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# Study on Application of Solar Water Heat Pump for Building in China

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**Abstract**

In order to solve the issue of applicability of solar water source heat pump for building, this article analyzes the load characteristics in different climate regions based on the three typical cities which are Harbin, Beijing, Shanghai, then sets up system mathematical models, uses the eQUEST set up the building model and puts the model into TRNSYS to do the optimization calculation. According to the theory of Life Cycle Assessment, this article analyzes the applicability of solar water source heat pump for building by taking feasibility, energy saving property, economy and environmental protection property as technical index and get the conclusion that the applicability of solar water source heat pump for building in severe cold region and cold region is well and the environmental benefit is obvious.


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*Keywords:* Solar; Water source heat pump; Heat load characteristic; Applicability analysis

## 1. Introduction

According to the climate regions of building, the area of the region that belongs to cold region and severe cold region is 2/3 of China's area, these regions' temperature is low in winter, so heating the building is the basic requirement to protect people's winter life. The warm summer and cold winter region in Yangtze river basin shows the heating need with upturning living standards and improving living environment. Our country has a large

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population and use coal as main energy source, the energy consumption of building causes severe environmental pollution and greenhouse gas emission. The form of most of the current application of renewable energy systems is the single energy system, their respective disadvantages are increasingly highlighted in the application process, such as the solar energy density is low, solar collector area is large, and it is extremely unstable, so this system needs to set energy storage device and auxiliary heating device [1], which adds the need of space and cost; Besides, all kinds of systems of heat pump also have some disadvantages [2], such as the energy accumulation of ground source heat pump and the problem of frosting in air source heat pump and so on. The solar water source heat pump system which combines the solar and heat pump can fill their gaps to achieve complementary advantages. So, the solar water source heat pump is developing trend of using the saving energy technology of solar and heat pump and it has significance to ease the building energy consumption and environmental problem.

Jordan R C and Therkeld J L started do the research of solar source heat pump from 1950s and put out taking solar heating system as heat source of heat pump which combining solar and heat pump together [3]. Charters W W S used the flat-plate solar air collector as the heat pump evaporator and studied its performance [4]. Zhou Qintao took the solar soil source heat pump as the study object and do the first attempts about solar soil source heat pump research [5]. Ma Yuanyuan analyzed the applicability of solar soil source heat pump for building [6].

The specialists and scholars have done a lot of work about solar water source heat pump for building, however their most work focus on researching system performance and barely focus on applicability of solar water source heat pump for building in different climatic regions, this article analyzes load characteristics in different climate regions, sets up system mathematical models and uses TRNSYS to do the optimization calculation, then, this article analyzes the applicability of solar water source heat pump for building by taking feasibility, energy saving property, economy and environmental protection property as technical index.

## 2. Analyzing the building load characteristics of different region

Our country have five climate regions, including severe cold region; cold region; hot summer and cold winter region; hot summer and warm winter region and temperate region. Due to the fact that there is no need heating at winter in the hot summer and warm winter region and temperate region, this article chooses the severe cold region, cold region, hot summer and cold winter region as the heat pump application regions and takes the Harbin, Beijing, Shanghai as the typical cities.

### *2.1. Computational model*

This article chooses one residential building as the optimization research object of solar water source heat pump, the building area is 320m$^2$, there is two layers on the ground and the floor height is 3.7m and 3.4m, the function room including: drawing room, bedroom, dining room and garage and the heating area is 310m$^2$.The building model established by eQUEST is shown in Fig. 1.

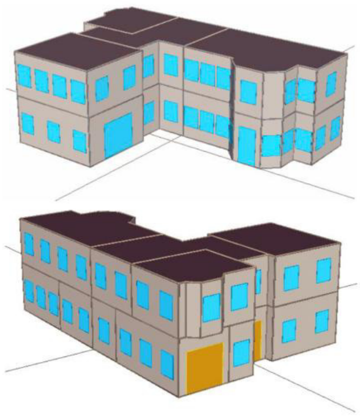


Fig. 1. 3D building model.

### 2.2. Load characteristics of severe cold region

The typical city of severe cold region is Harbin, the heating period of Harbin is very long, most heat load concentrates on December to March of next year, the proportion in total heat load is 79%. Harbin receives most sunshine in May and least sunshine in December, the radiant quantity is 575MJ/m$^2$ and 152MJ/m$^2$. Harbin's winter is very cold and lasts long, the summer is cool and refreshing and lasts short, annual variation of temperature is large. Therefore, in winter, enclosure structure heat load and fresh air heat load is very large, meanwhile, Harbin receives little sunshine, radiation heat gain is little; in summer, enclosure structure cooling load and fresh air cooling load is very little, meanwhile, Harbin receives little sunshine, radiation cooling load is little.

