THERMAL ENVIRONMENT AND ENERGY EVALUATION FOR HEAT ISLAND COUNTERMEASURE IN DIFFERENT RESIDENTIAL AREAS

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Abstract

Various countermeasures to urban heat island applied in the residential areas are evaluated for thermal environment improvement and year-round energy performance, using an urban canopy model coupled with a building energy model. The simulation shows that a combination of surface cooling measures and installation of heat pump water heater can lower the nighttime air temperature and reduce the annual energy consumption effectively. For the area with smaller and poorly insulated buildings, the surface cooling shows larger potential for reduction of the energy consumption for air-conditioning. For the area with larger and densely populated buildings, the heat pump water heater shows larger potential for nighttime cooling effect.

Key words: Urban Heat Island, Greening, Heat Pump Water Heater

1. INTRODUCTION

To mitigate the urban heat island (UHI) phenomenon, improvements in urban surface in terms of reducing heat accumulation by measures such as solar reflective coating, greening and water-retentive paving are considered to be effective. A massive installation of heat pump water heaters, which absorb heat from the outdoor air, can also be expected to have cooling effects (e.g., Tamura et al. 2003), which was verified by means of meteorological observation around an inhabited apartment building (Yamaguchi et al. 2009). The effects of these measures on thermal environment and energy demands are thought to depend on characteristics of targeted city areas, such as street geometry and construction of buildings. Based on this viewpoint, in this study, various countermeasures applied in two residential areas with contrasting characteristics are evaluated for their influence on urban thermal environment during summer in conjunction with year-round energy performance for buildings, using an urban canopy model two-way coupled with a building energy model (Ihara et al. 2008).

2. DESIGN OF EXPERIMENT

2.1. Areas for evaluation

In order to examine the effects of UHI countermeasures that depend on characteristics of city areas, two contrasting residential areas, each located in central Tokyo, were selected. The areas were designated Area-A and Area-B. As shown in Table 1, Area-A is a newly developed district of apartment units, and Area-B is an old low-rise district of apartments and detached houses. Buildings in Area are all four-story high with larger building area and smaller floor area per dwelling unit, and highly thermal-insulated outer walls, while those in Area-B are about two-story high with smaller building area,

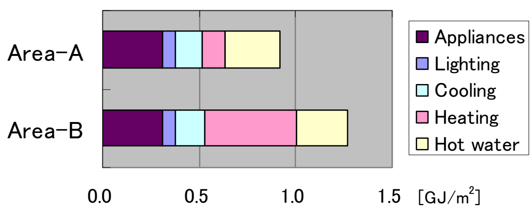

Fig. 1. Annual primary energy consumption per floor area for control runs.

Table 1. Street geometry and building construction of the evaluated areas.

Area ID	A	B
Gross building-area ratio [%]	31	21
Gross floor-area ratio [%]	122	44
Averaged building story	4	2.1
Avelaged buildig area [m^2]	365	108
Floor area per dwelling unit [m^2]	50	81
Thermal resistance of roofs [m^2K/W]	1.5	0.4
Thermal resistance of walls [m^2K/W]	1.4	0.2

Table 2. Simulation setup for countermeasure cases.

Cases	Conditions
Rooftop greening	Coverage: 86% area of rooftop, Soil thickness: 20cm, G_s*: 3.0 (summer), 0.9 (winter)
Rooftop solar reflective coating	Coverage: 100% area of rooftop, Albedo: Doubling (from 0.2 to 0.4)
Sidewall solar reflective coating	Coverage: 100% area of sidewall except for windows, Albedo: Doubling (from 0.2 to 0.4)
Shade planting with tall trees	Shade coverage: 50% area of the ground and sidewalls during summer
Water-retentive paving (or lawn planting)	Coverage: 100% area of the ground except for buildings, G_s*: 2.5 (summer), 0.0 (winter)

* G_s : Latent heat transfer conductance [mm/s]

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larger floor area per dwelling unit, and poorly thermal-insulated outer walls (i.e., Area-A is an area of larger, densely-populated and highly insulated buildings, and Area-B is an area of smaller, more sparsely-populated and ill-insulated buildings).

