Research on Pipeline Design of Solar Heating System Based on Oil-water Graded Heat Conduction

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Abstract. With the development of society, more non-renewable resources such as coal have been consumed, leading to energy shortage and environmental pollution. In winter, a large amount of coal is burnt for heating in the north, causing heavier smog nationwide, which is a great threat to people’s health. In recent years, some towns in the north also tried to provide heat for the buildings by burning natural gas to achieve boiler water circulation. However, that also caused environmental pollution to some extent. Research leads us to the invention of a solar heating system based on oil-water grading heat conduction and the design of pipelines and oil-water circulation in order to improve energy efficiency and improve heating quality in the north.

1. Preface
Nowadays, solar energy in China, as a clean energy, is being used more widely with the development of related products and technology. Solar heating, especially the solar water heater, is becoming ever more popular. However, in the northern part of China, especially some areas with a temperature of tens of degrees below zero, the water pipes of the solar water heater might get frozen. Moreover, water will evaporate at 100 °C, which poses higher requirements for the pipeline structure of oil-water grading heat device. Research on the pipeline design of solar water heating system based on oil-water grading heat conduction is to optimize the urban heating pipeline to satisfy the need of heat transfer and improve the heating efficiency based on the heat transfer oil and heating water.

2. Pipeline design of solar heating system based on oil-water grading heat conduction
The system consists of two major systems, namely, the closed pipeline circulation system and the water circulation system. The heat energy collected and converted by the solar heating system provides heat through the heat transfer oil and the heating water in the pipeline, and then the pipeline in the residential area.

Closed pipeline circulation system controls the heat transfer oil and heating water in order to reduce heat loss during transmission, thereby improving energy efficiency. The working medium pump drives circulation and optimizes the pipeline structure to achieve adaptive cycle of the heat transfer medium, thereby ensuring stable operation of the system.

Water circulation system controls the flow rate and temperature to ensure heating efficiency based on relevant research on the basic pipeline facilities, design of water flow rate, design of heating switch, and reasonable connection of the old and new heating devices.
3. Closed pipeline circulation system
The closed pipeline circulation system consists of six parts: oil storage tank, oil furnace for solar heat collection and transfer, circulation pump, expansion tank, safety control instrument, and pipeline design. The following is the design of related components of the pipeline based on relevant characteristics of heat transfer oil.

3.1. Criteria and characteristics of heat transfer oil

3.1.1. Criteria for selection
① Thermal stability of heat transfer oil, including anti-oxidation ability of the heat-conducting oil, anti-cracking, and polycondensation of the high-boiling component of the heat-conducting oil.
② Temperature applicable to the heat transfer oil: select heat transfer oil by evaluating the temperature range of the heated oil body in the furnace under the conventional condition based on heat supply efficiency of the oil furnace for solar heat collection and transfer.
③ Toxicity: As this heat transfer oil research will be applied to urban building heating, the toxicity of heat transfer oil, its gasification, and deterioration products should be considered when making a choice to ensure user safety.
④ Thermal oil viscosity and pipeline design: The viscosity of the oil body, especially the low-temperature oil, has a great influence on the flow properties and flow resistance in the pipeline.
⑤ Thermal conductivity of oil body heating and oil-water heat exchanging deserves consideration as it is closely related to the energy utilization efficiency of this research.

3.1.2. Temperature control of heat transfer oil
The device adopts simple two-position control to controls the temperature of the heat transfer oil. It means to heat the oil using electricity when the oil temperature is lower than the required heating temperature in winter. There are two ways for controlling oil temperature. The first one is to measure the oil temperature in the heating piece using the temperature sensor and then set the temperature interval according to human perceived comfort. The second one is to measure the indoor temperature and determine whether to start the heat transfer oil circulation pump so that the high-temperature heat...
transfer oil in the heat accumulator can be sent to the oil heating piece.

