ARCHITECTURAL RESEARCH, Vol. 19, No. 4(December 2017). pp. 101-108 pISSN 1229-6163 eISSN 2383-5575

Investigation on the Reduction Effect on Cooling Power Consumption and Operating Cost of Mist-spray Outdoor Units in Air Conditioner

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https://doi.org/10.5659/AIKAR.2017.19.4.101

Abstract The use of the air conditioner is increasing due to the rise of the outdoor temperature during summer, and the problems of the fire and the cooling performance deterioration are caused due to lack of maintenance of the outdoor unit. In particular, overall performance of cooling system and efficiency in outdoor units have been degraded due to an intake of high-temperature outdoor air thereby increasing cooling energy and operating cost. Thus, this study aimed to increase efficiency of outdoor units by evaporating and cooling intake air through mist spray at the intake port surface in the outdoor unit. The measurements results showed that total power consumption of misting outdoor unit compared to that of conventional outdoor units was reduced by 21% approximately, and total power consumption of the entire system including pump was reduced by 16.7%. In addition, the operating cost including water use was reduced by 13.5% approximately. In summary, if a mist-spray nozzle kit is installed in air-cooled outdoor units, the reduction in the usage of cooling energy and operating cost will be achieved without replacement of existing cooling systems or a large scale of repairs.

Keywords: Mist Spray, Outdoor Unit, Evaporative Cooling, Operating Cost, Cooling Efficiency

1. STUDY BACKGROUND AND PURPOSE

The Intergovernmental Panel on Climate Change (IPCC) in the United Nations (UN) has been established in Geneva, Switzerland to cope with rapid climate change globally According to the report by the IPCC, heat waves will occur more frequently and the duration of heat waves will increase due to an increase in average global land surface temperature (IPCC, 2014). The increase in outdoor air temperature during summer incurs frequent uses of air conditioner in buildings, which makes vulnerable to fires in outdoor units due to the lack of maintenance of outdoor units along with high temperature discharge air from the outdoor units. For example, the number of fires in outdoor units and surrounding buildings has increased steadily from 40% in 2014 to 45.6% in 2015 and 56% in 2016, which require the problem awareness and attention to the use and management of outdoor units in air conditioner (National Fire Data System in the Ministry of Public Safety and Security (MPSS), 2016).

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Furthermore, hot outdoor air due to climate change and global warming affects the performance of outdoor units. Kim (2011) investigated a sudden reduction in efficiency of outdoor units when high temperature outdoor air was introduced to outdoor units, and analyzed the performance degradation in the entire cooling system due to the sudden reduction in efficiency of outdoor units. The performance degradation in cooling systems is followed by increase in cooling power consumption, energy and operating cost. Nonetheless, most users are not aware of this effect of hot outdoor air introduced to outdoor units that degrades the performance of cooling system but want to increase the efficiency of equipment through replacement of cooling equipment, which is high cost. Thus, in this study, a mist spray nozzle device is installed in existing air-cooled outdoor units to induce performance improvements on outdoor units, and the reduction in cooling energy usage and changes in system operating cost including basic electricity charge and water billing are investigated.

2. THEORY OF EVAPORATIVE COOLING AND EXISITING RESEARCH TREND

(1) Principle of evaporative cooling in discharge and intake ports

The principle of evaporative cooling in the intake port surface is as follows : First, when a fan is run through the operation of outdoor unit, outdoor air in the atmospheric pressure in the stationary state is forcibly introduced thereby increasing an air flow rate by the fan speed (Boulard, T. & Baille, A., 1993). Since outdoor air is sufficiently high in the summer and water temperature supplied from the fan is lower than outdoor air temperature, misted water is likely to be evaporated due to the reduced pressure at the inlet of the fan. The reduced pressure caused by the forced air intake in the fan plays a role in reducing evaporation energy of water molecule to some extent so that evaporation of water molecule is facilitated during the collision between air particle and misted water, and the kinetic energy of collided air particles is lost to the evaporated water molecules thereby decreasing an air temperature. As a result, evaporative cooling occurs at the intake port surface.

