Evaporative cooling technologies that use the water supply system to improve the urban environment

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Abstract

Evaporative cooling technologies such as mist spraying, sprinkling of roofs, and water spraying onto air-conditioner outdoor units were taken up as environment measures for an investigative study.

Demonstrative experiments using an apartment house confirmed that mist spraying at windows and roof-top water sprinkling have an effect of reducing the air temperature in the room. The experiments confirmed also that all of the evaporative cooling technologies used have an energy consumption reducing effect.

Next, simulation analysis was conducted to calculate basic units showing the environment improvement effect per total building floor area by type of evaporative cooling technologies. The calculation made it clear that mist spraying is particularly effective as a heat-island countermeasure and water spraying onto air-conditioner outdoor units for business-purpose buildings is so as an energy-saving countermeasure. The environmental improvement effect on an urban level was estimated for a case where the evaporative cooling technologies are disseminated, and the estimation showed that, under the assumption that such countermeasures are taken in 20% of residential houses and 50% of business-use buildings in Osaka City, the sensible heat loading on the atmosphere can be reduced to a level of 60 to 80% of the target quantity set as the heat-island countermeasure.

Keywords

Evaporative cooling, Heat island, Mist spraying, Energy saving, Environmental water

1. Introduction

Global warming has become an international challenge as an environmental problem, while the heat island phenomenon has posed a challenge in urban areas. The heat island phenomenon refers to a phenomenon in which progress in urbanization causes the air temperature in urban areas to become higher than in suburban areas. Osaka City laid out a heat island prevention acceleration plan, making it a challenge for the Municipal Waterworks Bureau to contribute to the improvement of urban environments.

In response to this challenge, the Osaka Municipal Waterworks Bureau directed its attention to environmental measure technology based on waterworks systems, including evaporative cooling technologies and similar ones such as mist spraying. Mist spraying refers to spraying waterdrops finer than those used in water spraying. This paper reports the result of experiments on evaporative cooling technologies as well as the simulation analysis of the estimation of effects on urban environments of the widespread use of these technologies.

2. Experiments on Evaporative Cooling Technologies

2.1 Overview

One of municipal apartment houses, made uninhibited after the withdrawal of residents for rebuilding work, was used as the experiment field where the demonstrative experiment was conducted from August to October 2007. **Fig. 1** shows the appearance of the building used for the experiment. The building was five-storied with four residences on each floor. In the experiment, two adjoining residences were regarded as a set with the evaporative cooling technologies provided to one of the couple to make comparison between them as to the room temperature, air conditioning power consumption and other factors as a function of the presence or absence of such measures. The demonstrative experiment

Fig. 1 Apperance of the experimental facility

was conducted on three of the evaporative cooling technologies, namely, mist spraying, roof-top sprinkling, and water spraying onto air-conditioner outdoor units.

2.2 Method of Experiment

2.2.1 Mist Spraying

Mist spraying was performed on the balcony to verify the room cooling effect produced by the introduction of the outdoor air cooled by the balcony. As shown in **Fig. 2**, mist spraying nozzles were arranged as follows: four nozzles on the outdoor guardrail and four on the ceiling portion directly above on the south side veranda and two on the guard rail on the north side window (the amount of water sprayed: 13.4 liter/hour). A high-pressure pump pressurized city water, which was sprayed in dry type mist(average particle diameter：30 μm) from the nozzles(**Fig. 3**), and then the room temperature and humidity were measured.

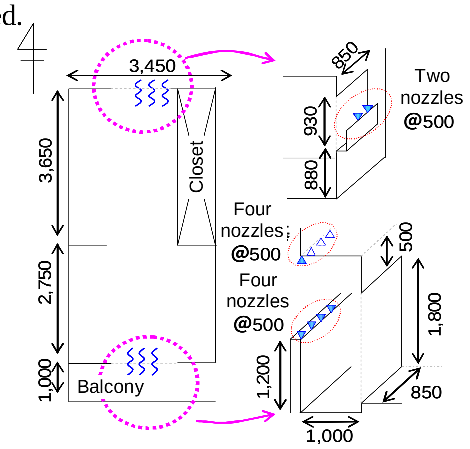

Fig. 2 Apperance of the experimental facility (Mist Spraying)

