SOLAR THERMAL CONTROL EFFICIENCY BASED ON AT SERIES MICRO-CONTROLLER

by

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Aiming at the problems of water temperature and water level control system of conventional solar water heater and low solar thermal control efficiency, this paper developed an AT series single-chip solar water heater control system for rural areas. In this paper, the detailed design of hardware and software is presented, and the method of evaluating the collector efficiency is simplified by the temperature rise rate and solar irradiance of the collector plate. The software compensation algorithm we adopted can effectively reduce the impact of different water quality on water level measurement and improve solar thermal control efficiency. It is found that the control system designed in this paper has the characteristics of low cost, high safety, and strong practicability.

Key words*: water level detection, AT series single-chip micro-computer, thermal energy control efficiency controller, in rural areas, solar water heater*

Introduction

As the most mature technology in the solar energy industry, solar thermal utilization has achieved unprecedented development, making it occupy an essential position in the solar energy industry and renewable energy utilization. The popularization and application of solar water heater in rural areas are beneficial to improving the rural ecological environment and improving farmers' living standards. Found in the long-term practice, however, the existing solar water heater control system on the market there are many factors is not suitable for application in rural areas, has affected the application of solar energy water heater in the rural areas, such as water level measurement result is not accurate, waterflood overflow or empty sun burning phenomenon such as electrical safety is not high, and expensive.

At present, the research on energy conservation of solar central hot water systems mainly focuses on local devices' performance, such as collector efficiency and thermal insulation measures. There is basically no research literature on energy conservation control of solar central hot water system. Because of the dispersibility, discontinuity, and instability of solar radiation, the solar hot water system is a complex non-linear system with time-varying parameters. Simultaneously, users' water demand will also change with random uncertain factors such as ambient temperature and water usage. At present, most solar hot water systems' control mode has nothing to do with the aforementioned factors, limiting the system's energy-saving effect to a certain extent [1].

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This paper introduces a water level and water temperature control system of the solar water heater suitable for rural applications. Meanwhile, based on the current evaluation method of collector efficiency based on temperature change rate, this paper adjusts system control parameters through real time evaluation of solar collector efficiency so that the solar hot water system can realize adaptive control of the system according to environmental conditions and users' water needs, to maximize the solar energy utilization rate of the system and to reduce the running time of auxiliary heat source under the premise of ensuring the user's water demand, to achieve the purpose of optimizing energy saving.

The efficiency of a flat plate collector and its energy balance temperature

A flat plate collector is a kind of common low temperature thermal utilization collector. As the collector temperature increases, the collector's heat dissipation rate speeds up, so the heat collecting efficiency of the collector decreases with the increase of the temperature:

$$\eta = \frac{Q_U}{AG} = (\tau\alpha)_c - \frac{U_L(t_p - t_a)}{G} \tag{1}$$

where Q_U is the energy acquired by the collector over a while, A – the collector area, G – the solar irradiance, $\tau\alpha$ – the significant product of the transmission ratio of the transparent cover plate, and the heat absorption ratio of the heat absorption plate, U_L – the total heat loss coefficient of the collector, t_p – the collector temperature, and t_a – the ambient temperature [2].

When the collector balances the heat converted from solar energy with the heat emitted by itself, its heat collection efficiency is zero. At this time, the collector temperature, t_p, is called the energy balance temperature. Figure 1 shows the change of the collector's outlet temperature with time under the condition that the ambient temperature is 23 °C, and the solar irradiance is about 600 W/m^2. The experimental data show that, under certain conditions, the collector's heat collecting efficiency decreases with the increase of its own temperature, and its change rule is basically consistent with eq. (1). The energy balance temperature of the collector is 85 °C.

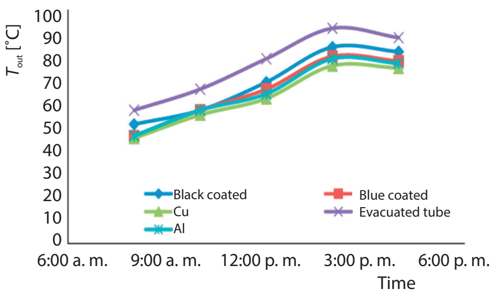

Figure 1. Variation of outlet temperature of the collector

In this paper, the current efficiency, η, of the collector is evaluated by calculating the average efficiency, η', per unit time of the collector with the temperature rise rate, T', (*i.e.*, the temperature change rate of the collector) and the solar irradiance:

$$\eta' = \frac{T'C_p P}{60G} \tag{2}$$

where C_p [Jkg^{-1}°C^{-1}] is the specific heat capacity of water, T' [°Cmin^{-1}] – the temperature rise rate of a collector, P [kgm^{-2}] – the water capacity in the unit area of collector, and G [Wm^{-2}] – the average solar irradiance per unit time. As the period of water temperature data collected by this system represents 1 minute, as long as G in eq. (2) approximately represents the average solar irradiance within 1 minute, the collector's current efficiency $\eta \approx \eta'$ can be recognized as the determined value. For a specific project, collector parameter P = 1 kg/m^2 and specific heat capacity of water, which are adopted in this experiment C_p = 4200 J/kg°C, can be substituted into eq, (2) to obtain:

$$\eta \approx 70\frac{T'}{G} \tag{3}$$

Equation (3) shows that the collector's current efficiency can be approximately evaluated as long as the temperature rise rate and solar irradiance are measured.

Water level detection method and improvement of solar water heater

The water level detection in the water tank is significant for the multifunctional and intelligent solar water heater. Manufacturers, developers, and academic circles at home and abroad attach great importance to solar water heaters' water level detection technology. They have developed a variety of water level sensors such as electrode type, float ball type, and capacitive type, but due to scale, cost and installation complexity*, etc.*, they have not been widely used. The resistive water level sensor is one of the most common water level sensors in the solar water heater [3].

Working principle of resistance type water level sensor

The basic principle of resistive water level sensor is that water containing inorganic salts or minerals has a specific electrical conductivity, which can short-circuit the resistance immersed in it, thus converting the liquid level into resistance output, realizing water level measurement. Shown in fig. 2 for the internal structure resistance type water level sensor, lead concatenated four resistance between A and B, typical resistance, respectively R_1 = 30 kΩ, R_2 = 10 kΩ, R_3 = 10 Ω, R_4 = 10 kΩ, placed in the water tank water level 0, 20%, 50%, and 80% of the position, and enclosed within the rubber rod, tube feet through the conductive rubber lead to resistance.

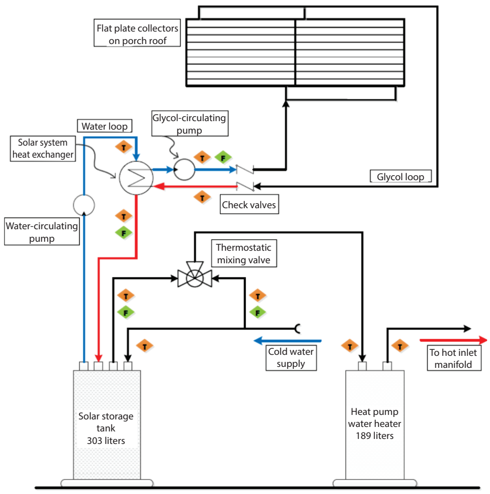

Figure 2. Schematic diagram of the water level sensor of electric resistance solar water heater

We measured, the sensors are vertically into the water tank, conductive rubber or immersed in water or expose in the air if the water dissolved minerals or inorganic salt, has the strong conductive ability, the resistance between the conductive rubber was a short circuit or equivalent in parallel A small resistance is negligible, leading to significantly reduce the resistance between A and B. The equivalent resistance values of sensors at level 0, 20%, 50%, 80%, and 100% are shown in tab. 1.

Table 1. Equivalent resistance values of sensors at different water levels

Water [%]	Equivalent resistance [kΩ]
0	60
20	50
50	40
80	30
100	0

When the system is applied, only the sensor's actual output resistance can be measured by various circuits, and then the real time water level in the water tank can be obtained by looking up the table. Found in the long-term practice, however, due to the rural areas into the solar water heater with well water, mountain spring water, stream, and pond water or river, mountain, and water quality and the coastal water quality difference are more prominent, under the same water level change on a wide range of sensor signal, so that measurement, the solar energy water heater waterflood overflow or empty sun burning wait for a phenomenon.

Influence of water quality on water level measurement

When the resistance is immersed in water, it can be equivalent to r_w water resistance in parallel between the resistance pins. If the difference in water resistance caused by the distance between the resistance pins at different taps is ignored, the sensor's equivalent circuit at different water levels is shown in fig. 3.

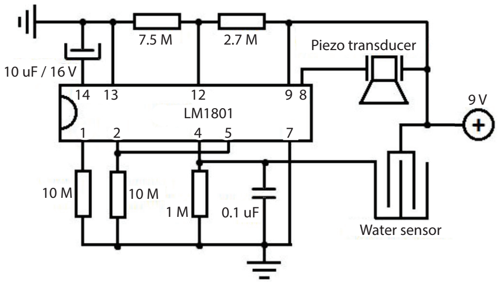

Figure 3. Equivalent circuit diagram of water level sensors at different water levels

As shown in fig. 3, water resistance, r_w, varies significantly with different water purity, and the output resistance of the sensor at all levels is shifted with the change, r_w. If the water level is judged in any case according to the data in tab. 1, the measurement results are highly biased. The higher the water's purity, the greater the r_w value, and the greater the error [4].

