International Journal of GEOMATE, March, 2017, Vol. 12, Issue 31, pp. 127-133
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: http://dx.doi.org/10.21660/2017.31.26329

EVALUATION THE PERFORMANCE OF LAKE WATER USED AS HEAT SOURCE FOR HEAT PUMP SYSTEM IN A TYPICAL JAPANESE RESIDENT BUILDING

*Liwei Wen[1]

[1]Faculty of Engineering, Yamaguchi University, Japan

*Corresponding Author, Received: 18 Nov. 2016, Revised: 03 Dec. 2016, Accepted: 10 Jan. 2017

ABSTRACT: The surface water, such as lake-water, sea-water, reservoir-water is considered as one kind of unutilized energy because that they own higher temperature in winter and lower temperature in summer than the ambient air. The energy saving is expectable when the surface water is employed as the heat source of heat pump system. This study examines the potential of lake water used as heat source of heat pump system in a residential building. Annual heating and cooling loads of a typical Japanese residential building were calculated using thermal net-work model of SMASH. The load calculation results indicate that the heating load dominates in the residential building. In addition, the heating load tends to decrease and cooling load minimally varies with the rise in insulation level. The air conditioning is generally operated at low load level in exception of the occasional high load level at the starting running stage. In comparison with the air source heat pump and air conditioner, the predicted energy saving effect for lake water heat pump could attain 60-70% and 30-45% during the cooling and heating periods in different locations, respectively.

Keywords: Unutilized energy, Lake-water, Heat pump systems, Heat source potential, Residential building

1. INTRODUCTION

Building section is approximately in charge of 40% of the total global energy consumption and one third of the total CO_2 emissions [1-3]. Additionally, the energy consumption of heating, ventilation and air conditioning (HVAC) accounts for a large amount of the total value associated with building section [4]. In the past ten years, heat pump system had been widely adopted to achieve energy saving in cooling and heating. The efficiency of heat pump system is largely affected by the temperature of heat source. The temperature of surface water, such as river-water, lake-water, sea-water and so on, experienced minor variation throughout the year. Furthermore, the temperature of these surface water was lower than that of outdoor air in summer and higher than that of outdoor air in winter. Thus, it is believed that the surface water had the potential to be used as heat source of heat pump system [5-8].

Some previous studies had been conducted on the application and development of heat pump with surface water as heat source in the district heat and cool supplying systems. Watanabe (2006) reported that 5.7 percent energy saving could be attained through using the sea-water as heat source in comparison with the cooling tower system [9]. In Nakanoshima area of Osaka, a river-water heat source heat pump system had been adopted to provide the office buildings with heating and cooling since 2005. The measured results indicated that the supplied amount of heat was in accordance with the estimated values. The average annual coefficient of performance (COP) raised from 0.86 in 2005 to 1.09 in 2009 due to the improvement of the system [10]. Moreover, the effect of energy conversation for dam lake-water served as the heat source for heat pump system had been experimentally confirmed by Büyükalaca (2006) [11]. However, the utilization of surface water heat pump system in residential building and small-scale building is still limited.

The aim of this study is to examine the performance of the lake water heat pump system (see Fig. 1) adopted in a typical Japanese residential building. The research object of Nukui Lake is located in Kake, Hiroshima prefecture, Japan. Section 2 represents the characteristics of calculated heating/cooling load using a typical Japanese residential building. Section 3 examines the energy consumptions of lake-water source heat pump, air source heat pump, and air-conditioner to evaluate the potential of lake-water heat pump system.

2. ANNUAL HEATING/COOLING LOAD CALCULATION USING A STANDARD RESIDENTIAL BUILDING

To evaluate the integration of lake water heat pump system into residential building, the annual heating/cooling load calculations were performed using a Japanese standard residential building.

