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Optimization of Solar Water Heating System in High-rise Residential Buildings

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Abstract

The limited roof area of high-rise residential buildings restricts the effective use of solar water heating systems (SWHS). Auxiliary heat sources and household water heaters have become an inevitable choice to ensure domestic hot water supply. To determine the heating quantity of auxiliary heat sources and the number of household water heaters, this study proposed an optimization model with minimum total cost as objective function. TRNSYS was used to establish the simulation model of a SWHS, which was verified by the measured data. Based on the calculated heat demand and simulated heat supply of the SWHS, a linear programming model was established with minimum total cost (including depreciation, maintenance, and energy costs) as the objective function. In this way, the number of household water heaters was determined. Results demonstrate that the combination of the SWHS and heat pump water heater is the optimal application of SWHS in high-rise residential buildings. The heat pump water heater is installed in low floors, and the hot water is supplied by the SWHS in middle and high floors to achieve the lowest total cost and high solar energy use rate. This study can provide a significant reference for developing a domestic hot water supply scheme in high-rise residential buildings.

Keywords: Solar energy, Economical efficiency, Optimization, Linear programming

1. Introduction

According to a report by the International Energy Agency, the worldwide growth rate of energy consumption in 2019 reached 2.3%, of which nearly 70% was fossil energy. Environmental problems caused by fossil energy have attracted increasing attention, and the renewable energy has been developed and utilized rapidly. One of the most widely used renewable energy is solar energy, the main forms of which are photo-thermal and photovoltaic. With the increasing domestic hot water consumption, the total energy consumption has reached 10%–20% of the total building energy consumption [1]. Compared with other water heating systems, the efficient solar water heating systems (SWHS) has a positive influence on resources, economies, and the environment [2], and has become an important mode of renewable energy utilization.

The agglomeration effect of cities leads to their continuous expansion. Faced with pressures caused by population increase, developers in cities have built high-rise residential buildings to use limited land resources efficiently. The roof of high-rise buildings have to meet the requirements of equipment installation, but the limited roof area restricts the utilization of SWHSs. Therefore, how to efficiently use SWHSs in high-rise residential buildings has become a research concern.

Scholars have conducted many studies on the SWHSs in high-rise residential buildings [3-5]; these studies have focused on the system efficiency but ignored the economic problems associated with it. Therefore, how to efficiently use solar energy and enhance the economic efficiency of SWHSs is an urgent problem for them in high-rise residential buildings.

This study established a verified simulation model of the SWHS by combining simulation and optimization. Moreover, the daily heat supply of the SWHS throughout the year was simulated. Finally, the optimization model was used to obtain the optimal scheme of domestic hot water supply for high-rise residential buildings.

2. State of the art

Scholars have conducted numerous studies to optimize the application of SWHSs, and they mainly discussed how to improve the efficiency of heat collection. Mandal et al. [3] developed a novel solar water heater with two channels and reflectors, which can improve the efficiency of the collector to 50.26%. However, the feasibility of this idea for a large-scale SWHS is unknown. Touaba et al. [4] designed a solar water heater with waste oil as absorbent and heat transfer working fluid and a photovoltaic system to supply various DC electrical devices, whose heating efficiency mean rate is 65% while its maximum efficiency reaches 80%; however, the small system can not supply hot water to high-rise residential buildings. Vasanthaseelan et al. [5] used two different turbulators to induce turbulence to improve the poor water circulation at the lower end of the solar water heater, but the idea was not tested in practical engineering. Some scholars have studied how to use new materials in solar water heaters. Manoj Kumar et al. [6] used a phase-change material (PCM) and a nanocomposite phase change material (NPCM) to improve the heat storage capacity of the solar water heater. The results showed that the final energy efficiency for without PCM, with PCM, and with NPCM were found to be 58.74%, 69.62%, and 74.79%, respectively.

