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New optimized model for water temperature calculation of river-water source heat pump and its application in simulation of energy consumption

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A B S T R A C T

The energy consumption calculation plays an important role in the analysis of project economic and social benefits. In order to calculate energy consumption accurately, this research presents a water temperature of condenser inlet calculation model of river-water source heat pump unit. The feasibility and calculation error of the model had been analyzed. Additionally, the new water temperature calculation model had been validated via an engineering case. The results showed that the hourly water temperature in 24 h could be replaced by daily average water temperature due to little change of the daily water temperature change. In this case, the calculation error could be less than 5%. It is found that despite water temperature has many influenced factors, there is a remarkable relationship between the daily average water temperature and daily average outdoor dry bulb temperature by data analysis ($R^2 \approx 0.9$). The influence of river sampling location on water temperature calculation of condenser inlet could be ignored due to slight temperature changes (within 0.15 °C). The method proposed in this paper met the engineering accuracy and provided a very effective method for the engineering calculation of energy consumption of water chilling unit.

1. Introduction

Energy efficient use has been paid more and more attention to internationally in recent years due to the limited preservation of existing fossil energy resources and urgent demands in slowing down anthropogenic climate change. A scientific and dynamic model was required to calculate the dynamic energy consumption of air conditioning system, which could further optimize the energy saving design and management of air conditioning system [1]. The energy consumption of water chiller, as the major energy consumer in central air conditioning system, approximately accounted for 50%–60% of electric loads [2]. Therefore, the energy consumption calculation of water chiller plays an important role in the analysis of project economic and social benefits, as well as in the selection of cold sources [3].

The coefficients of performance, including IPLV (Integrated Part Load Value) and NPLV (Non-Standard Part Load Value), had been frequently used to predict operation energy consumption of the host. Yao et al. employed the IPLV of air-conditioning system of the public building to evaluate operation status of air-conditioning system host by adding IPLV weight number [4]. Yuan et al. also found it is very hard to evaluate the host energy consumption just by using IPLV and makes the compatible analysis of the energy efficiency and thermodynamic perfectibility gradient of energy efficiency standards for different air conditioning products [5]. As already pointed out by Bettanini et al. [6], machines part load performance are seldom used and supplied. The IPLV or NPLV is only limited to the occasion with one unit running in the building. Therefore, the IPLV or NPLV had no practical significance for the occasions with two or more units [7,8]. The software of EnergyPlus, TRNSYS and DOE-2 were widely international recognized building energy simulation. Rahmi et al. investigated the energy consumption by EnergyPlus [9]. R. Chargui et al. conducted the numerical simulation of a cooling tower coupled with heat pump system associated with single house by using TRNSYS [10]. However, it is very difficult to input the actually selected cold and heat source

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List of symbols

$EER_i(h)$	the i-th capacity refrigeration coefficient of performance of the host hourly, W/W
$EWT(h)$	the hourly water temperature of condenser inlet,°C
$PLR_i(h)$	the i-th capacity Part load rate of the host hourly,%
EWT_{max}	the highest inlet water temperature of the hottest month, °C
EWT_{mean}	the annual average inlet water temperature, °C
T_{amax}	the highest outdoor air temperature under design condition of air condition, °C
T_{amean}	the annual average outdoor air temperature, °C
$T_s(h)$	the hourly dry-bulb temperature of outdoor air, °C
$T_a(h)$	the river water hourly temperature, °C
$T_s(d)$	the daily average water temperature, °C
$T_a(d)$	the daily average dry-bulb temperature of outdoor air,°C
$Q(h)$	the hourly air conditioning load, kW
$P_{i,j}$	the rated cooling capacity of the host which is the No. j in capacity i, kW
$r_{i,j}$	the binary variables (0 representing stop, 1 representing start)
$\sum_{i=1,j=1}^{i=M,j=N} P_{i,j} \cdot r_{i,j}$	the sum of the rated power of all started equipment, kW
$E(h)$	the host hourly energy consumption of the water source heat pump, kWh
E_c	the refrigeration energy consumption of the water source heat pump, kWh

model, relevant control strategies and other detailed information during the application of above software, and that limited their application and promotion in practical engineering [3]. Moreover, there was poorer pertinence and accuracy in calculations used traditional methods of equivalent full load operation and BIN [11,12].