Fig.3 Experiment in progress (Mist Spraying)

2.2.2 Roof-top Sprinkling

The roof-top temperature decrease effect due to roof-top water sprinkling and the temperature decrease effect on the room directly below due to the roof-top sprinkling were verified. Of the roof top surface, the portion($70m^2$) directly above the room provided with the environmental measures was allotted as the water sprinkling field (**Fig.4, Fig.5**) and 12 sprinkling nozzles were located. Water was sprinkled intermittently from 9 to 17 o'clock, the time zone during which the roof-top surface is affected by the sunshine. With the condition of evaporation from the roof-top on a clear day taken into account, a water sprinkling cycle was structured that consists of 15 seconds of water sprinkling and seven minutes of stopping (the amount of water sprinkled: 33 liter/hour). In addition to the measurement of the room temperature and humidity, the power consumption of an air conditioner installed in the room provided with the countermeasures and that of one installed in the room without countermeasures were compared.

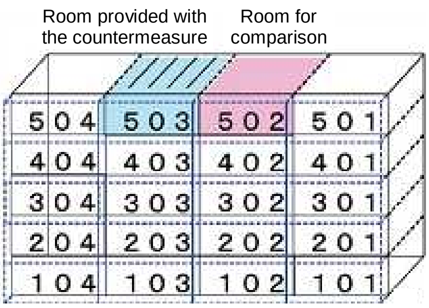

Fig.4 Schematic diagram of the housing (Roof-top sprinkling)

Fig.5 Experiment in progress (Roof-top sprinkling)

2.2.3 Water Spraying onto the Air-conditioner Outdoor Unit

A water spraying nozzle was installed on the air-conditioner outdoor unit to spray city water to the air intake of the unit during the air-conditioner operation to turn the exhaust heat into latent heat and to increase the air-conditioner efficiency (**Fig. 6**). The effect was verified of vaporizing water on the fin surface to decrease the fin surface temperature and thereby improve the air-conditioner efficiency. With the condition of evaporation from the fin taken into account, a cycle was worked out consisting of one second of spraying between 30 second intervals (the amount of water sprayed: 2.8 liter/hour).

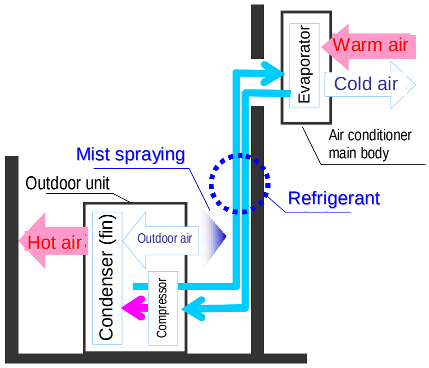

Fig. 6 Diagrammatic sketch of the experimental layout (Water Spraying onto the Air-conditioner Outdoor Unit)

2.3 Results of Experiment and Considerations

2.3.1 Mist Spraying

Compared with the room without the countermeasures, the room temperature dropped 2.0ºC on the average with a maximum drop of 2.7ºC, while the humidity rose 12% on the average with a maximum rise of 17%; in this way, it was confirmed that natural ventilation brings about an air temperature decrease effect in a ventilated living space (**Fig. 7**). SET*(a thermal comfortableness evaluation index calculated from the temperature, humidity, wind velocity, and the like) dropped 1.3ºC on the average, and it was made clear that a decrease in the air temperature improves total comfortableness, though accompanied by a rise in the humidity.

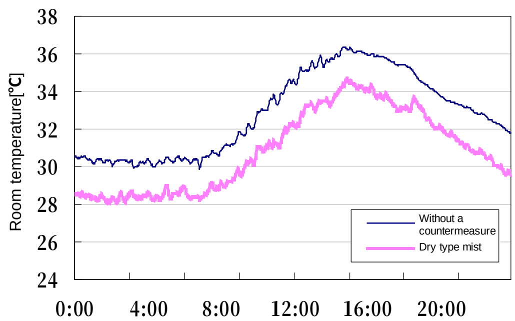

Fig. 7 Effect of mist spraying (Room temperature reduction effect)

2.3.2 Roof-top Water Sprinkling

① Roof-top surface temperature decrease effect

Fig.8 shows the variation in the roof-top surface temperature with time in a representative day. During the mist spraying time (9 to 17 o'clock), the surface temperature fell 16.4ºC on the average. Furthermore, it was confirmed that the roof-top surface temperature decreasing effect continues into the nighttime after 17 o'clock when water spraying was stopped. Since the decrease in the roof-top surface temperature leads to that in the upward long-wavelength raditaion, it provides a measure against the heat island phenomenon.