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However, the scholars did not discuss the economy of the heater after using phase-change materials. Sun [7] found that the Exergy efficiency gradually decreased with the increase of inlet flow, while the filling efficiency of the phase-change heat storage tank first increased and then decreased. However, how to apply these rules to practical projects was not discussed. Zhang [8] found that the phase-change heat storage ball could strengthen the thermal stratification effect of the heat storage tank. When the phase-change heat storage ball was at the bottom and the inlet flow rate was large, the thermal stratification characteristic of the heat storage tank was the best. The influence of the phase-change heat storage ball on the system efficiency was neglected. Some scholars also paid attention to the performance of a complex centralized SWHS. To achieve the optimal matching of key parameters in the air source heat pump-assisted SWHS, Zeng [9] optimized the collector area, collector inclination, water tank volume, and heat pump power with the system life cycle cost as the objective function; however, the conclusion was based on the annual data without considering the difference of monthly and daily hot water usage. Guo [10] calculated the solar energy contribution rate and annual energy efficiency coefficient of an air-source heat-pump-assisted SWHS in four typical cities in China. The results showed that the air-source heat pump could improve the system performance, but how to realize the coupling of the SWHS and heat pump water heater was not discussed. Gu [11] calculated the heating capacity of the centralized SWHS with single and double water tanks. The scholars found that the centralized SWHS with double water tanks was superior to that with a single water tank for the continuous water supply system, but the operation strategy of the system was not considered. Luo [12] tested the solar hot water system of high-rise residential buildings. The measured data showed that the efficiency of the heat collection system was highly correlated to the outdoor air temperature and inlet temperature; this conclusion failed to provide a useful reference for the SWHS.

Environmental and economic benefits of the SWHS are also important study directions. Lei [13] calculated the energy consumption of the SWHS in the entire life cycle and found that the energy recovery period was 0.9–2.8 years. However, the basic data was rough and could not be used to analyze the daily heat supply and demand. Zhou [14] found that the energy recovery period of the vacuum tube SWHS and flat SWHS was less than three months, the environmental recovery period was less than three years, and the initial investment recovery period was within eight years. However, the data could not be used to guide the design and operation of the SWHS. According to Nshimyumuremyi et al. [15], the efficiency of SWHS in Rwanda was 60%–76%, and the payback period was two years because of its high efficiency and design. Their study focused on product instead of engineering practice. Alayi et al. [16] asserted that solar water heaters can provide 70% of the energy consumption of hot water in Iran with dry and hot weather, but their study was too macroscopic and had minimal reference value for microscopic system analysis. Jahangiri et al. [17] pointed out that the solar water heaters in Zambia could reduce greenhouse gas emissions by 1320–1550 kg per year. However, their analysis was purely based on software simulation and lacked measured data. Siampour et al. [18] found that the annual heat output and carbon dioxide emission reduction of flat solar water heaters in Turkey were 132,605 kWh and 68.4 t, respectively, while those of solar water heaters with vacuum collector tubes were 228,814 kWh and 93.4 t. Their findings lacked guidance for the engineering practice of SWHS.

The above results focused on the optimization of the components of SWHS. Few studies have been published on the overall optimization of large SWHSs in high-rise residential buildings, and the analysis of the daily hot water supply and consumption is scarce. In this study, a verified simulation model of the SWHS was established by combining measurement, simulation, and optimization. By analyzing the daily heat supply of the hot water system and the heat demand of users, this study obtained an optimized domestic hot water supply scheme for high-rise residential buildings with minimum total cost as the objective function, which provided a feasible scheme for using the SWHS in high-rise residential buildings efficiently and economically.

The rest of this study is structured as follows. Section 3 introduces the components and parameter settings of the simulation model of the SWHS and establishes a linear programming model for optimization. In section 4, the daily heat supply and total heat demand of the solar hot water system and household water heater throughout the year were analyzed, and the optimization schemes of the domestic hot water supply of the SWHS and household water heater were obtained. Finally, section 5 summarizes this study and draws relevant conclusions.