Nomenclature	
$T_{air-A,B}$	Dry bulb temperature
$RH_{A,B}$	Relative humidity
$m_{w/a-C}$	Relative mass ratio at cooled air
$m_{w/a-B}$	Relative mass ratio at saturated air
η_{cool}	Cooling effect
COP	Cooling coefficient of performance
T_O	Outdoor air temperature
q	Evaporation quantity of heat
$l_{1,2}$	Condensation quantity of heat

The cooling effect of mist outdoor unit is calculated through a slope between two points as shown in Figure 1: state at ⓐ point of outdoor air and state at ⓑ point of intake port supplied to the indoor assuming that the discharge and intake ports are the same.

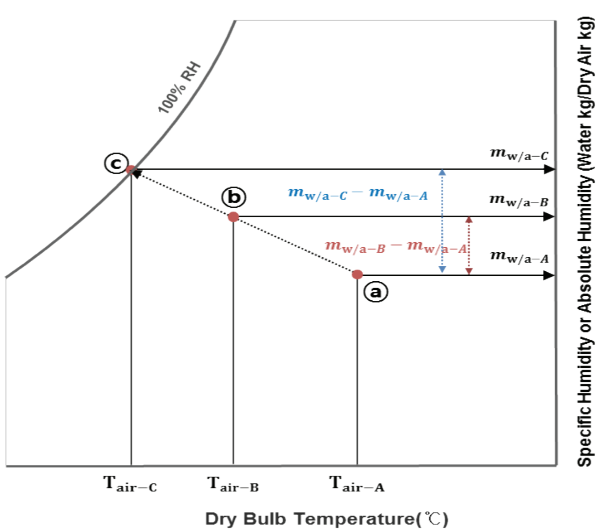

Figure 1. The cooling effect of mist spray outdoor unit (by psychrometric chart)

If water is sprayed to the atmosphere (hot air) in the state at ⓐ point where temperature is T_{air-A} and relative humidity is , humidity is increased due to water evaporation. Since calories emitted by air are absorbed by water molecules even if an air temperature is dropped due to water evaporation in this process, total energy of air and misted water does not change, and a change in air state follows the isenthalpic line in the psychrometric chart, to become temperature T_{air-B} and relative humidity. Although it is the best case to reach the state ⓒ at the optimal condition, it is not possible realistically, and outdoor air will reach some point ⓑ in the isenthalpic line. Assuming that a relative mass ratio (water vapor / mixed air mass) at the time of change from wet air at ⓐ into saturated air is $m_{w/a-C}$ and a relative mass ratio at cooled air ⓑ is , the cooling effect can be defined by the following Eq. (1) (McQuiston, F. et al., 2000).

$$\eta_{cool} = \frac{m_{w/a-B}-m_{w/a-A}}{m_{w/a-C}-m_{w/a-A}} \quad (1)$$

(2) Coefficient of performance in cooling system

The principle of cooling efficiency by decreasing an air temperature introduced to the condenser through evaporative cooling can be explained through the Mollier chart in Figure 2. The cooling coefficient of performance (COP) refers to a processing amount in the evaporation process compared to processing amount in the compression process, which can be expressed as presented in Eq. (2).

$$COP_1 = \frac{q}{l_1} = \frac{i_1-i_3}{i_2-i_1} \quad (2)$$

When a temperature in the condenser is decreased, a processing amount in the compression process is decreased as presented in Eq. (3), which is then followed by an increase in cooling COP.