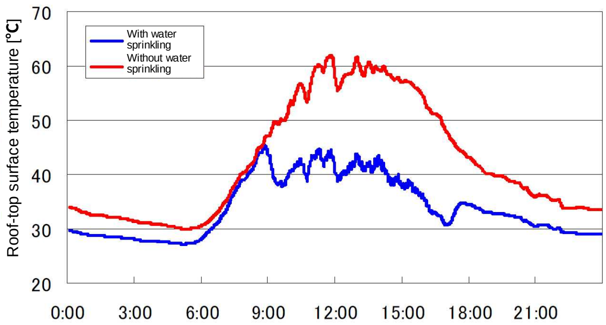

Fig.8 Effect of roof-top sprinkling (Roof-top surface temperature reduction effect)

② Room temperature decrease effect

Variation on a representative day with time of the temperature in the room provided with the countermeasures and that of the temperature in the room without the countermeasures are shown in **Fig.9 and 10**. It was confirmed that mist spraying on the roof-top has an effect of cooling the room directly below. The temperature decrease on the ceiling surface was 1.9ºC on the average over the entire day, 1.8ºC on the average over the spraying time, and 2.1ºC on the average over the non-spraying time, while the room temperatrure decrease was 1.2ºC on the average over the entire day, 1.0ºC on the average over the spraying time, and 1.3ºC on the average over the non-spraying time. The possible reason for a higher cooling effect at room temperature during the non-spraying time (after 17 o'clock) is that the existence of a certain heat capacity in the ceiling resulted in a delayed appearance of the roof-top surface temperature decrease effect due to water spraying.

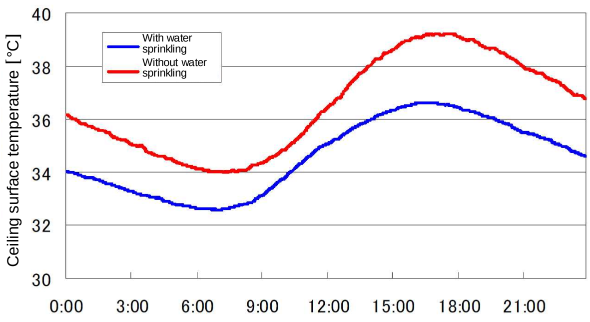

Fig.9 Effect by roof-top sprinkling
(Ceiling surface temperature reduction effect)

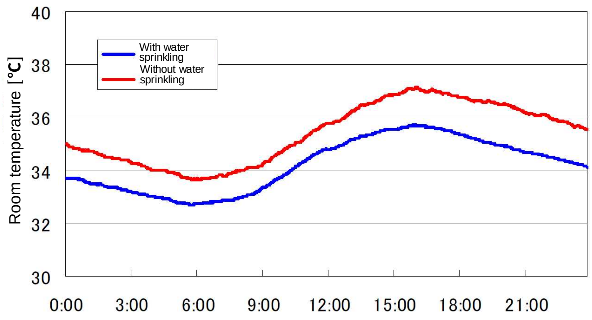

Fig.10 Effect by roof-top sprinkling
(Room temperature reduction effect)

③ Air-conditioner power consumption decrease effect

To verify the power consumption decrease effect of roof-top sprinkling on the residence, an air-conditioner was operated in the room provided with the countermeasures and in the room without the countermeasures at the same temperature setting.

The air-conditioner power consumption was 490 Wh on the average, a 9.7% reduction on the average. In this case, the amount of energy to deliver c ity water to be sprayed on the roof-top was 118.5 Wh. Even with this value taken into account, the air-conditioner power consumption was 372 Wh on the average, a 7.3% reduction.