Table 1 Heating/cooling operation schedule

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0
LDK	Weekday								←	—	→			←	→			←	—	—	—	—	—	—	→
	Weekend									←	—	—	—	→				←	—	—	—	—	—	—	→
Japanese style room	Weekday						←	→																	↔
	Weekend										↔													↔	
Bedroom	Weekday						←	→																	↔
	Weekend										↔													↔	
Kid room 1	Weekday							↔												←	→		←	→	
	Weekend										←	—	—	→								←	—	→	
Kid room 1	Weekday							↔												←	→		←	→	
	Weekend										←	—	—	→								←	—	→	

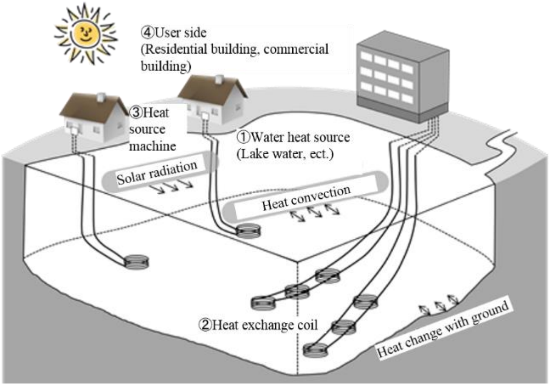


Fig.1 The image of lake water heat pump system

SMASH software based on a thermal net-work model was adopted in the simulation.

2.1 Calculation Conditions

The cooling loads in four selected locations were calculated in this paper. The four locations were Higashi Hiroshima city, Hiroshima city, Shobara city and Kake where the Nukui Lake was constructed. Expanded AMeDAS weather data from these four locations were adopted in simulation. According to the Japanese climate regions, Kake, Hiroshima city and Higashi Hiroshima city belonged to the IV region, while Shobara city was classified into the III region [12].

A two-floor model with an area of 125.9 m^2 was created with reference to the standard residential building of Architectural Institute of Japanese (AIJ) [13]. The main rooms in the first floor were living room, dining kitchen (LDK) and Japanese style room. The main bed room and two kid rooms were designed at the second floor. The total window area was 24.1 m^2 which accounted for 19.2 % of the wall area. Additionally, the thermal performance of the residential building was represented by thermal loss coefficient Q. According to the residential building energy saving code [12], the required Q value in the IV region was 2.7 W/(m^2 · K). To conduct a comparative study, the calculations under Q values of 1.6 and 3.6 W/(m^2· K) were also performed. Heating period was set from December 1st to March 31st and the cooling period was predefined from July 1st to September 30th. The operation schedule of heating/cooling system in each room during weekday and weekend was shown in Table 1. Heating and cooling site-point temperatures were 20 and 27 ºC, respectively. The air change rate for the adopted residential building was set at 0.5 ac/h.

2.2 Calculation Results

2.2.1 The annual heating/cooling load

The hourly heating/cooling load and the outdoor temperature in Kake with Q value as 2.7 W/(m^2· K) are shown in Fig. 2. It could be observed that the period of outdoor temperature in winter below zero was long. It was distinctive that the heating load was larger in comparison with the cooling load. The peak values of the heating and cooling loads were 23.1 kW (January 29th) and 8.5 kW (July 30th), respectively. All the calculation results in four locations and with three Q values were summarized in Table 2. At the same Q value, heating load was arranged in an increasing order as Hiroshima, Higashi Hiroshima, Kake, and Shobara. Conversely, the cooling load decreased according to this order. The cooling load of Hiroshima was the highest. The heating load significantly increased and cooling load minimally varied with the reduction of Q value. The heating load was higher than cooling load in all locations when the Q values were 3.6W/(m^2· K) and 2.7 W/(m^2 · K). In Shobara, Kake and Higashi Hiroshima, the heating load approximately covered 80 percent of the total amount of load. This ratio was around 60% for Hiroshima. The cooling load exceeded the heating load in Hiroshima at higher insulation level when Q value was adopted as 1.6 W/(m^2· K).