$$COP_2 = \frac{q}{l_2} = \frac{i_1-i_3}{i_{2'}-i_1} \quad (3)$$

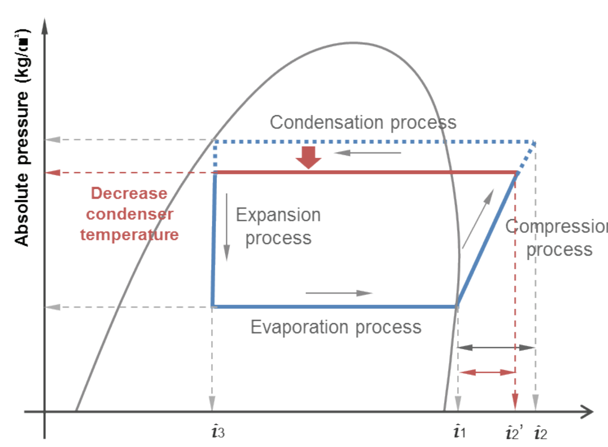

Figure 2. The principle of cooling efficiency(by Mollier chart)

(3) Trend of existing research on application of evaporative cooling

Studies on increase in efficiency of mist outdoor units have been conducted in the USA and Japan through case studies of mist spray outdoor units applied to rooftop. Narumi (2009) conducted a study on three types of mist spray technology: rooftop spray, veranda spray, and outdoor spray types in rooftop of apartment, and obtained measurement results that reduced energy consumption by 36% on average when a mist outdoor unit was employed. Casvendi (2010) concluded that evaporative pre-cooler installed in front of the air-cooled condenser was able to decrease an outdoor air temperature introduced to the condenser while consuming less than 15% of cooling water required in the cooling tower and evaporative condenser, and COP of air-cooled cooler was able to be increased by 14.7% at dry climate.

In Korea, an integrated air conditioner that reduced a size of outdoor unit has been developed using cooling tower and evaporative cooler (Yoon, Y. 2004). In addition, Park (2005) conducted mist water spray in the outdoor space of building during summer and determined the cooling effect in the outdoor space through measurements quantitatively. As a result, temperature reduction up to 5–7℃ and reduction in sensible temperature can be obtained.

Although studies using the principle of evaporative cooling have been conducted in Korea and other nations, few studies have been conducted on systems with general air-cooled outdoor units mounted with mist devices. In particular, no studies on operating cost considering water usage and basic power charge have been conducted.

3. OVERVIEW OF THE MEASUREMENT

The present study investigated practical performance and economic feasibility of the prototype. To do this, measurements were conducted by installing the mist spray nozzle kit at existing general air-cooled outdoor unit. The measurement method, configuration of the mist outdoor unit system, and acquired data are as follows :

(1) Measured target and period

Two rooms, which had the same aspect and area in a five-story office building located at Goyang-si in Gyeonggi-do, were chosen for the measurement. An area of each room was 3.3 × 5.4 × 2.4m (42.8㎥). Each room was equipped with one wall-type indoor unit and one outdoor unit. Figure 3 shows the mist outdoor unit, which are measurement targets. The outdoor unit was installed in the rooftop of the building.

Since residents in the heating, ventilation and air conditioning (HVAC) target space can set an indoor temperature arbitrarily and may work outdoor the building, cooling operating times may not be the same with each other. Thus, measurements were conducted at weekend where no residents were inside the rooms. A period of the measurement was one day in summer of 2014 and five days in summer of 2016, totaling six days. A cooling operation continued from 09:00 to 18:00 considering the operation characteristics of office buildings.

Figure 3. Outdoor unit with mist spray

(2) System overview

The model name of the measured air-cooled outdoor unit was AR06FCBM1DAX. Its specifications are presented in Table 1.

Table 1. Air-cooled outdoor unit's specifications

Classification	Contents
Year	2014
Shape	Wall type
Cooling area	18.7㎡
Cooling capacity	2300W
Cooling power consumption	0.54kW
Outdoor unit size	720 × 548 × 265 ㎜

The mist outdoor unit system was configured using a water tank that stored tap water to maintain a certain water level and inverter motor. A total of four spray nozzles, two at each of the intake and discharge ports in the outdoor unit, were installed. The mist installed at the discharge port was placed to reduce urban heat island, which was not related directly to operating performance of the outdoor unit. Thus, the mist spray at the discharge port was not conducted during the measurement period. A water pressure of mist spray was 2kgf/㎠, a water use rate was 5.6L/h per nozzle. The schematic diagram of the conventional and mist outdoor unit systems is shown in Figure 4.

