# THE HEAT TRANSFER CHARACTER ANALYSIS AND SOFTWARE PROGRAM DESIGN FOR LAKE WATER-SOURCE HEAT PUMP SYSTEM

*Yunqing, Fan, PhD student, Dep. Energy and Environment Engineering, Interdisciplinary Graduate School of Engineering Science, Kyushu University (Fukuoka, Japan)*
*Jun, Lu, Professor, Critical Laboratory of Three Gorges Reservoir Region's Eco-Environment of Ministry of Education, Chongqing University (Chongqing, P.R. China)*
*Tetsuo Hayashi, Professor, Energy and Environment Engineering, Interdisciplinary Graduate School of Engineering Science, Kyushu University (Fukuoka, Japan)*
*Chuck, Yu, Professor and Executive Director, International Society of the Built Environment (ISBE), (Milton Keynes, UK)*

**Abstract:** In this paper, the principles and methods for designing a software program are demonstrated. The program simulates the thermal performance of a shallow lake that functions as a supplemental heat rejecter of ground water-source heat pump systems. Chongqing, one of the municipalities in China, has an advantage to apply water-source heat pump system due to the abundant water resources in its area. As the water is one of renewable energy resources, the application of water-source heat pump system would contribute to the reduction of greenhouse gas emissions and the amelioration of the adverse impact to built environments. The developed software was applied to the project to reconstruct a school building in Chongqing. The programming, verification, parameter testing and optimization of the software are shown in this paper. The energy saving rate of the ground water-source heat pump system against an electrically heated boiler is predicted as could be 74.86% and that is equivalent to 432375.2 kW·h of electricity consumption. The software also predicts the environmental effect. Decrease of water temperature by 0.62°C during the operation of the lake water-source heat pump system satisfies the environmental protection requirement in Chinese standard GB3838-2002.

**Key words: Lake water-source heat pump, Computer simulation analysis, energy conservation, software development, heat transfer characteristics**

## 1 INTRODUCTION

In the viewpoint of the primary energy usage and electricity consumption, ground water-source heat pump (GWSHP) systems become increasingly popular in both heating and cooling with their higher energy efficiency comparing with conventional systems, and this can alleviate a large part of the primary energy consumption for building operation (Berntsson 2002) (Chen et al. 2006) (Lu et al. 2010) (Lu and Wang 2007). Due to the appearance of various intelligent software for heating, ventilating and air-conditioning (HVAC) system design, green building energy simulating technology have been optimized in the last decade (DOE 1998) (Henninger et al. 2004) (Zhai 2006). Base on the operation platform of Microsoft Visual Studio.net; a software for the design and assessment of GWSHP systems has been developed by using C# language in our laboratory (Fan 2010). The objective of this work was to exploit a design and simulation tool, the software in short, for modelling the performance of a shallow lake as a supplemental heat rejecter which has been usefully and cost-effectively integrated into a ground water-source heat pump system. The software demonstrates the

feasibility of using shallow lake as the supplemental heat rejecters for GWSHP systems based on economic benefit as well as the environmental impact.