2.2.2 Characteristics of heating load

Figure 3 shows the distribution of the hourly heating load frequency at various conditions of the locations and insulation levels. Although the high-heating load over 10 kW could be seen, they usually occurred at the starting stage of air conditioning system. Under the conditions of low insulation level (Q=3.6 W/(m^2· K)), the period for the high heating-load over 10 kW was 259 hours in Shobara and 104 hours in Hiroshima. The period of high heating-load over 10 kW was largely reduced once the insulation level was improved. In exception of the above high heating-load situations at the starting running stage,

Table 2 Annual heating/cooling load for all cases

Q Value		Annual Heating/Coling Load [GJ]			
		Kake	Hiroshima	Higashi Hiroshima	Syobara
3.6	Heating	27.9	18.4	25.0	29.5
	Cooling	4.2	9.6	5.5	4.1
	Sum	32.2	28.0	30.4	33.6
2.7	Heating	19.2	11.0	16.4	20.2
	Cooling	4.2	9.5	5.5	4.0
	Sum	23.4	20.5	21.9	24.2
1.6	Heating	8.2	2.5	5.8	8.4
	Cooling	4.2	9.5	5.6	4.1
	Sum	12.3	12.0	11.4	12.5

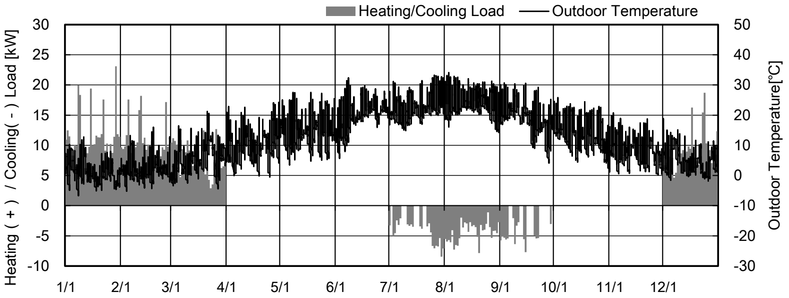


Fig.2 Hourly heating/cooling load and outdoor temperature (Q=2.7 W/(m^2· K))

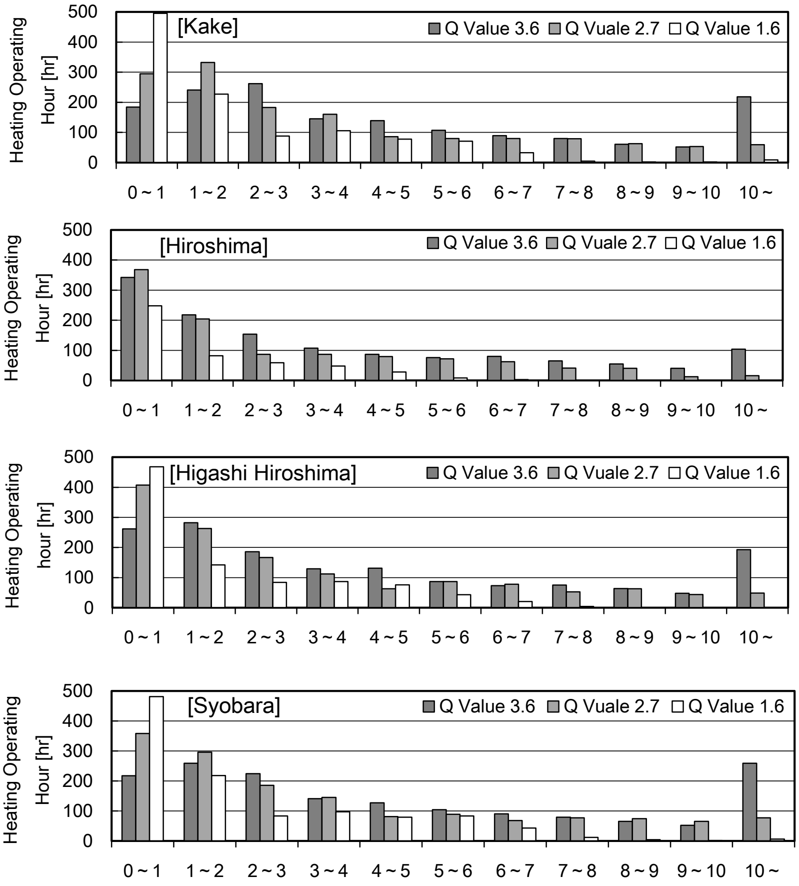
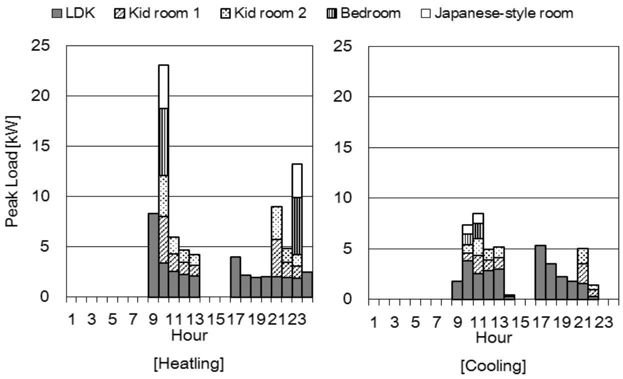