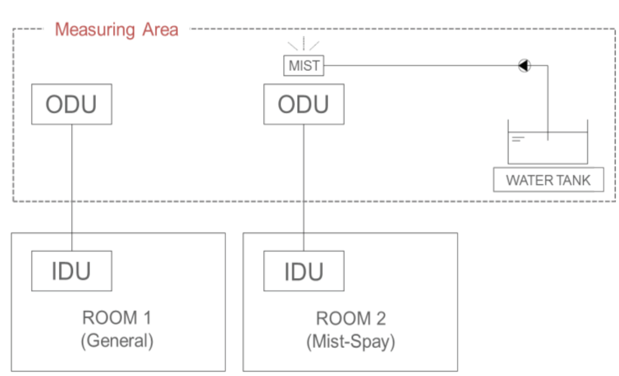

Figure 4. The schematic diagram of the conventional and mist outdoor unit systems

A temperature of intake air in the outdoor unit that was evaporated and cooled during mist spray was decreased by 4–5℃ compared to that of conventional outdoor air temperature, and cooling efficiency of the mist outdoor unit was expected to increase based on Eq. (4) that represented the efficiency of air conditioner in this study. Eq. (4) is a formula calculated from the relationship between external temperature and COP by the AR06FCBM1DAX product data applied to this study. T_O is the outdoor temperature, and the relation means the efficiency of the air conditioner when the room temperature is set to 26 ° C.

$$\mathrm{COP} = 0.0011{T_O}^2 - 0.1091T_O + 8.224 \quad (4)$$

The COP of the outdoor unit was 3.511 when an outdoor air temperature was 30℃, and the COP during outdoor air inflow of 25℃ that was evaporated and cooled via mist spray was 4.159 by using the above equation, which was expected to increase the COP by 18.5% approximately.

(3) Measurement scope and methodology

It is desirable to spray mist at conditions of specific outdoor air temperature or higher and specific relative humidity or lower to achieve economic mist operation. However, this study was at an initial stage of performance investigation so mist spray was inter-operated with the operating conditions of compressor in the outdoor unit. A spray amount from two nozzles at the intake port surface was calculated on the basis of operating hours of the outdoor unit and power usage in the inverter pump was measured. The measurement items were power consumption per min. of operating time of the outdoor unit, water usage according to mist spray, and inverter pump power usage.

Table 2. The outdoor air conditions and indoor conditions during the measurement period

	Outdoor temperature(℃)*	Indoor temperature(℃)	Relative humidity(%)
09/08/2014	28.2	24	42.0
28/06/2016	27.2	26	56.7
09/07/2016	29.6	25	56.0
24/07/2016	26.7	25	92.0
30/07/2016	29.4	25	69.8
31/07/2016	30.6	25	70.2

*Mean outdoor temperature for 9 hours

It was difficult to measure a temperature at the surrounding space due to mist spray at the intake and discharge ports. Thus, weather data were used in the analysis for outdoor air temperatures. The outdoor air conditions and indoor conditions during the measurement period are presented in Table 2. The indoor temperature was set to 25 ± 1℃, which was applied equivalently to both rooms where conventional and mist outdoor units were installed.

4. MEASUREMENT RESULT AND ANALYSIS

The power usage between conventional and mist outdoor units was compared through measurements and pump power usage and water usage used during mist spray in the intake port were calculated. The analysis details about power usage in the entire system are as follows :

(1) Comparison on power usage in the outdoor unit

The outdoor unit power was measured at intervals of 1 minute, and the outdoor unit power consumption was accumulated for 1 hour. This is shown in Fig. 5 and the power consumption of normal operation and mist spray operation is shown as August 9, 2014.

