

Design and Evaluation of a Heat-Pipe–Based Concentrating Solar Vacuum Photothermal Reactor

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Introduction

Currently, research on concentrating photothermal reactors primarily focuses on structural optimization, material properties, and spectral response[1-4].

Traditional vacuum photothermal reactors under concentrating conditions are prone to coating degradation at elevated temperatures and to tube fracture due to large temperature differentials between the inner and outer glass tubes[5-6]. This work designs a heat-pipe vacuum photothermal reactor featuring a double-layer vacuum glass-tube structure, an axial cylindrical heat-absorbing body in the inner tube, and heat pipes for heat export[7].

The reactor comprises a double-layer vacuum glass tube, axial cylindrical fins, a heat pipe, and an insulating plug. The heat pipe is positioned in the slots of the fins, which are coated with black chromium. The heat pipe and the axial fins are nested, while the inner glass tube remains isolated from the heat-storing medium. The condensate end of the heat pipe passes through the insulating plug and extends to the tube opening.

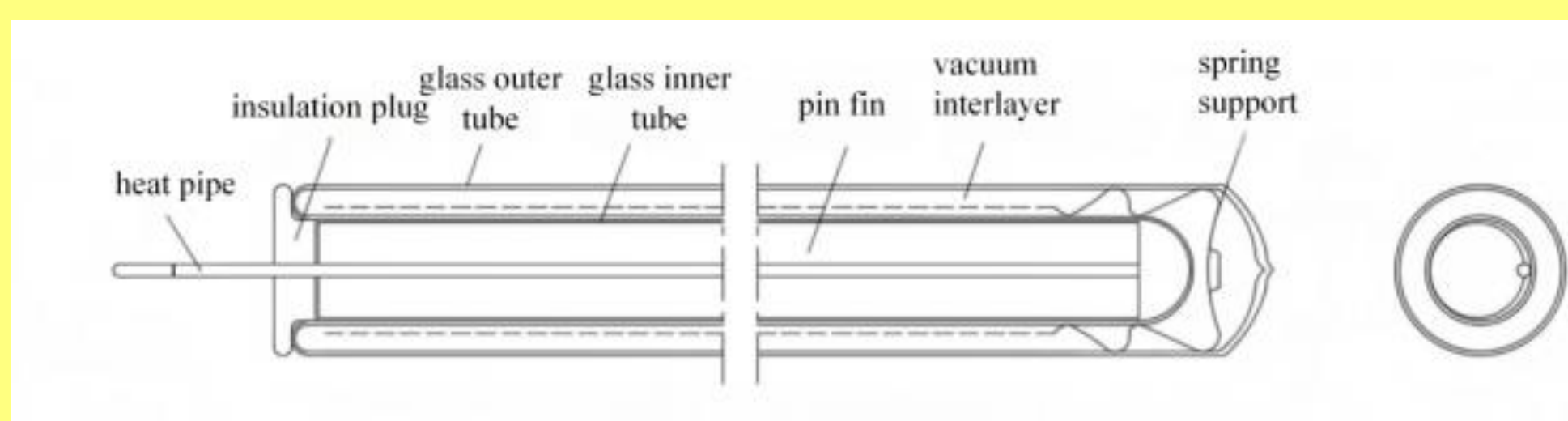


Fig. 1. System set-up.

Under concentrating conditions, the new reactor uses a high-temperature-resistant metal heat absorber, and the heat pipe exhibits high heat transfer efficiency; the glass inner tube does not contact the thermal storage medium, which effectively mitigates coating degradation and tube rupture.

