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Research Paper

Theory of energy level and its application in water-loop heat pump system

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HIGHLIGHTS

- Novel theory of saving energy and its application in water loop heat pump.
- Reverse energy caused by units to water loop and its solution.
- New method for determining the energy-saving range of water loop heat pump.
- Capacity model of auxiliary heat source and its size for all building types.
- Advice for reducing total energy consumption of water loop heat pump.

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ABSTRACT

It is a difficult problem to how to determine the reverse energy caused by units to water loop when a water-loop heat pump (WLHP) is in cooling and heating simultaneous mode, which not only has a great impact on energy-saving rate but also decides the use of auxiliary heat source in winter. This paper presents a theory of energy level to improve the research on WLHP system by using the relationship among building, circulating water and units. In this theory, the circulating water replaces building load as a new method to convert the reverse energy into energy change of circulating water and the equation of energy level also is built to determine the energy-saving range of WLHP system and report the capacity model of auxiliary heat source for all building types. An office building with different auxiliary powers is tested to analyze system operation characteristic and the effect of auxiliary heat source on unit and system and the results validate previous conclusions and suggest that an energy balance should be considered between units and auxiliary power to improve overall operation.

1. Introduction

Nowadays, the issues related to energy recovery [1–3] have evoked the wide interests among scientists and designers due to energy crisis and environmental concerns. As an energy-saving device heat pump can extract heat from the atmosphere, soil and water to provide heating and cooling for a building, so its theoretical [4,5] and applied [6–10] researches have become the frontier of engineering science.

With the development of water-source heat pump, the water-loop heat pump (WLHP) system [11–13] has successfully been applied in many countries and it uses a closed loop composed of small water-air heat exchangers to recover waste heat from a building to make up for heat loss. Circulating water simultaneously provides heating and cooling for different areas of the building in the system and its temperature is 16–32 °C according to the previous investigation [14]. Note that when the water temperature reaches the lower limit of the range an auxiliary heat source should be started to heat circulating water, similarly, a cooling tower also is switched on to remove the unwanted heat at the upper limit, and the schematic diagram of WLHP system is described in Fig. 1.

At present, the researches on WLHP system concentrated on analyzing its energy-saving rate and application area. Ma [15] proposed a static method of primary energy to build the dimensionless power equations and discussed the theoretical value of energy-saving rate by using heating load number *K*, and the method was general but it also had a certain limitation due to combined effect of cooling and heating load on coefficient Annamaria [16] used a dynamic simulation method to investigate the system operation in different European countries and reported its energy-saving rate and corresponding economic and environmental

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Nomenclature

ΔQ	building load [kW]
Δq	energy change of circulating water [kW]
ΔE	energy consumption of WLHP system [kW]
φ	transfer coefficient between building load and circulating water
k	transfer coefficient between circulating water and energy consumption
COP	coefficient of performance
Q_c	cooling load [kW]
Q_h	heating load [kW]
ε	coefficient of performance, here 4.49 is taken
μ	heating coefficient of heat pump, here 4.79 is taken
E_l	energy level of circulating water [kW]
η	load rate [%]
E_c	reverse energy caused by units to water loop [kW]
q_d	energy change of circulating water at design condition [kW]
φ	coefficient of energy conversion
Ψ	energy level number
q_h	rejected energy of circulating water [kW]
q_c	stored energy of circulating water [kW]
Q_a	size of auxiliary heat source [kW]
g	capacity coefficient
N	relative power
P	unit/system at partial load [kW]
P_m	unit/system at design load [kW]

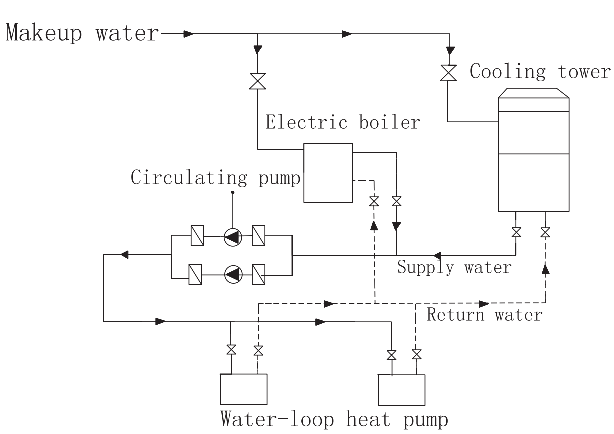

Fig. 1. Schematic diagram of WLHP system.

benefits compared to traditional air-conditioning system. These literatures used building load as a general method to solve the problem of energy consumption but note that several factors had different impacts on operation mode in WLHP system and building load was one of them for simultaneous heating and cooling, which forms a reverse energy caused by units to water loop to increase operation complexity. As far as application conditions were concerned, Lian [17] suggested its application area in China by analyzing the saving-energy rates in different cities and combined with a case, Chen [18] investigated system operation characteristic and controlling conditions in residential building. Recently, Shui [19] analyzed the effect of water temperature on compressor and cooling tower and put forward a practical strategy to determine an optimal temperature and Fuentes [20,21] presented that there was a close relation between load rate and energy efficiency by testing a water-source heat pump. These investigations showed that the WLHP system could achieve the higher energy efficiency in the building with inner-outer zone and pointed out that circulating water and load rate could provide new clues for the related research.

The previous investigations are true and they may be further improved if the following problems can be solved. First, the several impact factors should be converted into a function on single variable. Second, the reverse energy caused by units and corresponding energy-saving range should be determined in cooling and heating simultaneous mode. Third, the capacity model of auxiliary heat source and its size should be reported for all building types. Fourth, the WLHP system should be extended to a new building type. So, the objective of this paper is to report some new findings. The theory of energy level is proposed to determine the energy-saving range and size of auxiliary power. By testing an office building in Tianjin the energy balance between units and auxiliary power and double operation characteristics of WLHP system also are found and these conclusions contribute to provide a certain theoretical reference and data support for further research.

2. Theory of energy level

2.1. Research idea

In WLHP system, a general effect caused by several factors has different impacts on different areas of a building and the units provide heating or cooling for them to meet human's demands according to the primary effect, which rejects and extracts heat to and from a water loop to produce water temperature fluctuation. As the energy carrier which connects building with units the circulating water correspondingly forms a secondary effect to affect the COP of unit. So, the operation of WLHP system forms a chain of energy transfer and its structure is shown in Fig. 2.

In Fig. 2, the transfer relationship is summarized as follows.

$$\Delta Q \rightarrow \varphi(\Delta q) \rightarrow k(\Delta E) \tag{1}$$

So, whether using circulating water or building load, studies the response of energy consumption and their results are same in WLHP system. Note that load rate describes the system operation from two aspects of quality and quantity due to different requirements for heating and cooling and quality refers to the attribute of load and quantity is its size, so it not only changes the COP of units but also converts units operation into reverse mode, which reveals that the operation of WLHP system is of double attributes of generality and individuality compared to other heat pump systems. In addition, if the circulating water replaces building load as a novel method some advantages can be seen as follows. First, the accuracy and applicability of original method is improved because the research link is shortened. Second, the different effects are considered as an energy fluctuation caused by water temperature change to build a single function on circulating water. Third, the reverse energy caused by units to water loop is converted into the energy change of circulating water. Therefore, an idea on energy conversion of circulating water is introduced into WLHP system and it states that using an energy transfer chain composed of building, circulating water and units describes system operation