The measurement results on power usage in the outdoor unit during the measurement period are presented in Table 3, in this power usage in the outdoor unit during the measurement period is calculated in every hour. The measurement results during six days showed that daily maximum and minimum power usages in the outdoor unit was 2,526Wh and 1,275Wh, and total cumulative power usage for six days was 9,468Wh for conventional outdoor unit, and for mist outdoor unit, daily maximum and minimum power usages were 1,676Wh and 999Wh, and total cumulative power usage for six days was 7,477Wh. The data indicated that power usage reduction was 1,991Wh due to the use of mist outdoor unit, which was decreased by 21% compared to that of conventional outdoor unit.

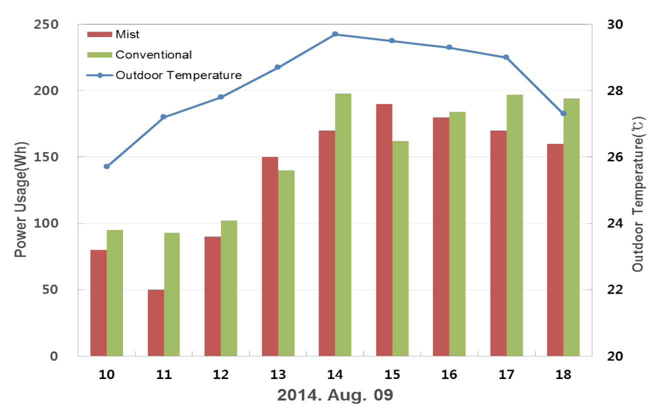

Figure 5. Outdoor unit power measured at 1 hour intervals

The evaporative cooling was conducted and the reduction in power consumption by 21% meant an increase in efficiency of air conditioner. The reason for the reduction in power consumption was due to an increase in efficiency of outdoor unit as a low temperature intake air was introduced when mist spray was used compared to conventional outdoor unit. Furthermore, the reduction was nearly matched with 18% of COP increase calculated previously using Eq. (4) that represented a performance curve of outdoor unit on the basis of outdoor air temperature 30℃ and 25℃.

Table 3. The measurement results on power usage in the outdoor unit during the measurement period

Date	Power Usage		
	Conventional ODU (Wh)	Mist-Spary ODU (Wh)	Reduction Rate (%)
09/08/2014	1,365	1,240	9.16
28/06/2016	1,637	1,296	20.83
09/07/2016	1,275	999	21.65
24/07/2016	1,369	1,221	10.81
30/07/2016	1,296	1,045	19.37
31/07/2016	2,526	1,676	33.65
Total	9,468	7,477	21.03

(2) Correlation with indoor and outdoor conditions

In this section, a reduction rate of power usage according to outdoor air temperature and indoor set temperature is investigated. A graph that displays a correlation between the daily reduction rate of power usage in the outdoor unit and outdoor air temperature is shown in Figure 6.

The outdoor air temperature was distributed in a range of 26.7℃ to 30.6℃ on average, and power consumption in the outdoor unit was reduced by 9.2% up to 33.7%. In particular, the reduction in power consumption in the outdoor unit was the highest on July 31 when the outdoor air temperature was the highest. The analysis result showed that when the mist outdoor was applied, a reduction rate of power consumption tended to increase compared to that of conventional air-cooled outdoor unit.

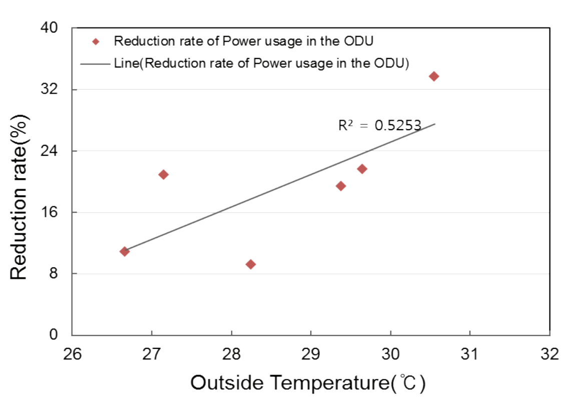

Figure 6. The daily reduction rate of power usage in the outdoor unit and outdoor air temperature

Next, Figure 7 shows a correlation between set temperature and reduction rate of power consumption in the outdoor unit. As shown in the graph, no significant correlation was exhibited between indoor set temperature and reduction in power consumption in the outdoor unit. Thus, there was no best indoor set temperature specified for mist operation.