3. Methodology

In this paper, a novel PSO algorithm is proposed for network clustering. In the proposed algorithm, a novel particle status update principle is defined, and, to improve exploration of the algorithm, a novel particle turbulence operation is developed. To enhance the exploitation, a local search strategy is introduced. This section will present a detailed description of the proposed algorithm.

3.1 Field test

In this study, the annual daily heat supply of the heat collection system was taken as the basic data to verify the simulation model. Therefore, the SWHS of a high-rise residential building was selected as the test object (Fig. 1). The field test data include outdoor air temperature T_0, total solar radiation H, and heat Q_j of the heat collection system. The test instruments include thermometers, total radiation meters, and heat meters. According to these data, the efficiency of the heat collection system can be calculated as follows:

$$\eta = Q_j / (A \times H) \tag{1}$$

where Q_j is the heat of the heat collection system (MJ), A is the total area of the collector (m^2), and H is the total solar radiation (MJ/m^2).

3.2 Simulation model

Based on the SWHS of the high-rise residential building, this study established a simulation model of TRNSYS (Fig. 2). The model includes 14 components: meteorological data, heat collector, water tank, water pump, controller, water load, monthly cumulative calculator, daily cumulative calculator, analog cumulative calculator, monthly calculation result printer, and total simulation calculation result printer. The components were connected according to the logical relationship of medium flow, mass flow, heat flow, and control signals. The calculation parameters are shown in Table 1. The meteorological parameters of typical meteorological years in Kunming, Yunnan Province (25.02° N, 102.68° E) were used in the simulation.

Fig. 1. Photo of the SWHS

Table 1. Calculation parameters of TRNSYS simulation software

Module	Parameter	Parameter value
Heat collector	Area	162 m^2
	Efficiency	0.50
	Inclination angle	30°
	Orientation	Positive direction
Water tank	Volume	4200 L
	Heat loss coefficient	0.3 W/(m^2 .°C)
	Height	3 m
	stratification	Three layers, 1 m per layer
	Type	Vertical
Water pump	Flow	2.4 T/h, power 125 W
Controller	Heat collecting water pump	When $T_1 - T_2 \geq 8$ °C, ON; $T_1 - T_2 < 2$ °C, OFF
	Auxiliary heat source	Starts when the water temperature is lower than 55 °C and shuts down when reaching 60 °C
	Overheating prevention	When $T_2 > 80$ °C, stop

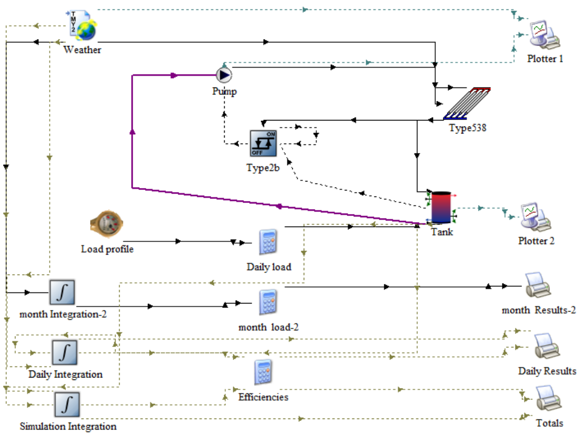

Fig. 2. TRNSYS simulation system diagram

3.3 Optimization model

In this study, the domestic hot water supply scheme of household water heaters and the solar hot water system was proposed. The number of household water heaters was determined according to the principle of minimum total cost. The optimization model was linear programming, which was expressed as follows:

$$\min\ Y = C_1 + C_2$$
$$\text{s.t. } Q_1 + Q_2 = Q_t \qquad (2)$$

where C_1 is the total cost ($) of the SWHS (including auxiliary heat source), C_2 is the total cost ($) of the household water heater, Q_1 is the heat supply (MJ) of the SWHS (including auxiliary heat source), Q_2 is the heat supply for the household water heater (MJ), and Q_t is the total heat demand (MJ).