Fig.3 The frequency distribution of heating load



[Heatling]

[Cooling]

Fig.4 Heating/cooling peak load (Kake, Q=2.7)

the lower the load was, the larger frequency of the heating load occurrence became in all cities at three levels of insulation condition. Consequently, it is necessary to consider the impact of partial load operation on the rated COP for the evaluation of the annual performance of heat pump system and the air conditioner.

2.2.3 Peak load characteristics

Figure 4 displays the peak heating/cooling load in Kake when Q value is 2.7 W/(m^2· K). The peak values for the heating and cooling load appeared at 10 am in January 29th (Weekend) and 10 am in July 30th (Weekend), respectively. It was indicated that the coincidence operation of air conditioning in different rooms also affected the peak load in exception of the severe climate conditions.

3. THE PERFORMANCE OF LAKE WATER AS HEAT SOURCE OF HEAT PUMP

3.1 Outline of System

At heat source side in Fig 1, the ② heat transfer coil submerged in the lake indirectly exchanged heat with the surrounding water as shown in Figure 1. In addition, the exchanged heat was directly or indirectly served as the heat source of heat pump system for the ④ user side such as residential buildings or commercial buildings. Currently, water source heat pump was not widely employed for residential buildings. The ground source heat pump machine could be operated under a wide range of heat source temperatures. Thus, the ground source heat pump was also believed to be applicable when the water was used as the heat source.

In the ④ user side, central heating and cooling methods of fan coil unit or warm water floor heating system were employed. The mode of air heat source system was selected as the comparison object. Specially, one approach was that the air conditioners was installed in each room for heating and cooling. The other one was the air source heat pump used for heating in winter and the air conditioners for cooling the space in summer.

3.2 Characteristics of Heating Source Equipment

Table 3 listed the rated capacity and COP of three heat source machines of lake water source heat pump, air source heat pump, and dispersive air conditioner. The temperature condition in user side was 40 °C during heating period and was 7 °C during cooling period. Firstly, the lake water source heat pump could be carried out under the partial load condition due to the compressor equipped with inverter system. COP of lake water source heat pump could be determined using Eqs. (1) and (2) under various load conditions and temperatures of heat source side/user side [14]. The energy consumption of pump at heat source side and user side were included in the evaluations.

Heating:

$$COP = -0.0650Q_{load} + 0.110T_{1in} - 0.114T_{2out} \tag{1}$$

Cooling:

$$COP = -0.0280Q_{load} - 0.192T_{1in} + 0.232T_{2out} \tag{2}$$

where, COP is the coefficient of performance (dimensionless), Q_{load} is heating/cooling load (kW), T_{1in} is the temperature of backwater at heat source side (°C) and T_{2out} is outlet temperature at user side (°C).

The air conditioner had been selected for each room with reference with the new maker catalog according to the calculated peak loads in section 2.2.3. The specification of air conditioner in each room was different due to the variable peak load. The selected air conditioner in Kake with Q value of 2.7 W/(m^2· K) can be seen in Table 3. The outdoor temperature and load rate influenced the COP value of air conditioner. Accordingly, COP could be decided using Eq. (3) proposed in previous study [15].