Figure 8 compares the outdoor relative humidity and the outdoor power saving ratio. In the case of humidity, there is little correlation with outdoor power. Theoretically, the lower the humidity, the higher the efficiency of the outdoor unit at low humidity, because the evaporation is active. This is because the control according to the humidity is not performed during the operation of the mist outdoor unit, so that it is impossible to grasp the correlation between the amount of outdoor unit electric power and humidity as a result of the operation according to the user's demand.

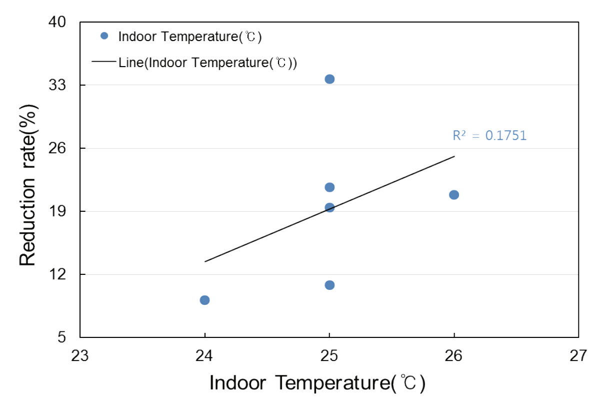

Figure 7. A correlation between set temperature and reduction rate of power consumption in the outdoor unit

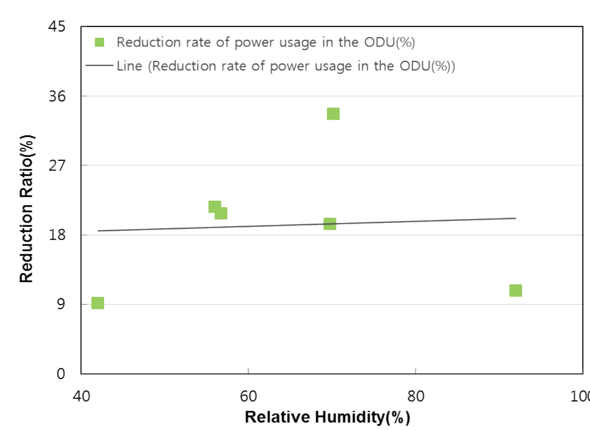

Figure 8. Correlation between relative humidity and power reduction rate

(3) Comparison on power consumption in the system

Since the mist outdoor system attached a mist spray nozzle kit to the conventional air-cooled outdoor unit, it incurs additional power consumption in pump required for mist spray in addition to power consumption of the outdoor unit during the operation of the mist outdoor unit. The power consumption of the inverter pump was calculated by measuring an operating hour of the mist outdoor unit. The calculation result was 55Wh in minimum up to 91Wh daily and total pump power for six days was 412Wh. The power consumptions in the systems of mist and conventional outdoor units including power consumption in the pump are presented in Table 4.

Table 4. The power consumptions in the systems of mist and conventional outdoor units

Date	Power Usage					
	Conventional ODU (Wh)	Mist-Spray System			Reduction Amount (Wh)	Reduction Rate (%)
		Mist-Spary ODU (Wh)	Pump (Wh)	System (Wh)		
09/08/2014	1,365	1,240	76	1,316	49	3.6
28/06/2016	1,637	1,296	74	1,370	267	16.3
09/07/2016	1,275	999	55	1,054	221	17.3
24/07/2016	1,369	1,221	60	1,281	88	6.4
30/07/2016	1,296	1,045	56	1,101	195	15.1
31/07/2016	2,526	1,676	91	1,767	759	30.1
Total	9,468	7,477	412	7,889	1,579	16.7