The idea of automatic compensation for water quality errors

The corresponding relationship between each stage's water level and the sensor resistance in water quality such as well water, mountain spring water, xitang water, river water, and tap water was determined by experiment and stored in different tables. Before the solar water heater is put into use, the water source used is set, and different data are selected according to different water sources to check the table and determine the actual water level.

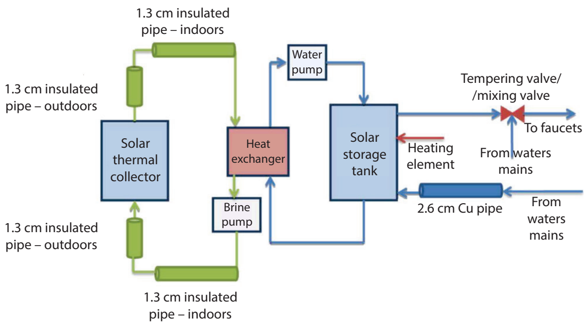

Figure 4. Control system diagram of solar water heater

Hardware design of control system

The solar water heater control system requires the functions of water level detection, water temperature detection, water injection control, auxiliary electric heating control, pipe insulation control, power loss data storage, lightning protection, and leakage protection. The system block diagram is shown in fig. 4.

The EM78P468 MCU

The EM78P468 is a cost-effective single-chip micro-computer launched by Yilong for middle and high end products, abundant internal resources, and a more straightforward system design. The bidirectional I/O port has the characteristics of high input impedance and large output current, which is very suitable for the occasion of capacitance charge-discharge resistance measurement. Moreover, the number of I/O ports is large, without external expansion. Another outstanding advantage is the choice of bare film in mass production, significantly reducing the product [5].

Water temperature and water level measurement circuit based on capacitor charge and discharge technology

In a solar energy water heater, a commonly used thermistor measures water temperature because this water temperature and water level measure essence is resistance measure. The standard methods of measuring resistance are the series voltage divider method and the bridge method. These measurements require A/D converters, which are expensive and do not meet the low cost solar water heater controllers' low cost requirements. The system USES the capacitive charging and discharging technology to convert the resistance into charging time, and the time value is measured and calculated to obtain the resistance value. Figure 5 shows the water temperature measuring circuit.