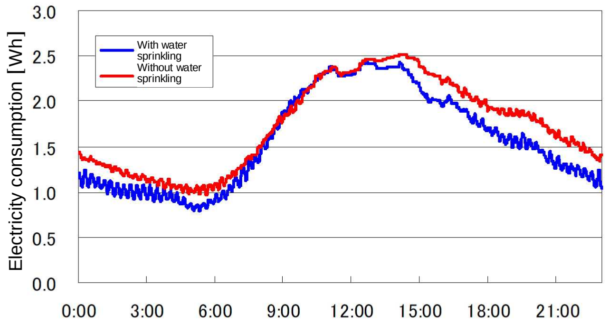

Fig.11 Effect of roof-top sprinkling
(Air-conditioner electricity consumption reduction effect)

As shown in **Fig. 11**, the power consumption reduction effect began to appear after 12 o'clock, and a maximum effect appeared from the time of termination of water spraying (after 17 o'clock) to 21 o'clock, with the efficacy lasting until the next morning.

2.3.3 Water Spraying onto the Air-conditioner Outdoor Unit

① Air-conditioner power consumption decrease (Energy-saving effect)

Compared with the room without the countermeasures, the one provided with the countermeasures exhibited a reduction in the air-conditioner power consumption of 2 kWh/day on the average, a 36% reduction (**Fig.12**). The possible reason for the remarkabke effect during the daytime is that the rise in the air temperature increases the vaporization efficiency of water on the fin surface (Fig. 9). The increase in the power consumption resulting from the increase in the water consumption for water spraying is less than 0.1 kWh/day.

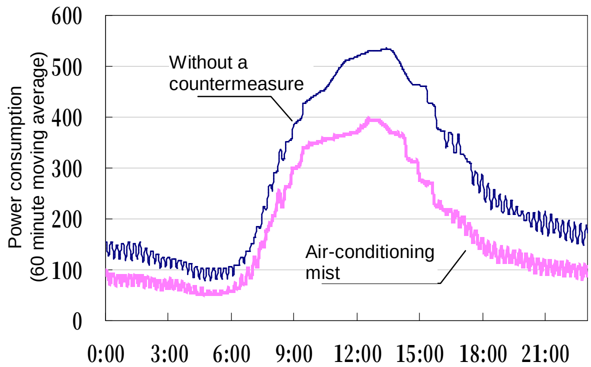

Fig.12 Effect of water spray onto the air-conditioner outdoor unit(Air-conditioner energy consumption reduction effect)

② Air-conditioner outdoor unit exhaust heat decrease (the heat island effect mitigation effect)

Compared with the room without the countermeasures, the one provided with them exhibited an average reduction in the amount of exhaust heat of 125 MJ, a 73% reduction, calculated from the temperature difference between the air intake and the exhaust outlet of the outdoor unit and the amount of air. (**Fig.13**).

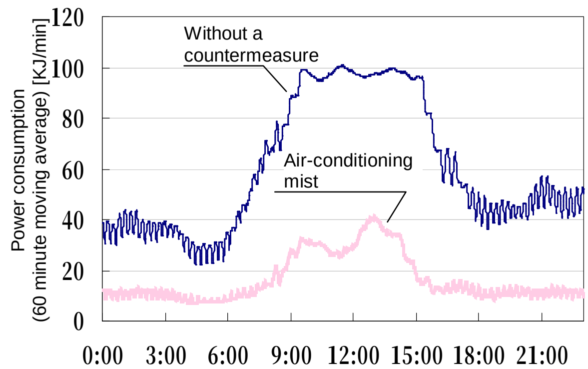

Fig.13 Effect of water spray onto the air-conditioner outdoor unit(Outdoor unit exhaust heat reduction effect)

2.3.4 Summary of the Experiment

It was confirmed that mist spraying at the window and roof-top sprinking have, respectively, an effect of lowering the air temperature in the room space by 2ºC or so and by 1ºC or so in addition to the outdoor temperature or roof-top surface temperature. It was also confirmed that all of three countermeasures have an energy consumption reduction effect exceeding the energy load resulting from the use of city water in substitution for air conditioning or laod mitigation. In particular, a result was obtained showing that water spraying onto the air-conditioner outdoor unit enables the air-conditioner energy consumption to be reduced by 36% on the average.