The maximum and minimum daily power consumptions in the mist system were 1,767Wh and 1,054Wh, and cumulative power consumption for six days was 7,889Wh. A difference in total power consumption between the mist spray and conventional outdoor unit systems was 1,579Wh, which was decreased by 16.7% approximately. The power consumption in the entire system was decreased by 4.3% compared to that only in the outdoor unit. This was due to the addition of power consumption in the pump used to spray mist in the outdoor unit.

Table 5. An amount of mist spray (min.)

Time (hour)	Amount of Mist Spray (L)					
	09/08/2014	28/06/2016	09/07/2016	24/07/2016	30/07/2016	31/07/2016
09-10	2.05	0.74	0.93	1.49	1.67	1.67
10-11	1.49	2.05	1.67	2.05	1.67	2.05
11-12	1.86	3.91	1.49	1.86	1.67	2.05
12-13	3.72	2.42	1.86	1.67	1.49	3.16
13-14	2.79	2.60	2.23	4.65	2.60	2.98
14-15	3.53	3.16	2.42	3.53	2.42	6.32
15-16	3.72	3.16	2.42	2.23	2.60	5.21
16-17	3.72	2.98	2.79	1.49	2.42	4.84
17-18	2.79	4.28	2.98	1.49	2.42	2.79
Total	25.67	25.30	18.79	20.46	18.97	31.06

Furthermore, an amount of tap water used in two nozzles installed in the intake port of the mist outdoor unit system was 5.6L/h. Since the mist spray time was equivalent to the operating time of the outdoor unit, an amount of mist spray was calculated with regard to an operating time (min.) of the outdoor unit, which is presented in Table 5.

5. INVESTIGATION ON THE OPERATION COST

(1) Operating cost during the measurement period

Table 6 presents operating cost of the system for six days of the measurement period. The minimum and maximum operating costs of the conventional outdoor unit were KRW 148 and 239 per day, and cumulative cost for six days was KRW 1,097 while those of the mist outdoor unit were KRW 136 and 229, and 1,022, resulting in KRW 75.6 cost reduction in total usage during the measurement period, which was reduced by 6.9% approximately.

However, monthly electricity charge was calculated by summing the basic charge and power consumption charge. Thus, comparison only on power charge for six days is not appropriate in terms of accurate cost calculation. Accordingly, a total operating cost based on one month was calculated in the next section.

Table 6. Operating cost of the system for six days

Date	Power Usage					
	Conventional ODU (KRW)	Mist-Spay System			Reduction Amount(KRW)	Reduction Rate (%)
		ODU+Pump (KRW)	Water Cost (KRW)	System (KRW)		
09/08/2014	158	153	20	172	-14	-9.0
28/06/2016	190	159	19	178	12	6.2
09/07/2016	148	122	14	136	11	7.8
24/07/2016	159	148	16	164	-6	-3.5
30/07/2016	150	128	15	142	8	5.3
31/07/2016	290	205	24	229	64	21.9
Total	1,097	914	107	1,022	76	6.9

(2) Operating cost based on one month

The operating cost based on one month for conventional outdoor unit was calculated according to power charge based on power consumption in the outdoor unit while that for mist outdoor unit was calculated by summing power charge including pump power and water charge used in mist spray. The power charge was calculated by summing basic charge on the basis of maximum power consumption contracted between Korean Electric Power Corporation (KEPCO) and user, power usage charge based on monthly power consumption, value-added tax, and electricity industry fund.

The maximum power consumption was used in the basic charge during the power charge calculation. The maximum power consumption can be reduced as much as the power reduction rate when the mist outdoor unit was used. Accordingly, for the contracted power, 0.54kW of outdoor cooling power consumption was set for conventional outdoor unit operation while 0.427kW was set for mist outdoor unit operation by taking the power reduction rate (21%) into consideration. Based on this assumption, basic charges are presented in Table 7. Afterward, the cost of power consumption in the office building was calculated based on the rate specified in High Voltage A Option I of General Service (A) I.