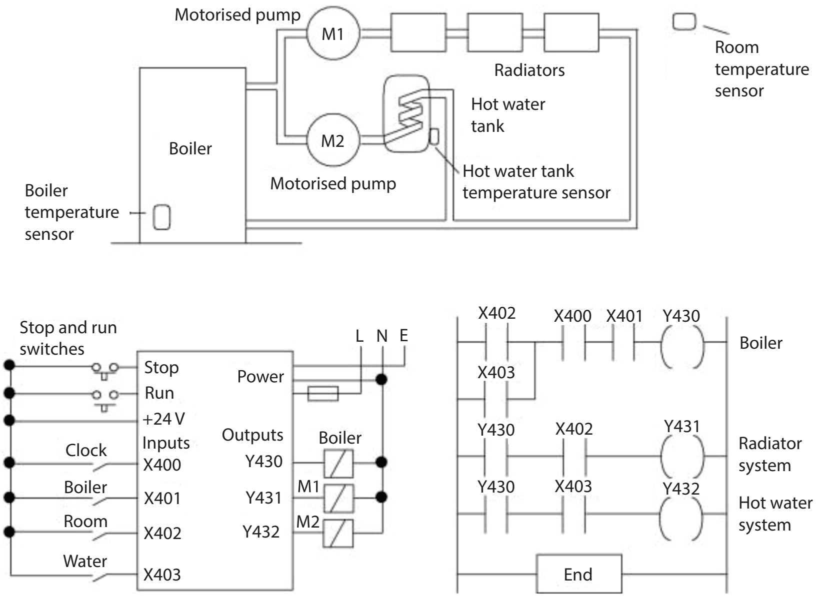

Figure 5. Water temperature and water level measurement circuit

To prevent lightning from rushing into the controller through the sensor cable, after the water level sensor, *Rs*, and thermistor, *Rt,* are connected to the circuit board, the system is first treated by the voltage-sensitive resistor. When measuring water temperature, P60 and P61 are first set as output pins to a low output level and keep it for a long enough time to fully make the capacitor discharge. Then, P61 is set as the input pin, P60 is set to a high output level, and the capacitor is charged through thermistor *Rt* until the voltage on the capacitor is higher than the threshold voltage of the MCU I/O port. The P61 is reversed to a high level, and the charging process ends. At the same time, the system USES a timer to count the charging time of the capacitor. The water temperature in the water tank of the solar water heater can be measured by the relationship between the predetermined charging time and temperature. Similarly, the system can measure the water level in the tank [6]. As an electrode, the conductive rubber on the water level sensor is immersed in hot water containing impurities for a long time, easy to scale, and insulated from the outside world. To this end, we should reduce the sensor's power supply time as much as possible and adopt the square wave driving technology. For example, after measuring the sensor resistance, set P63 to output a high level, and P62 to output a low level, generating a reverse current to flow through the water level sensor.

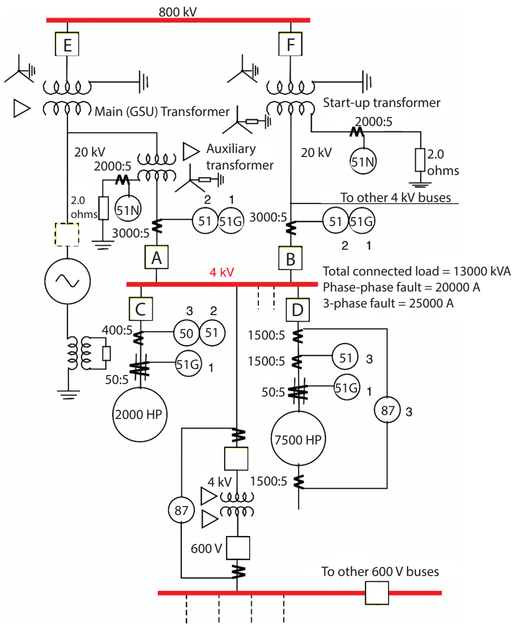

Figure 6. Schematic circuit diagram of an auxiliary electric heating control system

The auxiliary electric heating control circuit

The system USES relays to control the start and stop of heating wire. The circuit principle is shown in fig. 6. The MCU I/O port output high level, S8050 conduction, relay suction, heating wire heating. On the contrary, I/O port output low power naturally stop heating. Because of the current non-standard power connections in rural areas, two relays simultaneously control the fire line and zero lines to improve safety performance. The function of diode, D_1, is to prevent interference from infiltrating into a single-chip micro-computer through the I/O port and improve the system's anti-interference performance [7].

Leakage detection

The principle of leakage detection is an input current winding and an output current winding around an iron core. When there is no leakage, the input current and the output current are equal. If the vector sum of the two magnetic flux on the iron core is zero, the potential will not be induced on the third winding. Otherwise, the third winding will form an induction voltage after filtering and rectification drive the switch tube and alarm the SCM. Its schematic diagram is shown in fig. 7.

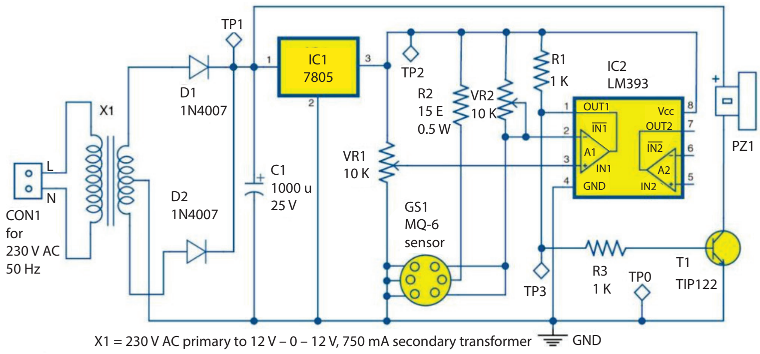

Figure 7. Leakage detection circuit

Power supply

The system needs three kinds of power supply, namely the 12 V power supply used to drive the solenoid valve, relay, and other operating devices, the power supply Vcc1 in regular operation, and the power supply Vcc2 a power failure. The circuit is shown in fig. 8. After 220 V voltage is reduced by the transformer, diode rectification, and capacitor filtering, +12 V voltage is generated, and then Vcc1 is obtained after 7805 voltage stabilization. The D_5 can prevent interference signals from jumping into 7805, and R4 and R5 are used for power loss detection. During regular operation, *Pd* outputs a high level. In case of power failure, *Pd* output is low. During regular operation, Vcc1 charges the battery B1 through R7. In case of power failure, B1 shall supply power to the MCU to ensure that the essential parameters in THE MCU RAM are not lost.