### 2.3. Load characteristics of cold region

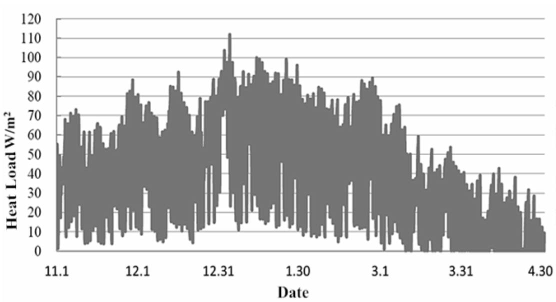
The typical city of cold region is Beijing, the heating period of Beijing is 4 months, most heat load concentrates on December to February of next year, the proportion in total heat load is 80%. Beijing receives most sunshine in May and least sunshine in December, the radiant quantity is 595MJ/m$^2$ and 218MJ/m$^2$. Beijing has distinct four seasons, winter is cold and summer is hot, the heat period is as long as cooing period. Therefore, in winter, enclosure structure heat load and fresh air heat load is relatively large, meanwhile, Beijing's solar radiation intensity is in mid-range level, the solar source is rich; in summer, enclosure structure cooling load and fresh air cooling load is very large, meanwhile, Beijing receives large sunshine, radiation cooling load is large.

### 2.4. Load characteristics of summer and cold winter region

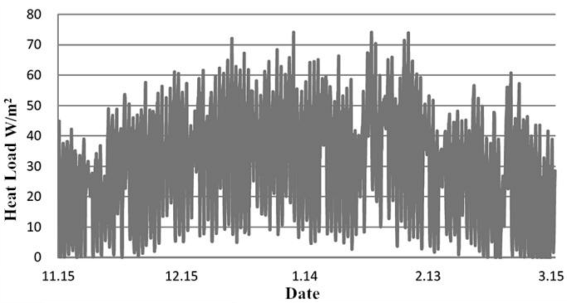
The typical city of hot summer and cold winter region is Shanghai, Shanghai belongs to semi-tropical monsoon climate and the heating period is short. The variation of annual monthly average temperature is large. Shanghai receives most sunshine in May and least sunshine in January, the radiant quantity is 623MJ/m$^2$ and 225MJ/m$^2$. Shanghai's winter is cold moist and lasts short, the summer is stuffiness and lasts long. Therefore, in winter, enclosure structure heat load and fresh air heat load is relatively little, meanwhile, Shanghai's solar radiation intensity is in large level, the solar source is rich; in summer, enclosure structure cooling load and fresh air cooling load is very large, meanwhile, Shanghai receive relatively little sunshine, radiation cooling load is little.

### 2.5. Simulation results

Do the building model's hourly load simulation based on the building model and design parameters of different regions and get the residential building's hourly load in heat period, they are shown in Fig. 2.




(a)

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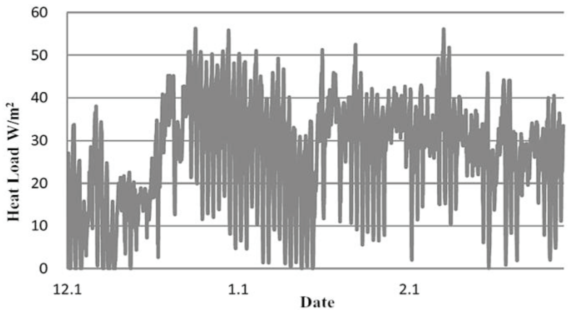


(c)

Fig. 2. Residential building's hourly load in heat period: (a) – Harbin, (b) – Beijing, (c) - Shanghai.

## 3. The system form and mathematical model

The solar water source heat pump uses the evaporator absorb heat and sends it to the room in order to meet the indoor heat load. When the heat pump works, it changes the low temperature heat gathering from sun into high temperature heat and sends the heat to the room. The system diagram is shown in Fig. 3.

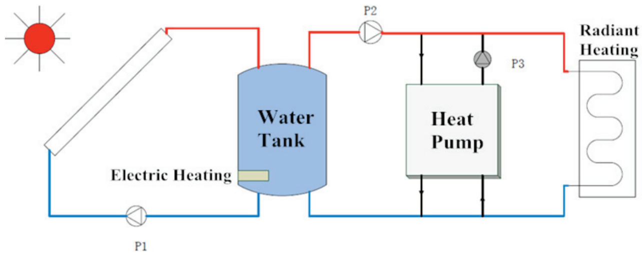


Fig. 3. The system diagram of solar water source heat pump.