The water charge according to mist spray used in the mist of the outdoor unit was calculated based on water charge rate at Goyang-si in Gyeonggi-do. Table 8 presents the water charges. Based on power and water consumptions for six days, a charge for one month was finally calculated on the basis of 24 business days according to the schedule of the office building.

Table 7. Basic charges

	Power Usage Charge (KRW/ kW)	Basic Charge (KRW/ kW)
General Service (A) I	115.9	7,170
Conventional ODU	0.54kW	3,872
Mist-Spary ODU	0.427kW	3,059

Table 8. Water charge rate at Goyang-si in Gyeonggi-do

	Water Usage(ton)	Applied price per ㎥ (KRW)
General purpose	1~100	598
	101~300	713
	301~1000	897
	1001~2000	1,197
	2001~	1,346
Water use charges		170

The estimated monthly power charge of the conventional outdoor unit calculated finally was KRW 8,261, and that of the mist outdoor unit was KRW 7,146. The cost reduction due to the mist outdoor unit was KRW 1,116, which was decreased by 13.5%. This result took water charge and pump power consumption into consideration, which was decreased by about 3%p compared to 16.68% of the system power reduction rate. Because the reduction in power consumption due to the mist outdoor unit was larger than a sum of pump power and water charge, overall cooling cost is likely to decrease when the mist outdoor unit was applied. Furthermore, monthly power charge when using the mist outdoor unit was KRW 6,716 compared to KRW 8,261 of monthly power charge using the conventional outdoor unit due to the reduction in contract power, resulting in KRW 1,545 reduction, which was decreased by 18.7%, which was an increase by 2%p than 16.7% of the system power reduction rate. This is expected to affect the overall cooling period and cooling system significantly. Furthermore, if tap water used in mist spray is replaced with recycled water, it can reduce the cost further.

6. CONCLUSION

This study aimed to resolve performance degradation in outdoor units and cooling system occurred when high temperature air was introduced to the outdoor unit. Thus, this study installed a prototype of mist spray nozzle kit to reduce cooling energy, and the following results can be summarized.

(1)The power consumption between the conventional air-cooled and mist spray outdoor unit was compared and the result showed that cumulative power consumption was reduced by 1,991Wh and 21% through the use of the mist outdoor unit. This was because the efficiency of the outdoor unit was increased due to the decrease in air temperature introduced to the outdoor unit when mist spray was employed.

(2) For power consumption in the system, overall power consumption in the system including power consumption in the pump was compared. The result showed that cumulative power consumption for six days in the mist outdoor unit was decreased by 1,579Wh compared to that of conventional outdoor unit, resulting in 16.7% reduction in power finally.

(3) The monthly system cost was calculated by summing water and power charges including power consumption in the mist outdoor unit as well as pump. The monthly total cost in the conventional outdoor unit was KRW 8,261, and that in the mist outdoor unit was KRW 7,146. Since water charge was added to the final cost due to mist spray, the final cost was reduced by 13.5% approximately.

When evaporative cooling was run through the mist spray nozzle kit installed to the existing air-cooled outdoor unit, efficiency of the outdoor unit and performance in the cooling system were improved thereby reducing cooling cost overall. In particular, increases in efficiency of the outdoor unit can incur the reduction in contract power due to the reduction in cooling maximum power consumption. Thus, cooling cost can be reduced efficiently with low cost without replacement of equipment.

Furthermore, when appropriate mist spray was conducted using outdoor air temperature and relative humidity, additional cost reduction in water charge and pump power consumption will be achieved. To do this, a study on finding outdoor air temperature and relative humidity conditions will be conducted to derive the optimal operating conditions of the mist outdoor unit in the future.

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(Received Aug. 11, 2017/Revised Nov.11, 2017/Accepted Nov. 25, 2017)