## 2 PROJECT DESCRIPTION

### 2.1 Project Introduction

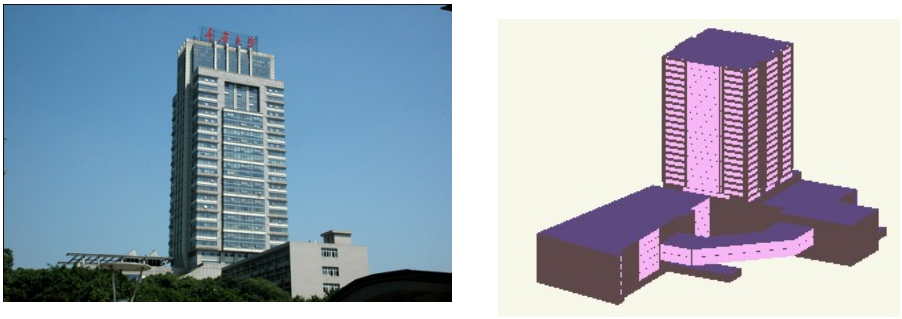


**Figure1: The simulative model of building**

The objective building and its simulative model are presented in Figure 1. The building has a coverage area of $7x10^4$ square meters and consists of underground, podium and upper floor tower levels. The calculated summer cooling load with DeST (Designer's Simulation Toolkit) was 8900kW, while the winter heating load was 1100 kW. Designer's Simulation Toolkit (DeST) software was developed by Tsinghua University (Chen and Jiang 2008) (Yang and Jiang 2005) as one of those sophisticated building thermal performance simulation. It optimizes the thermal performance of building fabrics and the indoor thermal interference. While sunshade, ventilation and sky radiation are considered comprehensively, the indoor thermal interference coming from personnel, lighting and equipment are fixed in the room type.

In order to adequately dissipate the imbalanced annual energy loads, a shallow artificial lake is installed as a heat rejecter of a water-source heat pump. The area of the lake is approximate 1x104 $m^2$, its mean depth is 2.5 meter and the annual relative stable water temperature is around 16-23°C which was ideal for the dissipation of heat loads (Andrew 2000). The outdoor air temperature in the city of Chongqing during the building simulation period, was 5.2°C in the winter and 37.5°C in summer (Climatic Data Centre 2005). Therefore, the lake water temperature would be much lower than the ambient air temperature in summer and higher than that in winter.

### 2.2 Model Parameter

The component parameters used for the project are shown in Table 1. The hourly cooling and heating load through a year (8760 hours) computed by DeST is used as the input data for the parameter of GWSHP systems software. The static water energy balance mainly depends on the heat exchange at the water surface such as solar heat gain, water evaporation and long-wave radiant heat exchange. Therefore, the ambient parameters should be included solar radiation, sky (atmospheric) radiation, dry-bulb temperature and either wet-bulb temperature or relative humidity.

**Table 1: Analogue input**

| Items | Input values |
|---|---|
| Heating time | 12-1~2-28 |
| Heating load | 1100 kW |
| Type of HPs | screw compressor |
| Number of HPs | 1 |
| Heating capacity | 1200 kW |
| Water draw temperature difference | 5°C |
| Water draw height difference | 15.06 m |
| Pump head | 37 m |
| Number of pumps | 2 |
| Pump power | 45 kW |

## 3 MODEL DEVELOPMENT

### 3.1 Water Temperature Model

Thermal stratification in water is caused by buoyant force due to density difference, its greatest density is at 4ºC (39.2ºF). However, the thermal stratification in ponds and lakes is only observed when their bottom is deeper than 6.1-9.1m (20-30ft) and its inflow rate is low. Therefore our simulation assumes that thermal stratification of shallow water can be neglected and the seasonal changes regard to its temperature-density profiles is remained steady state within Epilimnion (4 meters underneath the water surface). Base on the first law of thermodynamics, water temperature modelling for the supplement heat rejecter of GWSHP system has been developed using the DeST tool (Chen and Jiang 2008) as shown in Equation (1):

$$\rho V \mathrm{c}_p \frac{dT}{dt} = \sum \varphi_n = \varphi_{in} - \varphi_{out} \tag{1}$$

where $\varphi_{in}$ is the heat transfer to the lake (W/m$^2$), $\varphi_{out}$ is the heat transfer from the lake (W/m$^2$), $V$ is the lake volume (m$^3$), $\rho$ is the density of the lake water (Kg/m$^3$), $\mathrm{c}_p$ is the specific heat capacity of the lake water (KJ/(kg ºC)), and $dT/dt$ is the temperature change rate of the lake water. This approach assumes that temperature gradients in water can be neglected. Considering more practical heat transfer mechanisms, Equation (1) can be changed as:

$$\frac{dT}{dt} = (\varphi_{sr} + \varphi_{ar} - \varphi_{wr} - \varphi_e - \varphi_c \pm \varphi_{gr} \pm Q) / \rho V \mathrm{c}_p \tag{2}$$