### 3.1. Collector mathematical model

Based on the law of conservation of energy, getting the Collector mathematical model, it is shown in formula (1), we can get the outlet temperature of the collector by formula (1):

$$Q_h = A_h H \eta = Q_m - Q_n = A_h H (\lambda\theta)_\varepsilon - A_h U_j (T_h - T_e) = m_h c_p (T_{jo} - T_{ji}) \quad (1)$$

where $Q_h$ is the heat gain of collector and $A_h$ is the area of absorber plate, $H$ is solar radiation intensity, and $\eta$ is coefficient of collector, $Q_m$ is the heat gain of absorber plat, $Q_n$ is the heat loss of collector, $(\lambda\theta)_\varepsilon$ is the absorption coefficient; $U_j$ is the loss coefficient of collector, $T_h$ is the average temperature of absorber plate, $T_\varepsilon$ is the environment temperature, $m_h$ is the mass flow rate of water in collector, $c_p$ is specific heat of water, $T_{jo}$ is the outlet temperature of collector, $T_{ji}$ is the inlet temperature of collector.

### 3.2. Water tank mathematical model

We use the N nodes method to set up the water tank mathematical model. The N nodes method is that splitting the water tank into N parts, every part is one node and have the same temperature, the temperature changed with the node. Supposing that water flow into the water tank in low velocity and get to the part whose temperature is as same as its temperature, we can get the formula：

$$m c_p \frac{dT_m}{dt} = F_h m_c c_p T_{jo} + m_c c_p T_{m-1} \sum_{i=1}^{m-1} F_i - m_c c_p T_m \sum_{i=1}^{m} F_i + G_h m_l c_p T_{Lo} + m_l c_p T_{m+1} \sum_{i=m+1}^{n} G_i -$$
$$m_l c_p T_m \sum_{i=m}^{n} G_i - U_s A_m (T_m - T_e) + F_d W_d \tag{2}$$

where $m$ is Water quality of m layer and $T_m$ is the water temperature of m layer, $t$ is time, and $U_s$ is heat loss coefficient of water tank, $A_m$ is water tank's superficial area of m layer, $W_d$ is power of electricity heater, W; $F$, $G$, $F_d$ is control function.

### 3.3. Load mathematical model

$$Q_L = m_l c_p (T_{li} - T_{lo}) \tag{3}$$

where $m_l$ is mass flow rate and $T_{li}$ is inlet temperature of heating coil, $T_{lo}$ is outlet temperature of heating coil.

## 4. Applicability of solar water source heat pump for building

Life Cycle Assessment is the process about quantitative evaluation of product and system. Life Cycle Assessment including four parts, they are: ensuring The target and scope, inventory analysis, impact assessment and result interpretation.

Based on the Life Cycle Assessment, this article takes the applicability of solar water source heat pump as the target and takes the feasibility, energy saving property, economy and environmental protection property technical index as the inventory analysis, the life cycle is 20 years, by comprehensively comparing the inventory analysis results, this article can get the evaluation of applicability of solar water source heat pump for building.

### 4.1. Evaluation of feasibility

Solar fraction is a major constraint to the feasibility of solar water source heat pump. Solar fraction is the ratio of the heat gain of collector to the building load, that is：

$$f = \frac{Q_h}{Q} \tag{4}$$

where $f$ is solar fraction and $Q_h$ is the heat gain of collector, $Q$ is the building load.

Accumulating the heat gain and the building load by integrator, and using the TRNSYS calculation model simulate the heat gain and the building load, getting the Solar fraction which is shown in Table 1.

Table 1. Solar fraction of different region.

| Region | Heat gain of collector (*kW*) | Heating load (*kW*) | Solar fraction (%) |
|---|---|---|---|
| Harbin | 34278 | 53885 | 64 |
| Beijing | 17455 | 27903 | 63 |
| Shanghai | 8579 | 17951 | 48 |

As the table 1 show, Harbin's solar fraction is biggest, Beijing is second and Shanghai is last. Taking the solar fraction as the evaluation index, we can get that the applicability of solar water source heat pump for building from high to low is severe cold region, cold region, hot summer and cold winter region.

### *4.2. Evaluation of energy saving property*

Energy efficiency ratio during heat period: SCOP = total heat load/(total energy - consuming of unit + total energy-consuming of water pump)

Calculating the heating capacity and operation consumption based on the simulated results, so we can get the energy efficiency ratio of different regions which is shown in Table 2.