Table 3 Characteristic of heat source machines

		Rated Capacity [kW]		Rated COP [-]		Note
		Cooling	heating	Cooling	Heating	
Water Source Heat Pump (Ground Source Heat Pump of A company)		10.0	10.0	3.2	3.7	Rated COP is the value for compressor; Cooling: heat radiation side30°C、cold water7°C; Heating: heat absorption side0°C、warm water35°C
Air Source Heat Pump (B company)		—	6.0	—	4.0	Warm wate(supply/return): 40/22°C、Outdoor side:7/6°C、Flow rate:5l/min
Air-conditioner	LDK	Based on the catalogs from maker				Cooling: indoor side27/19°C、outdoor side35/24°C; Heating: indoor side20/15°C、outdoor side7/8°C
	Japanese style room					
	Bedroom					
	Kid room 1					
	Kid room2					

$$COP = COP_r \times c_l \times c_o \tag{3}$$

where, COP_r is the rated COP (dimensionless), c_l is the revised coefficient of partial load (dimensionless), and c_o is the revised coefficient of outdoor temperature (dimensionless).

Finally, the COP of air source heat pump at various outdoor temperature and partial load conditions could be expressed in Eq. (4) [16]. The floor heating was adopted in user side for winter. The air conditioner was used to cool the space in summer. The evaluation on COP of the air conditioner could be found in Eq. (3) mentioned above.

$$\begin{aligned}
&COP = f(T_o)/f(7) \times (c_1 r^3 + c_2 r^2 + c_3 r) + 1.0 \qquad (4)\\
&f(T_o) = 0.11715T_o + 2.5178\\
&r = Q_{load}/Q_{ca}, c_1 = -0.120389T_{2out} + 11.270\\
&c_2 = 0.45852T_{2out} - 33.397, c_3 = -0.40182T_{2out} + 26.888
\end{aligned}$$

where, T_o is the outdoor temperature (°C), r is the load rate (dimensionless) and Q_{ca} is the rated capacity (kW).

3.3 Heat Source Temperature

The temperature of lake water varied in accompany with the heat absorption and release when the lake water was employed as the heat source. However, the temperature of lake water in this paper was regarded as a constant from the measured results without considering the influence of heat absorption and release. Figure 5 shows the measured hourly temperature of lake water at surface, at depth of 15 meter and at the bottom of lake between July and December in 2007. The average temperature of water at focused depth of 15 meter as 17.7 °C in summer (from July to September) and 11.5 °C in winter (December) were used as the temperature of water heat source in the evaluation. In the case of air source, the AMeDAS weather data was adopted in the evaluation.

3.4 Potential of Lake Water Heat Pump

Figure 6 shows the temperature of heat source plotted against the electricity consumption and average COP in Kake with Q value of 2.7 W/(m^2· K). Under heating condition, the COP increased and electricity consumption reduced with the rise in temperature of heat source. The average value of COP was 3.5 and electricity consumption was 1279 kWh when the temperature of lake water was 11.5 °C in the heating period. Conversely, the lower the heat source temperature was, the better the performance of water source heat pump became under the cooling condition. The slope of the heat source temperature and COP curve in cooling condition was larger than that determined in heating condition. The reduction in heat source temperature would largely improve energy saving performance.

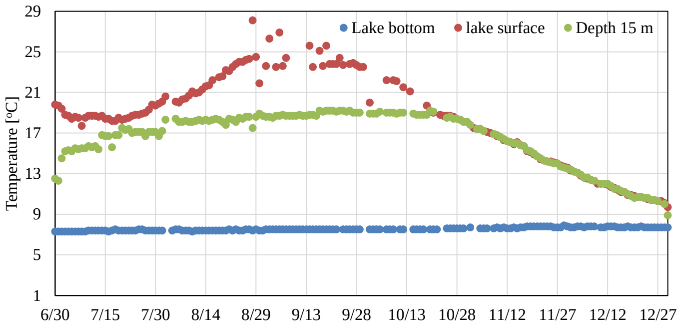


Fig. 5 Measured temperatures of lake water

The average value of COP was 4.87 and electricity consumption was 199 kWh when the temperature of lake water was 17.7 ºC in cooling period.

