, the reason for the difference is that the simulation consider only the reasonable energy use and does not consider the unreasonable one e.g. leaving lighting, air-conditioning and appliances switched-on while unoccupied.

On the other hand, the values estimated from the unit energy consumption are larger than the statistic value. This is because that the 'unit energy consumption per household' method tends to overestimate when one-person and two-people households occupy a large portion since the field survey usually investigates just households with more than three members.

In the comparison between the simulation result and estimation from the unit energy consumption from the viewpoint of the composition of use, it is clear that appliances and heating energy use of the simulation result is smaller and cooling energy consumption is larger.

Evaluation of Energy Saving Standard for Thermal Insulation and Room Air Conditioner

To examine the effectiveness of thermal insulation standards for residential building, energy consumption under three conditions; no insulation, 1992 standard ("New Energy Conservation Standard") and 1999 standard ("Next Generation

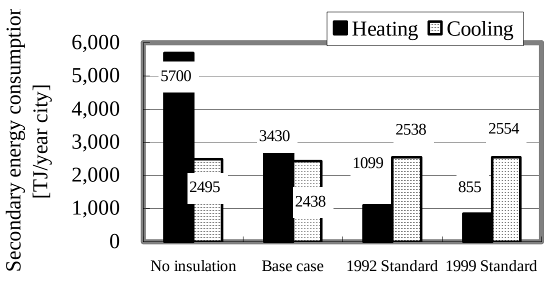

Figure 12 Effect of thermal insulation standard

Energy Conservation Standard"), are simulated. The 1999 standard is stricter than the 1992 standard and thermal insulation of base case is not adapted to the 1992 standard.

Simulation results of annual energy consumption by residential sector in Osaka City are shown in figure 12. Heating energy consumption is reduced greatly by insulation. But cooling energy consumption is not changed. If all dwellings in Osaka City are adapted to 1999 standard, total energy consumption is reduced by 7.7%.

As well as thermal insulation standard, Japanese government incorporated new appliance energy standard (commonly known as "Top-Runner Approach") into the Law Concerning Rational Use of Energy in 1999. In this standard, averaged energy efficiency in 2004 must be higher than the most efficient model in 1999. For example, the average value of cooling and heating COP of a room air conditioner must be larger than 4.90 for the models between 2.5kW and 3.2kW. Therefore energy efficiency of Japanese appliances has been improved rapidly in recent years. Figure 13 shows the comparison of simulated annual electricity consumption by room air conditioners in Osaka City. By this standard, energy consumption of residential sector in Osaka City is reduced by 4.0%.

The Japan Refrigeration and Air-Conditioning Industry Association (JRAIA, 1999) proposed the estimation method of annual power consumption for room air conditioner and this method has been used generally. However, this method has a problem with accuracy since unrealistic conditions are assumed (e.g. RAC is operated 18hours/day). To examine the accuracy of this estimating method, simulated result is compared with the estimated energy saving by the JRAIA's method. The number of RACs in Osaka City is obtained from the simulation result. The result of estimation by JRAIA method is shown in figure 14. It is clear that both annual electricity consumption and the amount of conserved energy by JRAIA method are overestimation.

All of these things make it clear that the simulation model which is developed in this study can estimate the city- or regional- scale effect of various energy conservation policies accurately.

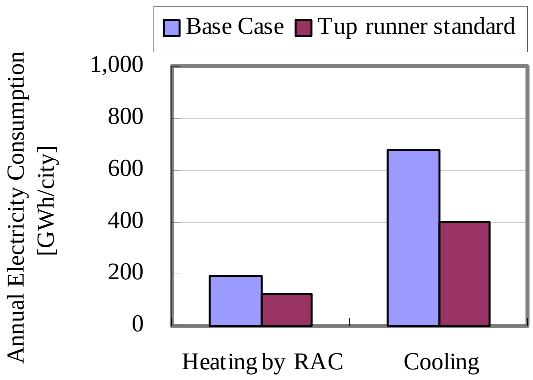

Figure 13 Energy Conservation by Adapting "Top runner standard" to Room Air Conditioner.