Each heat transfer term used in Equation (2) is defined as follows;
$\varphi_{sr}$ is solar heat gain (W/m$^2$), $\varphi_{ar}$ is radiation heat from the atmosphere (W/m$^2$), $\varphi_{wr}$ is radiation heat from water surface (W/m$^2$), $\varphi_e$ is the heat/mass transfer due to evaporation (W/m$^2$), $\varphi_c$ is convective heat transfer from air (W/m$^2$), $\varphi_{gr}$ is the heat transfer to/from the ground surrounding the water (W/m$^2$), and $Q$ is inlet/outlet heat due to building air-conditioning load (W/m$^2$).
Endothermic or exothermic parameter $Q$ was assumed that the hourly air-conditioning load

disperses into whole lake water as natural heat equilibrium model. An integrative boundary condition coupling natural heat gains and anthropologic heat load is utilized for unsteady heat transfer calculation as shown in Equation (3). By a finite sequence of computational mathematics operations, every immediate water temperature can be calculated through iteration of $\Delta t_j$ (temperature incremental per second) and $\Delta \tau$ (time increment). The Net Calorific Value of the system can be calculated via Equation (4) which uses algebraic superposition of hourly natural heat gain and air-conditioning load exhausted by heat pump system.

$$\Delta t_j = \frac{\varphi_{j-1} + Q_{j-1}}{\rho c_p V} \Delta \tau \tag{3}$$

$$Q_T = \sum (Q_i \frac{EER+1}{EER} + \varphi_n + E_g) - \sum (Q_i \frac{COP-1}{COP} - \varphi_n + E_g) \tag{4}$$

### 3.2 GWSHP Unit Energy Consumption Model

The GWSHP unit energy consumption model is shown below as Equation (5):

$$f_1 = N \sum_{i=0}^{2} \sum_{j=0}^{2} D_{ij} (T_{cl} - \overline{T}_{cl})^i (T_{el} - \overline{T}_{el})^j \tag{5}$$

Where, $f_1$ is actual power of heat pump unit (kWh), *N* is nominal power of heat pump unit (kWh), $T_{cl}$ is inlet cooling water temperature (ºC), $T_{el}$ is inlet chilling water temperature (ºC); $\overline{T}_{cl}$ is mean value of cooling water temperature parameter (ºC), $\overline{T}_{el}$ is mean value of chilling water temperature parameter(ºC), and $D_{ij}$ is a regression coefficient which is dependent on the practical performance of the heat pump unit.

The performance of heat pump unit is influenced not only by the operative thermal levels but also by the building requirement to operate the heat pump unit under partial loads. The reference (Ding et al. 2009) reported the importance to consider the influence of partial load operation on long term efficiency of the equipment. As most of air conditioning systems are not limited to operate merely under full load, taking the relation between load rate and time-frequency into account is a preferable way to reflect the influence of partial load operation. Practically taking $\eta_i$ and $\eta$ into account, the performance of heat pump system can be estimated. Where, $\eta_i$ is the percentage rate of full load power divided by input power and $\eta$ is ratio of load condensation.

### 3.3 Water Extraction System Model

Heat pumps can provide wintertime heating by extracting heat from a source though a drafting system and transferring it to the building. Two kinds of water piping systems (open type and close type) that were well known as ground water-source heat pump systems water supply network (ASHRAE 2006). Direct exchange systems circulate refrigerant underground, closed loop systems use a mixture of anti-freeze and water, and open loop systems use natural groundwater.

In the open loop model, the power of water intake is calculate by Equation (6)

$$P_s = \frac{q_i \times (H_i + S \times q_i^2) \times \rho \times g}{3600 \times 1000 \times \eta_0} \quad (6)$$

Where $P_s$ is hourly water intake power (kWh), $q_i$ is hourly required volume ($m^3/h$), $H_i$ is drift elevation (m), and $\rho$ is water density ($kg/m^3$). Symbol $S$ is piping impedance which can be approximately solved based on the pump parameter and design drift elevation in engineering ($h^2/m^5$), $\eta_0$ is total efficiency when pump is operated in various speed, the average value is 0.6. In the close loop model, the power of water intake is calculate by Equation (7):

$$N_P = \frac{\Delta H G}{367 \eta_P \eta_m} \quad (7)$$

Where $N_p$ is hourly water intake power (kWh), $\Delta H$ is piping integrative impedance $(\mathrm{m})$, $G$ is cycle volume ($m^3$), $\eta_P$ is total pump efficiency, and $\eta_m$ is total efficiency.
The total resistance of close-type water supply network is consisted of coil resistance and heat exchanger resistance of heat pump unit. It can be calculated via Hazen-Williams empirical Equation (8):

$$\Delta H = 6.8193 L_P \left(\frac{u}{C}\right)^{1.852} D_i^{-1.167} \quad (8)$$