When heat transfer oil is sufficient, its temperature must not exceed the designed value. In this regard, the heat of the heat transfer oil must be taken into account in the design. The most feasible way is to pre-arrange stainless steel coil in the vacuum accumulator as the preparation for the circulation of cold water. On the one hand, the excess heat of the heat transfer oil is absorbed; on the other hand, hot water for daily use can be obtained. It helps to reduce the use of coal and electricity for heating fresh water. However, since the water has a small operating temperature range and is directly provided to the user, it is necessary to have a fixed temperature value, which can be achieved with constant value control.

(1) Control system based on indoor temperature: The indoor temperature can be conveniently measured with a temperature sensor, which is adopted in all air conditioning systems to start and stop the compressor. An upper and lower limit temperature can also be set in this device. When room temperature is lower than the lower limit, the circulating pump and the indoor bypass valve are turned on. If heat is insufficiently stored due to lack of sunlight, electric heating can be adopted to heat the heat transfer oil, making it equivalent to ordinary electric heating oil. When room temperature is higher than the upper limit, turn off the indoor bypass valve. As the upper and lower limit of temperature of this kind of indoor temperature sensing can be reasonably set, heat and electricity can be saved, in the meantime, less heat is wasted.

(2) Control system based on the temperature of indoor heating piece: There are two sets of electric heating devices at the bottom of the heating piece, with one controlling two thermal resistors to heat simultaneously for high temperature heating while the other controlling one thermal resistor for low temperature heating. It is possible to determine whether to start the circulation pump and the indoor bypass valve by comparing the oil temperature with the upper and lower limit. When there is no solar energy, electric heating can be adopted for low or high temperature heating.

3.1.3. Flow rate design of heat transfer oil
As the organic heat carrier (heat transfer oil) flows in the tube, it forms a boundary layer whose thickness affects the medium temperature. The thicker the boundary layer, the greater the difference between the medium temperature and the main temperature, leading to overheating, decomposed heat transfer oil, colloid, and residual carbon on the tube wall. Residual carbon further deteriorates heat transfer, accelerating deterioration and failure of the heat transfer oil. The thickness of the boundary layer is related to the flow of fluid in the tube. Generally speaking, the faster the oil body flows, the thinner the boundary layer. However, if the oil flows too fast, it will be insufficiently heated for ideal heat collection. Therefore, it is necessary to explore the appropriate equilibrium point of the flow rate of the oil body to obtain a relatively thin boundary layer, enhance heat transfer, lower the temperature of boundary layer, and produce no excessive resistance.

The flowing fluid satisfies the continuity equation and the momentum equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_x}{\partial x} + \frac{\partial \rho u_y}{\partial y} = 0
\]

u_x and u_y are the components of the fluid velocity in the x, y direction in a two-dimensional plane. x and y represent the coordinate axis direction respectively corresponding to the fluid velocity. \(\rho\) is the fluid density;

The momentum equation is as follows:
\[
\rho u_i \frac{\partial u_i}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu + \mu_1\right)\frac{\partial u_i}{\partial x_j} + \frac{\partial S}{\partial x_i}
\]

u is the flow velocity, p is pressure. \(S\) is the generalized source term of the momentum equation. i and j represent the different flow directions.
3.2. Design of pipeline related components

3.2.1. Expansion tank
The expansion tank is placed at the top of the oil circulation system for balancing the expanded volume caused by temperature increase of the heat transfer oil so as to stabilize system circulation. At the same time, pressure is posed on the inlet of the circulation pump to prevent pump cavitation. The expansion tank is sealed to prevent the contact the heat transfer oil and the air so as to avoid oxidative deterioration.

3.2.2. Oil tank
When the whole system is shut down for maintenance, the heat transfer oil in the oil furnace for solar energy collection, the oil-water heat exchanger, pipeline and its accessories must be completely exhausted. Therefore, the volume of the oil storage tank should be set at least 1.2 times the circulation volume of heat transfer oil in the oil circulation system. Meantime, it should be installed at the lowest point of the entire system.