The total cost C is calculated according to the following formula:

$$C = C_p + C_m + C_0 \qquad (3)$$

where C_p is the annual equipment depreciation cost ($) and the salvage value rate is 0, C_m is the annual equipment maintenance cost ($), C_m is 10% ($) of C_p, and C_0 is the annual energy cost.

The total cost C_1 of the SWHS is calculated according to the following formula:

$$C_1 = 1.1 C_{p1} \times n + \frac{P_1}{Q_n \times \eta_e} \times X_1 \qquad (4)$$

where C_{p1} is the depreciation expense of the SWHS per household ($); n is the total number of households with a value of 132; P_1 is the unit price of energy, $0.074/kWh; and the unit price of natural gas is $0.492/m3. X_1 is the heat supply of the auxiliary heat source (MJ); Q_n is the calorific value of unit energy, with electricity of 3.6 MJ/kWh and natural gas of 35.6 MJ/ m^3 ; η_e is the efficiency of hot water equipment, which is 3.5 for the heat pump water heater and 0.8 for the household natural gas water heater.

The total cost C_2 of household water heater is calculated according to the following formula:

$$C_2 = \left[1.1 \left(C_{p2} - C_{p1} \right) \times n + P_2 \times \frac{Q_h}{Q_n \times \eta_e} \right] \times X_2 \qquad (5)$$

where C_{p2} is the depreciation expense of household water heater equipment ($), P_2 is the unit price of energy, Q_h is the heat demand of each household (MJ), and X_2 is the number of household water heaters.

The heat supply Q_1 of the SWHS is calculated according to the following formula:

$$Q_1 = \left(Q_j + X_1 \right) \times \left(1 - \eta_l \right) \qquad (6)$$

where η_l is the heat loss rate of the solar hot water system, which is 0.1. (The heat loss of the water tank has been considered in the simulation model in section 3.2.)

The heat supply Q_2 of the household water heater is calculated by using the following formula:

$$Q_2 = Q_h \times k \times X_2 \tag{7}$$

where k is the required coefficient, 0.9.

The total heat demand Q_t is calculated according to the following formula:

$$Q_t = Q_h \times k \times n \tag{8}$$

The heat required by each household Q_h is calculated according to the following formula:

$$Q_h = N \times w \times (t_1 - t_2) \times c \tag{9}$$

where N is the number of families; w is the daily hot water consumption per person (kg); t_1 is the hot water temperature (°C); t_2 is the cold water temperature (°C); and c is the specific heat capacity of water, 0.0042 MJ/(kg. °C).

The annual solar energy utilization rate is calculated by using the following formula:

$$U_r = \sum \frac{q_1}{Q_j \times (1 - \eta_l)} \tag{10}$$

where q_1 is the heat actually used for heating (MJ) in the heat supplied by the daily heat collection system.

4 Result Analysis and Discussion

4.1 Simulation model verification

The test object had 33 floors on the ground, with 6 households on each floor. The roof collector covered an area of 162 m^2, the roof was equipped with 900 vacuum tubes (Φ58 × 1800 specification) and a hot water storage tank of 10 m^3, and the auxiliary heat source was a heat pump water heater (COP is 3.5). The test time was 1 day per month in 2021, with 12 tests in total.

Based on the outdoor temperature T_0, total solar radiation H, and system heat gain Q_j during the 12 test days (Figs. 3 and 4), the efficiency of the heat collection system can be determined according to equation 1. Under the same environmental parameters, the heat gain of the system was obtained by simulation using the model established in section 3.2. Then, the efficiency of the heat collection system was obtained according to equation 1. Comparing the measured and simulated heat gain of the system with the efficiency of the heat collection system (see Figure 4), we found the error range was within ±7%, so the simulation model passed the verification.