2.2. Setup for the building energy model

Schedules for occupancy, air-conditioning, hot water demand, appliance use and lighting were set up with the use of an auto-generation program for livelihood schedules (SCHEDULE Ver. 2.0) provided by The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, assuming 2.5 and 3 persons per household for Area-A and Area-B, respectively. As for air-conditioning equipments, it was set that electric heat pump systems constitute 100% and 34.5% of cooling and heating, respectively, and other fuel-fired systems make up the remainder (65.5%) of heating. Water heaters are conventional gas-fired systems with 80% heat efficiency, or electric heat pump systems with COP dependent on temperature of outdoor air and feed water (simulated annual value 3.16). The model was integrated for one year using observed weather data from June 2002 to May 2003 at Tokyo Meteorological Observatory.

2.3. Control runs

Figure 1 displays the breakdown of annual primary energy consumption per floor area for control runs (with gas-fired water heaters, no countermeasures). The comparison shows that energy demands for air-conditioning are significantly smaller in Area-A, while hot water demands per floor area are nearly the same between the areas. The small energy demands for air-conditioning in Area-A are attributable to the buildings with highly thermal insulated outer walls and larger dimensions (smaller surface area per unit volume) reducing heat transfer through the walls, in particular, during wintertime. The summer cooling load, however, shows little dependence on the heat-insulating conditions of walls, since large portion of the cooling load is due to solar heat gain through windows.

3. EVALUATION RESULT

3.1. Improvements in urban surface

A set of numerical experiments was performed for cases where various cooling measures for urban surface (described in Table 2) were individually applied in each area. Figure 2 displays averaged surface air temperature changes in August for the countermeasure cases (difference from the control run). The comparison shows little difference between the areas, with shade planting and water-retentive paving (or lawn planting) indicating relatively larger cooling effects. Figure 3 shows changes in annual air-conditioning energy consumption for the countermeasure cases, which reveals that the influence from each countermeasure is distinctly smaller in Area-A than in Area-B, which is attributable to the difference of the heat-insulating conditions of the buildings. That is, highly insulated wall reduces the influence from lowered exterior temperature achieved by the measures. The solar reflective coating cases show increased annual total energy consumption, since increase in winter heat-

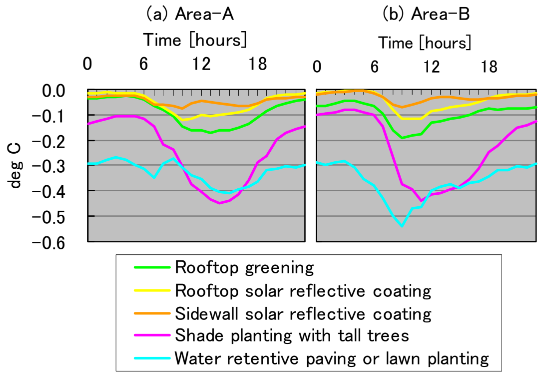

Fig. 2. Averaged surface air temperature changes in August for (a) Area-A and (b) Area-B.

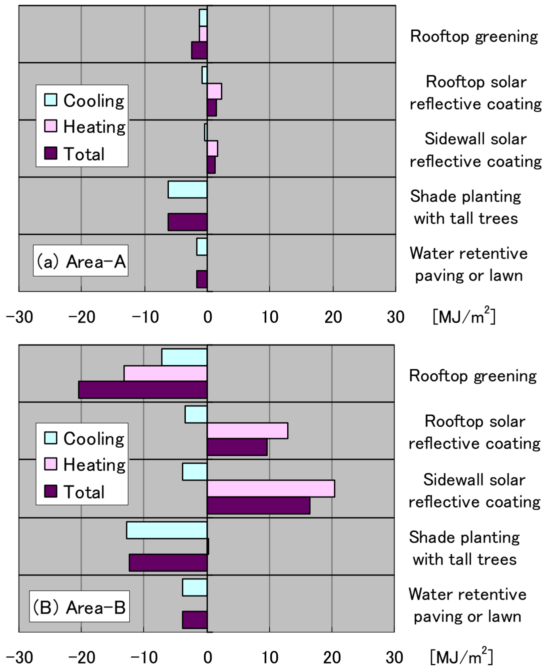

Fig. 3. Changes in annual air-conditioning energy consumption for (a) Area-A and (b) Area-B.