The performance of water source heat pump was examined in four selected locations at a fixed heat source temperature. The heat source temperature in Kake was the measured value as shown in Section 3.3. In Kake, the differences between the annual average outdoor temperature and the average lake water temperature in summer and average lake water temperature in winter were 5.2 ºC and -1 ºC. Thus, the values of heat source temperature in other three locations were simply assumed to be the summation of individual average outdoor temperature and the temperature difference of summer and winter obtained from Kake. Figure 7 displays the average COP during heating/cooling period in four locations at three levels of insulation. It was noted that the difference of COP in four locations was minimal as 0.5 under the same Q value. Under cooling condition, the variation in average COP was minor with different Q values irrespective of the locations. The COP exhibited a decreasing tendency with the reduction of Q value under heating condition. It was attributed to that the efficiency was diminished due to the long period operation at low load rate under smaller Q value.

Figure 8 shows the annual performance of the three adopted heat source machines in all the four locations with Q value of 2.7 W/(m^2· K). The arrangement order of electricity consumption from low to high in all locations was: lake water source heat pump, air source heat pump and air conditioner. The efficiency was highest when the lake water source heat pump was used. Especially for cooling condition, the energy consumption was reduced by 60-70% in comparison with the value calculated from air conditioner. The obvious efficiency of energy saving was resulted from the higher COP under the adopted range of lake water temperature.

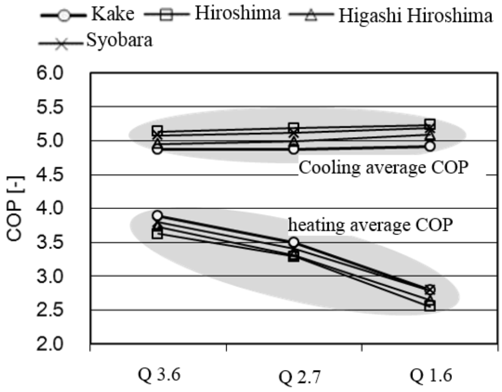


Fig. 7 Average COP of lake water heat pump

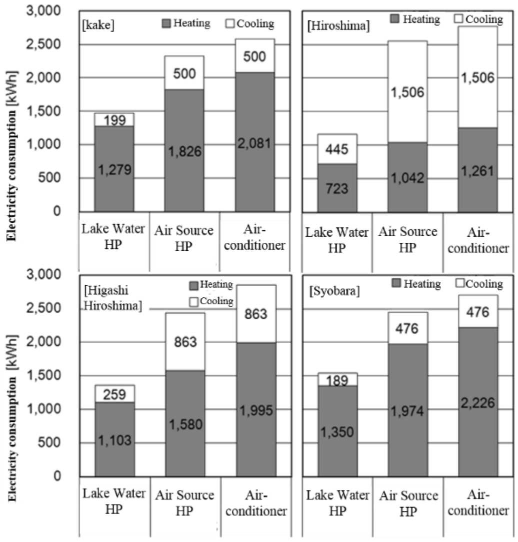


Fig.8 Annual performances of three systems in four locations

Under the heating condition, the lake water heat pump could approximately save 30-32% of the energy in comparison with the same central-controlled mode of air source heat pump. This energy saving percent increased to 39-45% in comparison with the air conditioner. Besides, the energy consumption of defrost was not included in Eq. (4) for the performance evaluation of air conditioner. Thus, a higher application performance of lake water heat pump could be obtained.

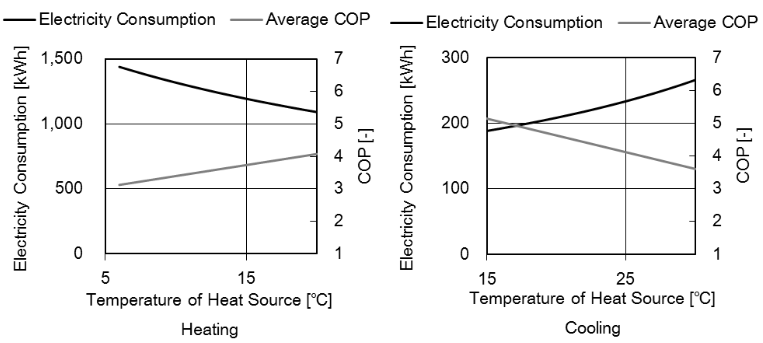


Fig. 6 The relationship between the performance of lake water heat pump and heat source temperature