4.2 Optimization model parameter calculation

According to equation 4-5 and the following data, the total cost of the SWHS C_1 and the total cost of the household water heater C_2 can be calculated: The equipment costs of the SWHS, household natural gas water heater, and household heat pump water heater were \$446.10, \$267.66, and \$431.23 per household, respectively. The depreciation periods are 15, 10, and 15 years, respectively. The annual depreciation costs are \$29.74, \$26.77, and \$28.75, respectively.

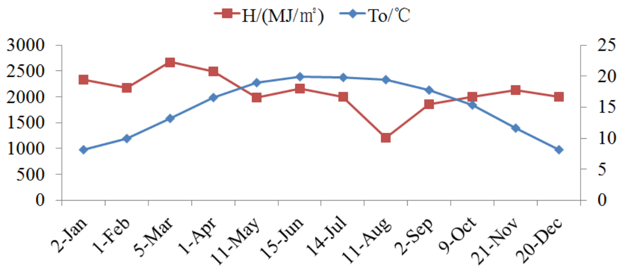

Fig. 3. Measured outdoor average temperature and total solar radiation

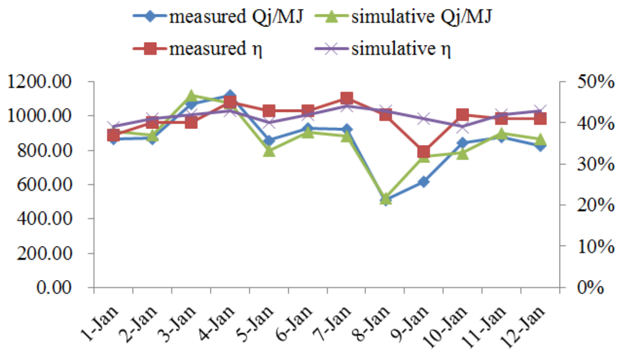

Fig. 4. Comparison between measured values and simulated values of system heat gain and heat collection system efficiency

Based on equation 9 and the following data, Q_h can be calculated: The number of families N is 2.5, the daily hot water consumption W of each person is 40 kg, the hot water temperature t_1 is 60 °C, and the cold water temperature t_2 from January to December is 8.2, 7, 8.2, 11.6, 16.1, 20.7, 24, 25.2, 24, 20.7, 16.1, and 11.6 °C, respectively.

Based on the verified simulation model, the daily heat gain Q_j and heat supply Q_s of the heat collection system can be obtained after simulation $Q_s = Q_j \times (1 - \eta_l)$ (Fig. 5). According to the calculation results, the annual heat supply of the heat collection system is 312842.78 MJ, and the annual total heat demand is 798236.21 MJ. The proportion of Q_s to Q_t is 39.19%.

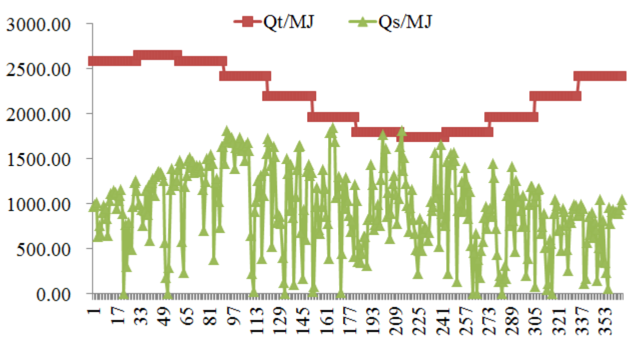

Fig. 5. Heat supply and total heat demand of heat collection system throughout the year

According to the calculation results and equations 3-9, the final optimization model can be obtained as follows:

$$\min\ Y = 11.831 + 0.005873 + \left(a + b \times Q_h\right) \times X_2$$
$$\text{s.t. } 0.9X_1 + 0.9 \times Q_h \times X_2 = 118.8Q_h - 0.9Q_j \qquad (11)$$

where, for household natural gas water heaters, *a* and *b* are -0.00895 and 0.01728, respectively. For household heat pump water heaters, a and b are -0.00298 and -0.005873, respectively.