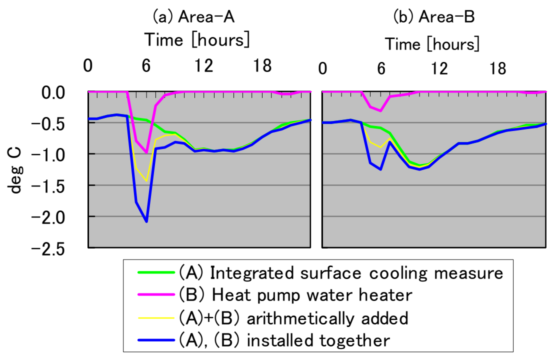

Fig. 4. Averaged surface air temperature changes in August for (a) Area-A and (b) Area-B.

ing demands exceed decrease in summer cooling demands, while the rooftop greening cases indicate decrease in winter heating demands due to the heat insulating effect from the soil. The shade planting cases show relatively large reductions in cooling demands even in Area-A of the highly insulated buildings, with the solar heat gain through windows effectively reduced, and little influence on heating demands, since deciduous trees are assumed for the planting. A comparative evaluation based on the simulated result indicates that rooftop greening, shade planting with tall trees, and water-retentive paving (or lawn planting) on the ground is the most effective combination that achieves a good balance between thermal environment improvement and year-round energy performance for the both areas. We designated the combination "integrated surface cooling measure".

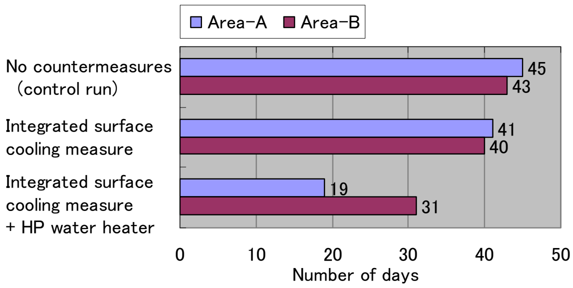

Fig. 5. Annual number of tropical nights.

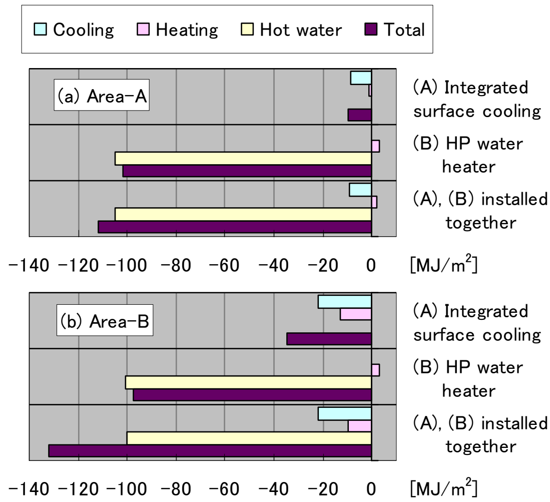

Fig. 6. Chages in annual energy consumption for (a) Area-A and (b) Area-B.

3.2. Installation of heat pump water heaters

Another set of numerical experiments was performed for cases where heat pump water heaters were installed entirely in each area. The simulated result shows substantial air-cooling effect at nighttime when multiple heat pump water heaters operate concurrently (Fig. 4). In particular, the decrease in air temperature induced by heat pump hot waters is significant in Area-A, where hot water demands per land area is greater. For the cases where the "integrated surface cooling measure" and the "heat pump water heaters" are installed together, the cooling effects are enhanced with cold exhaust air from the heat pump less diffused due to atmospheric stabilization caused by the integrated surface cooling measure, which results in substantial reduction of the number of tropical nights (minimum temperature ≥ 25°C) as displayed in Fig. 5. As for the energy performance, it is indicated that the additional energy-saving effect from "surface cooling" is quite limited in Area-A, where the energy demands for air-conditioning are basically low, while the energy-saving potentials from the heat pump water heaters are significant in both areas (Fig. 6).

4. CONCLUSION

Various UHI countermeasures are evaluated for two contrasting residential areas, using an urban canopy model coupled with a building energy model. The simulated result shows that a combination of urban surface cooling measures and installation of heat pump water heaters is effective in aspects of thermal environment improvement and year-round energy performance for both areas. It is also indicated that the surface cooling shows larger potential for reduction of the energy consumption for air-conditioning for the area with smaller and less insulated buildings, while the heat pump water heater shows larger potential for nighttime cooling effect for the area with larger and more densely populated buildings.

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