Where $\Delta H$ is piping synthesize impedance (m), $L_P$ is coil length (m), $D_i$ is internal diameter (m), $u$ is tube velocity (m/s), and $C$ is pipe wall roughness coefficient.

## 4 DESIGN AND SIMULATIVE SOFTWARE

This software was based on the operation platform of Microsoft Visual Studio.net and its main purpose is to produce design and assessment software for Ground water-source heat pump systems.
Figure 2 presents the main interface of the software (Lu. et al. 2010). This software is appropriate for the river water heat pump system as well as the lake water heat pump systems.




**Figure 2: The main interface of software**

The basic modules involves the numerical solutions of equations for different parts of a total heat pump system, and provide four types of basic functions as illustrated in Figure 3.

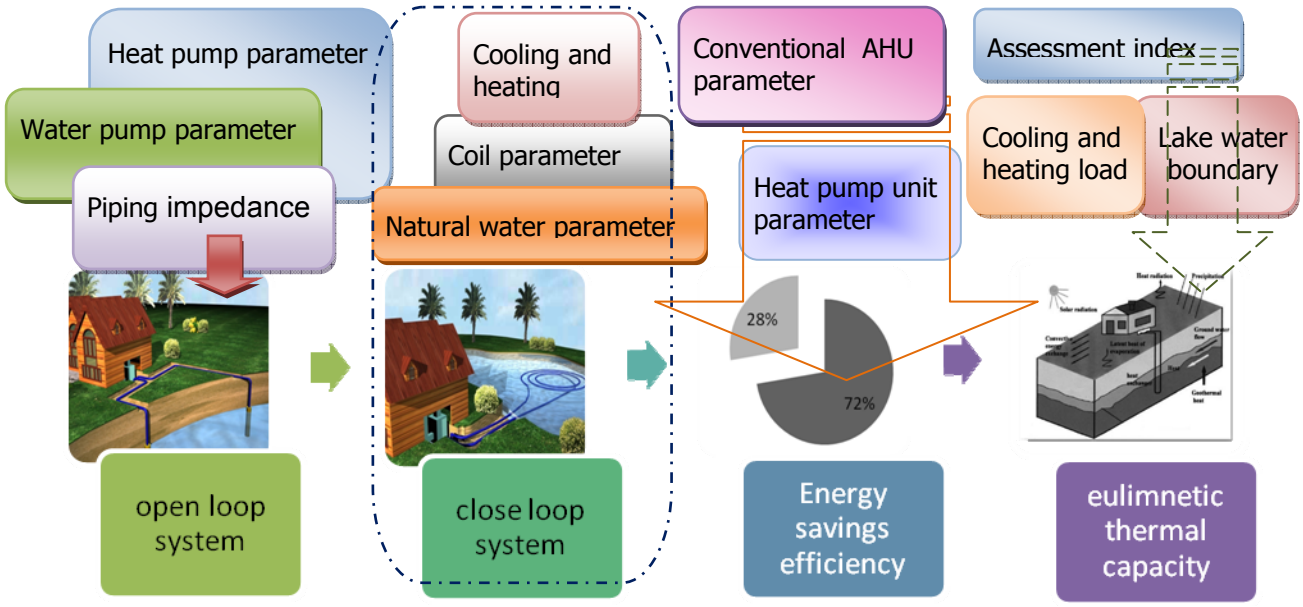



**Figure 3: Basic functions of software**

According to the various needs of users who intend to apply GWSHP systems, this design and estimation software includes subsystems such as energy consumption of heat pump unit, piping dynamic model for open/close type, pipe and coil design, thermal capacity analysis of eulimnetic lake wate, comparison of total energy saving ratio with traditional air-conditioning.