3. Simulation

3.1 Overview

Next, using the results of the experiment, the environmental improvement effect on an urban level was estimated on the assumption that evaporative cooling technologies are disseminated extensively. The simulation analysis was conducted on a two-stage basis, that is, in the form of basic analysis on a unit level and in the form of large-scale analysis on an entire urban level.

3.2 Basic Analysis

3.2.1 Method of Analysis

The basic analysis targeted eight building models for residences and business buildings depending on the use, form, and heat insulating properties. On these models, basic units showing the environment improvement effect per total building floor area were calculated by type of evaporative cooling technology from the viewpoint of measures against the heat island phenomenon and energy-saving measures. This analysis used an air-conditioning energy prediction technique[1)] that models the residents' behavior of adjusting room temperature in the air-conditioning season.

①Selection of building models

Regarding residences and business buildings, the eight building models shown below were selected depending on the use, form, and heat insulating property:

• Stand-alone house(low heat insulation)　• Stand-alone house (high heat insulation)
• Apartment house (low heat insulation)　• Apartment house (high heat insulation)
• Office (small-scale)　• Office (large-scale)　• Store (small-scale)　• Store (large-scale)

②Selection of countermeasure technologies

A countermeasure of highly reflective roofs was put to verification as an object not using water in addition to three evaporative cooling technologies put to demonstrative experiments (mist spraying on the balcony, roof-top sprinkling, and water spraying onto the air-conditioner outdoor unit).

(Mist spraying on the balcony)

The water spraying condition of using 24 nozzles for a stand-alone house and 18 nozzles for an apartment in a apartment house was set on the basis of the contents of the experiment. The latent heat of the mist, sprayed under the above conditions, was used in the calculation of the reduction in the sensible heat loading on the assumption that all such mist is evaporated.

The room SET* reduction effect due to mist spraying was assumed to be 1ºC on the basis of the result of the demonstrative experiment, being incorporated into the calculation. The calculation was performed on the assumption that mist spraying starts if the SET* of the room where the resident is found exceeds 27ºC with the air conditioner not in operatrion and stops if the value exceeds 28ºC with mist being sprayed and the air conditioner kept in operation thereafter.

(Roof-top sprinkling)

The effect of roof-top water sprinkling was calculated on the assumption that sprinkling is performed over the entire surface of the roof-top for all building models. The operating condition of roof-top sprinkling is such that the operation is started if the roof-top surface temperature exceeds 40º C and is continued until 17 o'clock of the day. The water sprinkling condition is the same as in the demostrative experiment. When water is sprinkled under this condition, the amount of water used is given by 0.46 per roof-top area (= 33 (the amount of water sprinkled per hour)/(9.7 × 7.4) (roof-top area)) [L/m^2/h] .

（**Water spray onto the air-conditioner doutdoor unit**）

The effect of water spraying onto the air-conditioner outdoor unit in a residence was estimated on the basis of the demonstrative experiment. In other words, the calculation was performed on the assumption that the water spraying condition is identical to that in the demonstrative experiment, that the ratio of reduction in the sensible heat exhaust resulting from the turning of exhaust heat into latent heat is 73%, the average during the experiment period, and that the ratio of reduction in the air-conditioner energy consumption resulting from the COP improvement is 36%, the average during the experiment period. It was assumed also that the water spraying onto the outdoor unit is performed simultaneously with the air conditioner operation.

The effect of water spraying onto the air-conditioner outdoor unit in business-use buildings（offices and stores）was calculated using the relational expression between the COP improvement ratio and the ratio of an decrease in sensible heat vs the ambient air temperature, being incorporated into the air-conditioner energy consumption and the air-conditioner exhaust heat. The amount of water sprayed was calculated on the assumption that the amount of water corresponding to the reduction in the sensible heat was consumed.

（**Highly reflective roof**）

A highly reflective roof refers to a technique in which highly reflective paint is applied to the roof surface to increase the reflectance to the incident sunlight, being a means to reduce the amount of heat entering the building. In the current analysis, studies on highly reflective roofs were conducted in the course of improving the reflectance of the of surface for which the initial condition was 10% up to 60%.