3.2.3. Pipeline
Pipeline material, welding method and valve matching are explored through calculation and simulation based on safety requirements of the whole circulation system. Bypass adjustment is added to the pipeline of the traditional heat-conducting oil furnace. In this way, valve is automatically adjusted to control the circulating flow rate in the heat-conducting oil furnace according to the thermal load change of the user pipe so as to maintain and the flow rate of the heat transfer oil as designed.

3.2.4. Safety control instrument
It mainly includes the temperature transmitter of the solar collector oil furnace outlet, the liquid level transmitter of the expansion tank, and the liquid level sensor of the oil storage tank.

4. Water circulation system
This system can be divided into two subsystems: original heating pipelines of urban residential buildings in the north and additional water heating devices in this study, which is consist of a constant pressure pump, a hot water tank, an expansion tank, pipeline design, and related control instruments. The following is the detail:

1) Basic antifreeze facilities for pipelines
   In order to prevent the pipeline exposed outdoor from freezing, the length of the pipeline should be shortened as much as possible without influencing its original functions. At the same time, pipeline antifreeze facilities with good performance should be installed.

2) Design of water flow rate
   The water flow rate through the water-oil heat exchanger should be set according to the demand for heating. The water pressure in the pipeline does not provide a suitable water flow rate to the heat exchanger. Therefore, a constant pressure pump is needed to ensure smooth water supply.

3) Adaptive control of switching and coordination of primary and secondary heating systems
   All types of solar energy-saving devices are limited by weather conditions. This device takes solar heating as the main heating system and electric heating as the auxiliary system. Since weather changes irregularly, it is necessary to design a procedure to achieve adaptive control of the switching and coordination of the primary and secondary heating systems.

4) Reasonable docking between the newly installed heating device and original heating pipelines of the residential buildings in the north.

4.1. Water temperature control
Water temperature control: Temperature is a physical quantity with large inertia. PID is used in traditional temperature control. Although it is simple, the parameters such as overshoot, adjustment
time and rise time are not stable in application. In addition, the optimal combination of parameters such as PB, Ti, Td is difficult to find. If the parameters are changed, it is hard to restore the best performance. To this end, the paper adopts the sliding mode control algorithm in modern control theory and studies the water temperature control system as a nonlinear system in order to establish an accurate mathematical model to maintain its original nonlinear characteristics for better control. The procedure of controlling temperature of oil and water is shown in the following figure.

![Flow chart of temperature control](image)

**Figure 2. Flow chart of temperature control**

The following is a temperature experiment based on the sliding mode control algorithm, the result of which can be applied in this study. First, establish an accurate mathematical model of the system:

\[
\begin{align*}
\dot{c}_m_1 &= Q - \alpha_1 (T_1 - T_2) F_1 \\
\dot{c}_m_2 &= \alpha_2 (T_1 - T_2) F_2 - c k_2 u_2 (T_2 - T_0)
\end{align*}
\]

Then obtain the structure of the controller:

\[
\begin{align*}
u_1^+ &= d_1^{-1} (c_1 x_2 - a_1 T_1 - b_1 T_2 + k_1 s_1 + \varepsilon_1) & s_1 > 0 \\
u_1^- &= d_1^{-1} (c_1 x_2 - a_1 T_1 - b_1 T_2 + k_1 s_1) & s_1 = 0 \\
u_1^- &= d_1^{-1} (c_1 x_2 - a_1 T_1 - b_1 T_2 + k_1 s_1 - \varepsilon_1) & s_1 < 0
\end{align*}
\]

It can be seen that the modern sliding mode control algorithm is suitable for temperature control of large inertia by comparing the results of the PID, as shown in Figure 3 and Figure 4:
Simple electrical components such as switches, contactors and relays or PLC can be used in the aforementioned two-position control. The control of water temperature involves the establishment of the mathematical model and the realization of a control algorithm, so it is necessary to use an embedded single-chip system.

5. Conclusion:
Recent years have seen the increasing popularity of solar energy and decrease of fossil fuel consumption and loss of non-renewable energy. Solar heating has also been recognized and supported by the society. Therefore, further study on the selection of heating equipment and pipeline design are conducive to the promotion of solar heating.

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