## 5 RESULTS AND DISCUSSIONS

A review of the energy consumption and coefficient of performance (COP) is given in Table 2, targeting the building previously shown in Section 2.1. Based on the research scope of the "Heat Pump and water draw pump" system, the conventional air conditioning system would consume as much as 54043 $m^3$ natural gas in winter and the annual energy consumption is 72.47 tons standard coal. The constant flow rate heat pump system would reduce energy consumption by 12.35 tons standard coal, 28.1% of energy saving rate, and reduce carbon dioxide emission by 49.89 tons during the winter. The energy saving rate via variable flow heat pump system reaches up to 74.86% and energy saving amount is 33.62 tons standard coal and 133.6 tons carbon dioxide emission is reduced. In accordance with the commercial electrical price of ¥0.843 RMB/kWh and natural gas as ¥2.21 RMB/$Nm^3$, the operating costs of the water-source heat pump for heating would be ¥2,248,000 RMB lower than the conventional fuel gas boiler.

**Table 2: Energy consumption and COP of heat pump system**

| Items | Winter ( Constant /Variable flow ) |
|---|---|
| Heat load summary ( kW·h ) | 427217.5 |
| Water draw amounts ( $m^3$ ) | 111360 / 74709 |
| Energy consumption for pumps ( kW·h ) | 39150 / 15627 |
| Energy consumption for HPs ( kW·h ) | 120460.8 |
| Energy consumption for system ( kW·h ) | 184671.8 / 120004.6 |
| Energy efficiency for HPs ( COP ) | 3.9 |
| Energy efficiency for system ( System COP ) | 2.31 / 3.56 |

Note: Air conditioning period: Dec 1th~Feb 28th. Statistical data only include HPs and water draw pump

According to the "ground surface environmental Quality Standard" (GB 3838-2002), the thermal capacity was stipulated as the maximum weekly temperature rise in static water and should be not more than 1°C during the summer; while in the winter, a maximum temperature drop, weekly, should be not more than 2°C. The "satisfaction" in the report only appears when both of the two conditions were accomplished. Temperature fluctuation during operating time of heat pump system is shown in Table 3. The maximum temperature drop of 1.26°C per week satisfied the requirement of the energy efficiency and engineering assessment of GB 3838-2002.

**Table 3: Temperature during operating time of heat pump system (**°C**)**

| Temperature fluctuation (°C) | | | | | | | Actual total temperature jump (°C) | maximum hebdomadal temperature rise (°C) |
|---|---|---|---|---|---|---|---|---|
| Summer | Apr | May | Jun | Jul | Aug | Sep | 0.1900 | 0.0091 |
| | -0.0053 | 0.0039 | 0.0059 | 0.0072 | 0.0127 | 0.0274 | | |
| Winter | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | -1.209 | -0.6160 |
| | 0.0137 | -0.4923 | -0.0507 | -0.1510 | -0.6941 | -0.2168 | | |

Note: Air conditioning period: May 1th-Sep 30th for Summer, Dec 1th Feb 28th for Winter.

## 6 CONCLUSIONS

In this work, a design and evaluation software for lake water source heat pump systems was developed and applied to the test. The software evaluates the system performance, energy conservation and economical benefits of a high-raised building in Chongqing.

The software calculates the performance of heat exchange, coefficient of energy distribution and water importing system of heat pump. Comparison of system cost and energy consumption between the heat pump system and a traditional system shows that the energy saving ratio using this lake source heat pump system is 74.86%.

The capacities of heat supply and extraction of heat pump systems are evaluated using *Ground surface environmental Quality Standard*. According to the prediction of environmental effect during the design stage of the building, the maximum weekly temperature decrease in winter is 0.616°C, which is consistent with the normal regulation for heat pump system and this satisfied the environmental protection requirement of the Chinese standard GB3838-2002.

By modelling and dynamic loading, the transient temperature change under the effects of

importing and exporting heat in building was analysed. This demonstrates the feasibility of the system and the effectiveness for reducing cost and environmental impacts against conventional HVAC system.

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