③ Determination of the weather condition

The Reference Weather Year Data of the Expanded AMeDAS Weather Data（Osaka）was used as the weather condition for the current calculation. The reference weather year data is weather data for an average one-year period from 1981 to 2000.

3.2.2 Results of Analysis and Considerations

Tables 1 and 2 summarize the reduction basic units for the countermeasure technologies. The calculated basic units show that mist spraying is particularly effective as a heat island countermeasure, while water spraying near air-conditioner outdoor units in business-use buildings is particularly effective as an energy-saving measure.

Table 1 Basic unit for the sensible heat load reduction

(MJ/m²/day)

	Roof-top water sprinkling	Mist spraying	Water spraying onto the outdoor unit	High reflectance roof
Stand-alone house; low heat insulation	2.0	4.7	0.5	1.5
Stand-alone house; high heat insulation	2.0	5.1	0.4	1.5
Apartment house; low heat insulation	4.0	3.0	0.3	3.4
Apartment house; high heat insulation	4.0	3.1	0.3	3.4
Office	3.0		2.0	1.4
Store	2.7		2.2	1.2

Table 2 Basic unit for energy reduction

(Wh/m²/day)

	Roof-top water sprinkling	Mist spraying	Water spraying onto the outdoor unit	High reflectance roof
Stand-alone house; low heat insulation	3.0	5.0	13.7	2.3
Stand-alone house; high heat insulation	4.8	7.7	10.7	5.2
Apartment house; low heat insulation	8.5	4.5	7.7	6.5
Apartment house; high heat insulation	3.1	6.5	8.3	2.2
Office	28.8		674.6	15.4
Store	28.5		757.5	14.5

In the following , the features of effects of reducing sensible heat load and air-conditioner energy through countermeasure technologies are summarized by building model.

① Stand-alone houses

- Mist spraying on the veranda is most effective in reducing sensible heat load.
- With the air-conditioner exhaust heat being small in comparison with the sensible heat load for the entire building, water spraying onto the outdoor unit has a smaller sensible heat reduction effect than spraying mist on the veranda, roof-top water sprinkling that provides a countermeasure for the building surface, or a high reflectance roof.
- Differences in sensible heat reduction effects between countermeasure technologies due to heat insulation conditions were not clearly observed.
- Spraying water onto the outdoor unit exhibited the greatest effect in terms of the air-conditioner energy consumption reduction effect.

② Apartment houses

- Mist spraying on the balcony is most effective in reducing sensible heat load.
- As in the case of a stand-alone house, water spraying onto the outdoor unit is far less effectirve than other counter measures in terms of the sensible heat load reduction effect; However, it displays a

noticeable reduction effect in terms of the air-conditioner energy consumption reduction effect.

- It can be confirmed that a roof-top sprinkling scheme reduces more sensible heat load and air-conditioning energy than a high reflectance roof scheme.

③ Business-use buildings (stores and offices)

- Water spraying onto the outdoor unit, which exhibits the least sensible heat load reduction effect among environment addressing technologies for stand-alone houses, provides the measure that exhibits the greatest sensible heat load reduction effect for business-use buildings. This is because a business-use building is subject to a large internal heating value, and hence requires large air-conditioning energy with the ratio of the air-conditioning exhaust heat in an entire building increasing.
- It can be confirmed that roof-top sprinkling reduces more sensible heat load and air-conditioning energy than the high reflectance roof scheme.

3.3 Large-scale Analysis

3.3.1 Method of Analysis

As a large-scale analysis, the environment improvement effect on an urban level, fo r a case where evaporative cooling technologies using the waterworks system is disseminated extensively, was estimated using basic units obtained through the basic analysis. With Osaka City taken as the object of calculation, reduction effects were calculated on the basis of the total floor area of different buildings. The total floor areas by category considered in this simulation are summaized in **Table 3**. As the method of expansion, the reduction basic unit, determined by residential model and business-use building model in the basic analysis, was multiplied by the total floor area. Through the multiplication of the ratio of air-cooled air-conditioning, the assumption of the introduction of water spraying onto the outdoor unit was limited to buildings using air-cooled system.