The energy consumption calculation of water source heat pump system was much more complicated in comparison with the traditional water chiller because the environment temperature fluctuation could affect the cooling load of air-conditioning system and water temperature of water source simultaneously. Furthermore, the inlet water temperature changes could lead to changes of the coefficient of performance of water chiller. The complicated energy consumption calculation of the hosts depended on such above coupling relationship. The complicated coupling relationships between air temperature, water temperature, the load of air-conditioning system and the coefficient of performance of water chiller could lead to the uncertainty of hourly inlet water temperature, which will finally lead to complex energy consumption calculation of host. Therefore, it was very necessary to develop accurate and practical energy consumption calculation model of water source heat pump system. While, hourly water temperature of condenser inlet is a key problem of water source heat pump energy consumption calculation.

The performances of water source heat pump system have been carried out experimentally and numerically. Young-Jin investigated performance enhancement potential of a seawater-source heat pump [13]. Byeong-Hak Park describes the importance of thermal dispersivity in designing groundwater heat pump (GWHP) systems [14]. By using a parallel micro-channel evaporator, the model of refrigerant distribution was validated by HF Tuo through experimental method [15]. Shu Haiwen has systemically investigated on the energy-saving judgment of electric-driven seawater source heat pump in the boiler house district heating system [16,17].

The Refs. [1,3,18] had specifically studied on the energy consumption calculation model of water source heat pump system. In addition to this, Luca et al. proposed a simplified model to evaluate the seasonal energy performance of water chillers and this mathematical model were a reliable tool to be implemented into dynamic building-plant energy simulation codes or into building energy certification tools [19]. Li Zhen et al. performed the numerical simulations of seawater temperature field by using a two-dimensional convection–diffusion equation model [20].

So far as we know, a simple and optimized method to obtain hourly water temperature of condenser inlet has not been investigated, especially for the Yangtze River. As a result, the energy consumption calculation model of water chiller was limited due to the lack of hourly water temperature data, which furthermore affected the application of water source heat pump system. To overcome this problem, a new optimized water temperature of condenser inlet calculation model of river-water source heat pump unit was proposed, and the effectiveness and accuracy were validated by a case project. This new optimized calculation model could be well employed to predict the energy consumption of river-water source heat pump units in case of lacking hourly water temperature data.

2. Proposing a new optimized model

2.1. Background of model

The performance of cold source equipment depend on a variety of factors, such as the structural design, load conditions, environmental conditions and control methods. While the accuracy and reliability of host performance calculation has a significant influence on the system energy consumption. During the practical operation, previously mentioned factors have been always changing; therefore dynamic numerical simulation is necessary. Currently, the regression model and physical model, as two kinds of cold source equipment models, have been widely applied. Regression model was generally employed in energy consumption simulation by obtaining the regression empirical formula. This formula could be deduced from the performance data provided by the equipment manufacturers, to further display the operation characteristics of cold and heat source equipment. Running load rates, cooling water inlet temperature, chilled water supply temperature are the critical factors to affect the performance of the refrigeration machine [21]. The energy efficiency ratio (EER) is often expressed as a function between inlet water temperature of condenser and inlet water temperature of evaporator in the form literature [22]. It is usually assumed that a host works at the designed water temperature when the energy consumption forecast is conducted. In this case, the temperature of water source heat pump chilled water was determined, and then the host load and water temperature of condenser inlet are the main factors affecting the refrigeration coefficient of performance EER refrigerator. Therefore, the EER of chiller could be expressed as a function of above two variables [21,23,24]:

$$EER_i(h) = F[EWT(h), PLR_i(h)] \tag{1}$$

As it's easier to obtain the hourly load rate, the key issue to calculate hourly energy consumption of water heat pump is to determine hourly water temperature of water source in typical meteorological year.