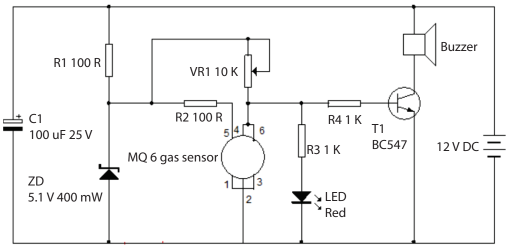

Figure 8. Power circuit

Software design of measurement system

The solar water heater control system has many tasks, and each task is coupled to each other. The system draws on the idea of modular program design to decompose the total task into several program modules with specific tasks. Messages are used for communication among each task, and the task scheduling is carried out by time slice rotation method. The system design program structure is clear, the combination is flexible, and the debugging maintenance is very convenient.

Task scheduling algorithm

Based on a chip timer, the system realizes multiple virtual timers and completes each sub-task scheduling. Timer TCC interrupts every 1 ms, adds 1 to each virtual timer in the interrupt service subroutine, and judges whether the virtual timer corresponding to each subtask overflows in the main program to determine whether the subtask needs to be executed. Table 2 lists the subtasks of the system and their respective execution cycles [8].

Table 2. System sub-tasks and each execution cycle

The subtasks	Cycle [ms]	The subtasks	Cycle [ms]
Buttons to scan	20	Leak off detection	5
Dynamic display	20	Water level and temperature measurement	1 000
Leakage processing	20	The key to deal with	500
Flood control	500	Electric heating control	500
Alarm processing	500	Pipe insulation control	500

Water level measurement and calibration program

Before the test, we took one copy of well water, mountain spring water, existing water, river water, and tap water from the mountainous and coastal areas. We calibrated the charging time under different water quality with capacitor charging and discharging technology. The data obtained was stored in a single chip micro-computer. During our measurement, the user selects the water source and then looks up the table in the corresponding table according to the charging time to determine the final water level.

Water injection control subroutine

There are three water injection control modes: manual water injection, timed water injection, and protective water injection:

– Users can manually fill the water tank at any time by pressing the button and stop when the tank is full.

- The user can start filling water at a preset time and stop when the present maximum water level is reached.
- When the system detects that the water level in the water tank is lower than 20% and the temperature in the water tank is less than 70 °C, it will automatically fill water to 20%.
- If the water level in the water tank is lower than 20% and the water temperature is higher than 70 °C, automatic water filling is prohibited to prevent pipe explosion.
- If the water level in the water tank is lower than 100% and the water temperature is higher than 99 °C, water will be filled automatically to make full use of solar energy.
- No matter in which mode the water injection starts, the user can stop the water injection at any time by pressing the button.
- When the user is injecting water, it is necessary to count the time of injecting water. If the water level does not rise after 30 minutes of continuous water injection, the water injection should be stopped, and the users should be reminded of the possibility of water pipe rupture or low water pressure by sound and light alarm [9].

Auxiliary electric heating control subroutine

There are three auxiliary electric heating control modes: manual heating, regular heating, and constant temperature mode.

- Users can manually heat at any time by pressing the button and stop when the water temperature rises to the highest temperature.
- The user can start heating at the preset time and stop when the present maximum water temperature is reached.
- If the user sets the constant temperature mode, the water temperature will start heating when it is lower than the set minimum temperature, stop heating when it reaches the highest temperature. The water temperature in the water tank will remain constant.
- No matter in which mode the heating starts, the user can stop at any time by pressing the button.
- During heating, if the water level is lower than 20%, stop heating to prevent open burning; In case of leakage signal, immediately cut off the power supply, and send sound and light alarm signal.

Conclusions

Aiming at the practical problems existing in the popularization and application of solar water heater in rural areas, a water temperature, and water level control system is designed. The designed system has the following characteristics.

- We use software to realize the automatic compensation for water level measurement error under different water quality, which improves the precision and versatility of water level measurement.
- The capacitor charge-discharge technology adopted in this paper converts the analog water temperature and water level signals into digital signal output. The system does not need the A/D converter, and the cost is low.
- In the auxiliary electric heating control system, we use two relays to control the fire line and zero lines, respectively, which avoids the electric shock accident caused by irregular wiring in rural areas and enhances the system safety.
- The application of modular programming method, inter-task messaging mechanism, and time-slice task scheduling algorithm makes the system program have the characteristics of clear structure, flexible combination, and convenient debugging and maintenance.

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