4.3 Optimization calculation results and discussion

According to equation 11, the linear programming function linprog of MATLAB is used for calculation. The final results are as follows: the number of households with natural gas water heaters is 0, while the number of households with heat pump water heaters is between 7 and 131, with 98 results. The reasons are analyzed as follows:

(1) Installing household natural gas can reduce the depreciation and maintenance costs, but its proportion to the total cost is less than that of the energy cost. Therefore, the main factor that determines the total cost is the energy cost.

(2) Low efficiency of the household natural gas water heater leads to higher energy cost, and its total cost is greater than that of the auxiliary heat source. Therefore, in the total heat demand, except for the heat supplied by solar energy, the rest of the heat is provided by the auxiliary heat source, so the installed quantity is 0.

(3) Under the same efficiency, the energy cost of the household heat pump water heater decreases due to low heat loss, and its total cost is less than that of the auxiliary heat source. Therefore, in the total heat demand, except solar energy, the rest of the heat is provided by household heat pump water heaters. Meanwhile, the change of total solar radiation in a year leads to an extraordinary number of installations.

On the premise of considering both cost and solar energy utilization, the final installation number of household heat pump water heaters is determined based on the principle of minimum annual total cost and high annual solar energy utilization. According to equation 11, the total daily cost can be determined and the total annual cost can be obtained after accumulation. The annual solar energy utilization rate is calculated according to equations 11. The final calculation results are as follows (Fig. 6):

When $X_2 > 54$, $C > 7500$ and $Ur < 96\%$. When $X_2 \le 54$, $C < 7500$ and $Ur > 96\%$. When $X_2 = 29$, $C_{\min} = 7461.139$ and $Ur = 99.64\%$.

5. Conclusions

To realize the optimal application of the solar hot water system in high-rise residential buildings, this study proposed a hot water supply scheme of the solar hot water system and a household water heater. The number of household water heaters was determined after calculating the total heat demand and simulating the heat supply of the heat collection system, with the goal of minimum total cost and high solar interest rate. The following conclusions can be drawn:

(1) The heat supply of the SWHS in high-rise residential buildings is less than 40% of the total heat demand. Auxiliary heat sources and household water heaters are needed to ensure the hot water supply.

(2) Household water heaters can reduce equipment depreciation and maintenance costs, and household heat pump water heaters have higher efficiency and lower total cost. Therefore, household heat pump water heaters should be used.

(3) The goal of minimum cost and high utilization rate of solar energy can be achieved by installing household heat-pump water heaters in low floors of high-rise residential buildings and solar water heaters in middle and high floors.

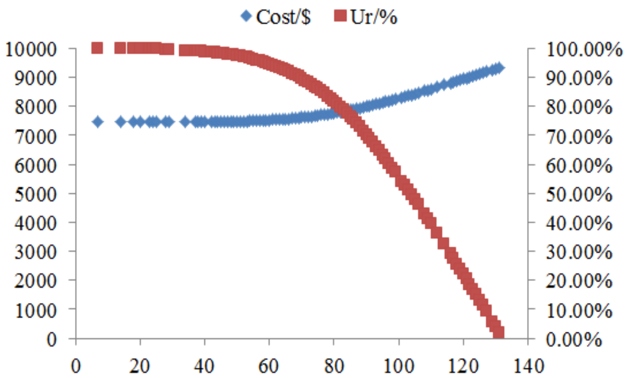

Fig. 6. Annual total cost and solar energy utilization rate of different numbers of household heat-pump water heaters

In this study, field measurement, numerical simulation, and optimization were combined to minimize the total cost and maximize the utilization rate of solar energy. The optimization scheme of the household heat pump water heater and solar hot water system was proposed, which can serve as a reference for solving the domestic hot water supply problem in high-rise residential buildings. The lack of actual data on users of domestic hot water is a problem to be solved in future study. A more feasible optimization scheme can be obtained based on the analysis of actual data on domestic hot water.

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