Table 3 Total floor areas by category considered in this simulation

		Total floor area	Percentage
Stand-alone house		36, 493, 849 ㎡	30. 8%
	Low heat insulation	30, 326, 389 ㎡	25. 6%
	High heat insulation	6, 167, 460 ㎡	5. 2%
Apartment house		46, 451, 522 ㎡	39. 2%
	Low heat insulation	39, 112, 182 ㎡	33. 0%
	High heat insulation	7, 339, 340 ㎡	6. 2%
Office		25, 370, 274 ㎡	21. 4%
	Small-scale	14, 928, 163 ㎡	12. 6%
	Medium-scale	5, 778, 644 ㎡	4. 9%
	Large-scale	4, 663, 467 ㎡	3. 9%
Store		10, 223, 725 ㎡	8. 6%
	Small-scale	6, 478, 400 ㎡	5. 5%
	Medium-scale	1, 619, 600 ㎡	1. 4%
	Large-scale	2, 125, 725 ㎡	1. 8%

The effect produced by the countermeasure is determined on the assumption that the countermeasure technologies are adopted in 20% of houses and 50% of business-use buildings. These percentages of dissemination are based on the result of the public opinion poll conducted by Osaka City and other data. (The amount of water used under this assumption is 70,000 m^3/day, which the Osaka Municipal Waterworks Bureau is capable of supplying for environmental water.)

3.3.2 Result of Analysis and Considerations

Fig.14 shows the results of calculation of the sensible heat load reduction and the target chievement rate for the case where the countermeasure has been introduced. The sensible heat load reduction and the target value were selected as follows. With the aim of mitigating the summertime heat island phenomenon in Osaka City, the target was set at the level of the amount of sensible heat exhaust in a 1970s urban heat environment, and at the same time, the possible sensible heat load in 2030, for which the population and the improvement of equipment efficiency are taken into consideration, was estimated. The difference in the sensible heat load between the two years was selected as the target value for sensible heat load reduction. As a result, an estimate was obtained in which one is allowed to expect a reduction in the sensible heat loading on the atmosphere by 60 to 80% of the target amount.

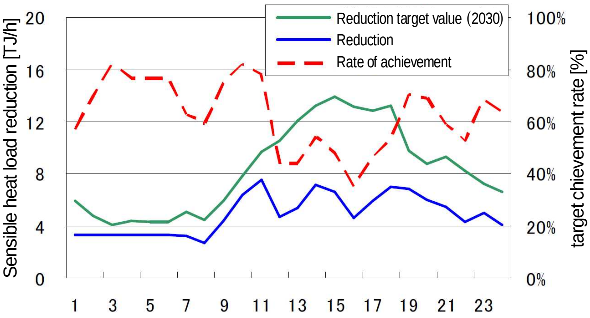

Figure 14 the sensible heat load reduction and the target chievement rate

It was confirmed that the energy reduction effect resulting from this woulf be 7.1 GWh of electricity (equivalent to about 2520 t CO_2) for the entire Osaka City. Thie is equivalent to the electric energy consumed by 710,000 ordinary households in a day.

4. Conclusions

This investigative study confirmed the quantitative characteristics of the effect of evaporative cooling technologies using city water as well as those anticipated when the technologies become widespread. The results of the investigative study will form the basis of implementing approaches of environmental measures using the waterworks system, and at the same time, will indicate the direction in which such approaches should be implemented. On the basis of the results obtained through the study, the Osaka Municipal Waterworks Bureau has created a system to help introduce model projects and apparatuses to promote the dissemination of mist spraying. Environmental measure technologies using the waterworks system provide an approach toward the securing of sustainability of waterworks operations that explore new demands while producing environmental efectiveness. It is hoped that a variety of methods of utilization will be developed and that environmental measures utilizing the waterworks system will be expanded over the entire municipality.

Reference

1）Uhara, Narumi, shimoda, mizuno（2004）,Estimation of Residential Air-conditioning Energy Consumption through the Modeling of the Residents' Behavior of Adjustiung Room Temperature 11-2, Journal of Human and Living Environnment, Tokyo, Japan, pp.83-88.