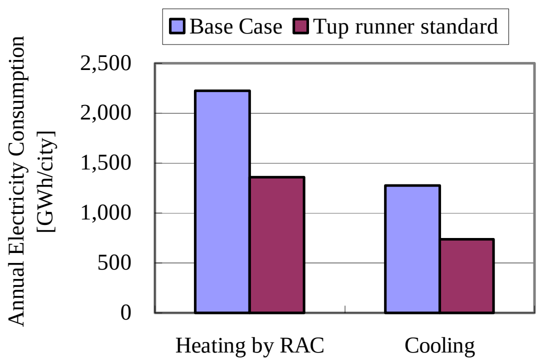

Figure 14 Estimated Energy Conservation by JRAIA method

Evaluation on the Influence of Urban Heat Island

In large Japanese cities, energy consumption for heating, cooling and hot water supply is supposed to be affected by urban heat island phenomena, which increases air temperature in cities artificially. To evaluate this effect quantitatively, annual energy consumption using weather data of Hirakata City, which is 25km to the north-east of Osaka City, is simulated. Figure 15 shows the estimated electricity load curves in summer using Osaka weather data and Hirakata weather data and their outdoor air temperatures. Figure 16 shows the comparisons of annual energy consumption for cooling, heating and hot water supply.

Electricity consumption for cooling in Osaka City is larger than that in suburb. On the other hand, energy consumption for heating and hot water supply in Osaka City is smaller than that in suburb since heating load is decreased and city water temperature and COP of room air conditioner (heating mode) are increased by air temperature increase.

Energy consumption in Osaka City is decreased by the urban heat island phenomenon. The difference in this case corresponds to 6% of total energy consumption in the residential sector in Osaka City.

CONCLUSION

In this paper, the simulation model which predicts city-level energy consumption for the residential sector is developed. The unique characteristics of this model are as follows:

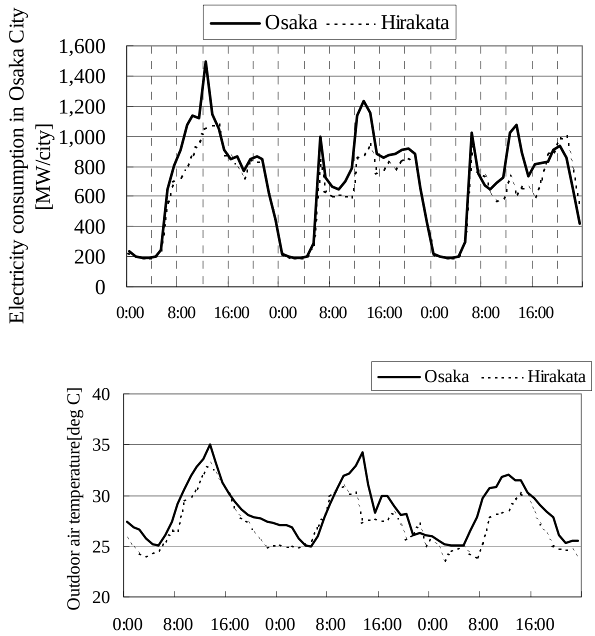

Figure 15 Electricity load curves and air temperatures of Osaka weather data and Hirakata weather data

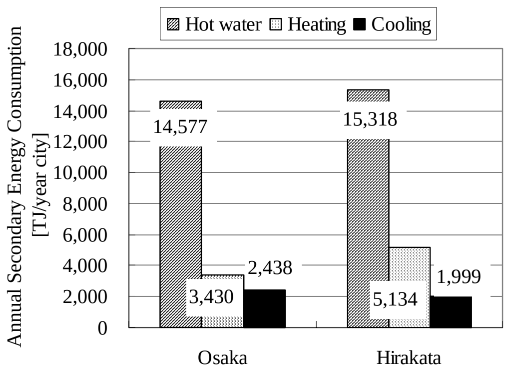

Figure 16 Calculated energy consumptions under different weather data

1) The distribution of household type and dwelling type in the region is considered.
2) Since energy use of appliances are linked to living activity of occupants, the effect of life style change on energy consumption can be examined.
3) The impact of changes in the efficiencies of appliances can be evaluated.
4) Since heat load calculations are included in this model, the effect of thermal insulation and differences in climate can be considered.

Therefore, this model can evaluate the effect of various energy conservation policies. By adding the scenario of how dwellings and appliances stock will change and how the population and the composition of household will change, the model can predict the change of energy consumption in the future.

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