4. CONCLUSION

Unutilized energy adopted as heat source of heat pump system is considered as an efficient approach to reduce the relevant energy consumption with respect to heating/cooling. This paper concentrated on the utilization of lake water which was regarded as one of surface water. The potential of lake water source heat pump system used in a residential building was also evaluated in this study. Heating/cooling loads were calculated using a typical Japanese residential building. The heating load was dominant in the residential building. The heating load exhibited the decreasing tendency but cooling load minimally varied with the rise in insulation level. The air conditioning was majorly operated at low load level in expectation of the occasional high load level at the starting running stage of air conditioning. The energy efficiency of lake water source heat pump was examined through a comparison study among the air source heat pump and dispersive air conditioner system. The energy saving effect for lake water heat pump could attain 60-70% and 30-45% during the cooling and heating periods, respectively. The influence of heat adsorption and release on the temperature of water heat source should be investigated in further study.

5. REFERENCES

[1] Zhang, Y., He, C. Q., Tang, B. J., & Wei, Y. M., China's energy consumption in the building sector: A life cycle approach. Energ. Buildings, Vol. 94, 2015, pp. 240-251.

[2] Schlueter, A., & Thesseling, F., Building information model based energy/exergy performance assessment in early design stages. Automat. Constr., Vol.18, No.2, 2009, pp. 153-163.

[3] Hong, T., Chou, S. K., & Bong, T. Y., Building simulation: an overview of developments and information sources. Build. Environ., Vol. 35, No.4, 2000, pp. 347-361.

[4] Ministry of Economy, Trade and Industry, Japan: a white paper of energy, 2013 (in Japanese)

[5] ASHRAE, Geothermal energy, in: ASHRAE Handbook HVAC Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2003, pp. 11-28.

[6] IEA Heat Pump Centre, Ground-source Heat Pump Systems, in: IEA Heat Pump Centre Newsletter, 2005, pp. 23-4.

[7] Zou, S. & Xie, X., Simplified model for coefficient of performance calculation of surface water source heat pump. Appl. Therm. Eng., Vol. 112, 2017, pp.201–207.

[8] Rubio, D., López-Galindo, C., Casanueva, J. F., & Nebot, E., Monitoring and assessment of an industrial antifouling treatment. Seasonal effects and influence of water velocity in an open once-through seawater cooling system. Appl. Therm. Eng., Vol. 67, No.1, 2014, pp. 378-387.

[9] Watanabe, K., Study on energy saving effect at a district heating and cooling plant utilized with unused energy, J. Environ. E., AIJ, No. 607, 2006, pp. 79−86.

[10] Kunimatsu, Y., Planning and Evaluation of the DHC system using Thermal Energy of River Water (Part1-11), Proceeding of the Society of Heating, Air-Conditioning Sanitary Engineers of Japan

[11] Büyükalaca, O., Ekinci, F., & Yılmaz, T., Experimental investigation of Seyhan River and dam lake as heat source–sink for a heat pump. Energy, Vol. 28, No.2, 2003, pp. 157-169.

[12] Takamoto Y., Next-generation energy saving reference, the society of Heating, Air-conditioning Sanitary Engineers of Japan, No.74, 2000, pp. 543-550

[13] Mitsuhiro, U., The proposal of standard sentences (Standard sentences for residual building), Proceeding of the 15th heating symposium of the Architectural Institute of Japan.

[14] Sayaka T., Prediction of the annual heating/cooling performance in a Low Energy House. Proceeding of Annual conference in Hokkaido branch of the Society of Heating, Air-conditioning and Sanitary Engineers of Japan, 2007.

[15] Tanaka,T., Sakamoto, Y., Sawachi, T., Hosoi, A., Hasegawa, A., Standardization of method for Calculating amount of energy used by residential air Conditioner: Part-2 focus on Load rate and energy consumption. Proceeding of the Annual conference of the Architectural Institute of Japan. 2008, pp.1107-1108.

[16] Ogawa, T., Ida, H., Kindaichi, S., Kim, S., Akamine, Y., Mae, M., Sakamoto, Y., Application of air source heat pump for hydronic floor heating system: Part-2 Partial load characteristics of heat pump unit. Proceeding of the Annual conference of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. 2008, pp.1687-1690.