Table 2. Energy efficiency ratio of solar water source heat pump

| region | operation consumption (*kWh*) | heating capacity (*kWh*) | energy efficiency ratio |
|---|---|---|---|
| Harbin | 12870 | 53885 | 4 |
| Beijing | 9148 | 27903 | 3 |
| Shanghai | 9157.5 | 17951 | 2 |

Primary energy ratio of solar water source heat pump：

$$PER_S = COP \times \eta_E \tag{5}$$

where *COP* is the performance coefficient of the solar water source heat pump and $\eta_E$ is power efficiency, it is 30.4%.

At present, primary energy ratio of boiler in china is 0.5~0.7, the primary energy ratio of solar water source heat pump in Harbin is 1.28, the primary energy ratio of solar water source heat pump in Beijing is 0.93, primary energy ratio of solar water source heat pump in Shanghai is 0.61, so the primary energy ratio of solar water source heat pump in Harbin and Beijing is higher than the primary energy ratio of boiler, the primary energy ratio of solar water source heat pump in Shanghai is almost as same as the primary energy ratio of boiler.

### *4.3. Evaluation of economy*

Initial cost. We can get the initial cost of solar water source heat pump in different regions based on the component of initial cost. Equipment investment is consist of the cost of heat pump units, solar collectors, water tank and accessory structure. The initial cost in Harbin, Beijing, Shanghai respectively are 345 yuan/m$^2$, 304 yuan/m$^2$ and 203 yuan/m$^2$.

Operation cost. The operation cost is depend on the operation consumption of water pumps, heat pump units and accessory structure The operation cost in Harbin, Beijing, Shanghai respectively are 20 yuan/m$^2$, 14 yuan/m$^2$ and 14 yuan/m$^2$.

The common technical and economic comparison method is payback period of additional investment method. Supposing the increment of additional investment is $\Delta E$, the decrement of operation cost is $\Delta M$, so：

$$\tau = \frac{\Delta E}{\Delta M}, \quad \Delta E = E - E_C, \Delta M = M_C - M \tag{6}$$

where $E$, $E_C$ is the initial cost of solar water source heat pump and $M$, $M_C$ is the operation cost of solar water source heat pump.

After calculation, the payback period of solar water source heat pump in Harbin, Beijing, Shanghai respectively are: 10.5 years, 8.5 years, 4.6 years.

### *4.4. Evaluation of environmental protection property*

The solar water source heat pump system need to consume energy when the system runs. Now, our country depends on coal-fired plants which emit lots of $CO_2$, $SO_2$, and $NO_2$ pollution gas. So, the environmental protection property index is gas pollution emission load when the system runs in Life cycle, it is *EM*:

$$EM = \frac{EN \times (i + j + k)}{1000} \tag{7}$$

where $i$, $j$, $k$ is $CO_2$, $NO_2$, $SO_2$ emission factor of 1kg standard coal burning, they are 2600g, 9g, 6g. Consumption of standard coal $EN$=total energy consumption × $\phi$, coefficient of electrical energy converted into standard coal $\phi$=0.345×10$^{-3}$, kg/kWh. The results are shown in Table 3.

Table 3. Environmental benefits of solar water source heat pump in different regions

| Region | Harbin | Beijing | Shanghai |
|---|---|---|---|
| Greenhouse-gas emission reductions (*kg*) | 230.9 | 164.1 | 148.2 |
| Soot emission reductions (*kg*) | 0.8 | 0.57 | 0.51 |
| Cinder emission reductions (*kg*) | 0.53 | 0.38 | 0.34 |
| The total emission reductions ($kg/m^2$) | 232.23 | 165.05 | 149.05 |

It can be seen from the results of the pollution gas emission reductions, emission reductions of the region with high load demand is higher than in the region with low load demand, this shows that the higher load demand, the more significant environmental benefits of solar water source heat pump.

## 5. Conclusion

This article uses the eQUEST set up the building model and put the model into TRNSYS to simulate. Based on the simulated results and the theory of Life Cycle Assessment, this article analyzes the applicability of solar water source heat pump for building and gets different conclusions based on different technical index:

- Feasibility: severe cold region>cold region>hot summer and cold winter region.
- Energy saving property: severe cold region>cold region> hot summer and cold winter region.
- Economy: hot summer and cold winter region>cold region>severe cold region.
- Environmental protection property: The more load, the bigger environmental protection property.

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