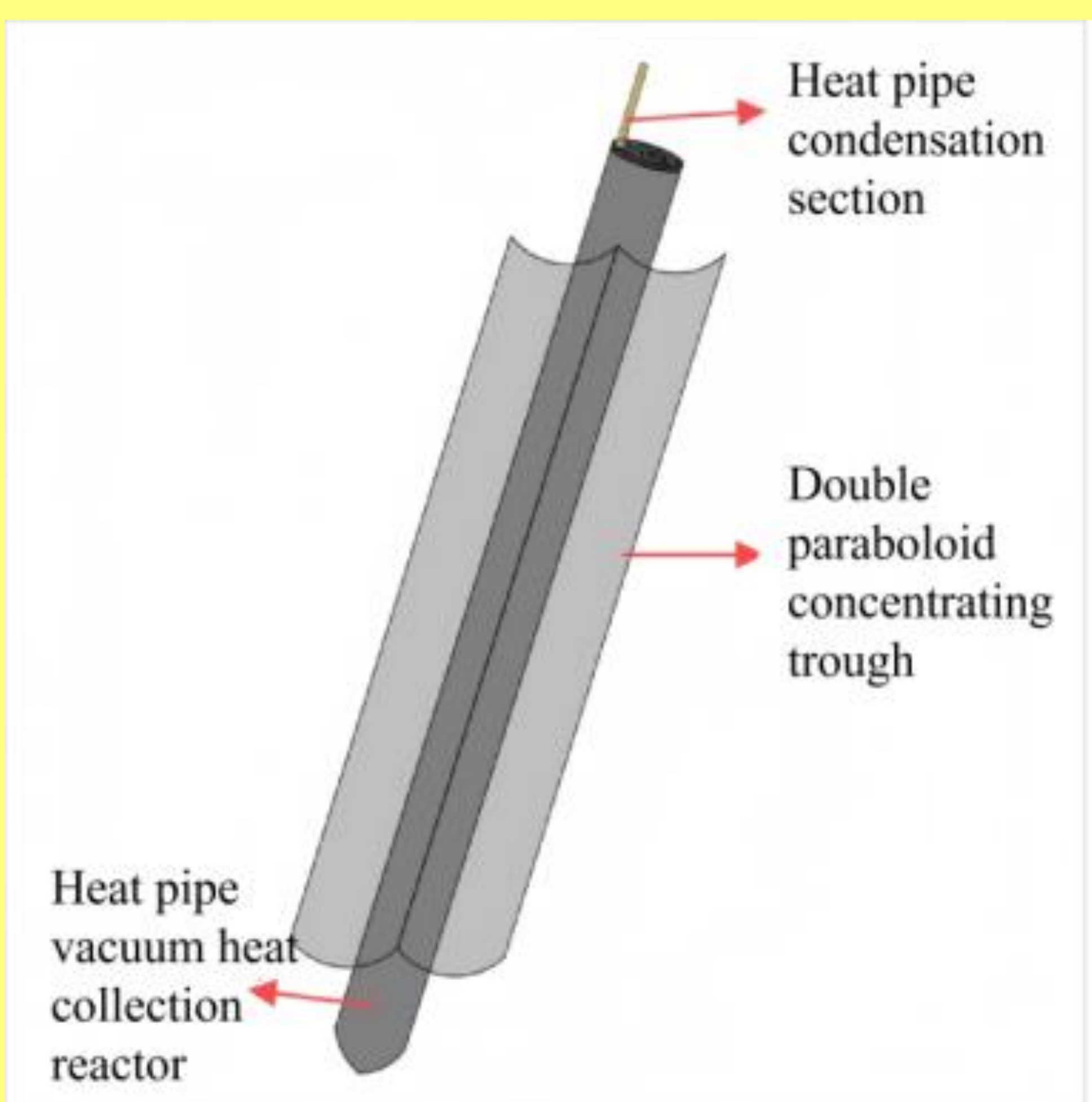


Fig. 2. Testing system

Outdoor Testing

Outdoor testing was conducted under identical dimensions using a traditional all-glass vacuum-tube as a control under the same concentrating conditions, and the daily useful heat was calculated as q_{17} (the daily heat corrected to a solar irradiance of 17 MJ/m²). Theoretical quantities were obtained using the following relations[8]:

Under concentrating conditions, the temperature in the water tank varies with time as shown in Figure 3. The final water temperature in the experimental group is 70.2 °C, while that in the control group is 60.1 °C, the experimental group is higher by 10.1 °C. The experimental group's average heating rate is 0.15–0.20 °C/min, compared with 0.08–0.12 °C/min for the control group, with the experimental group being evidently higher. The analysis attributes this phenomenon to the synergistic enhancement arising from the heat-pipe phase-change heat transfer mechanism and the dual-parabolic-cone concentrator.

$$Q_c = \rho_w V_s c_{pw} (t_e - t_b) \quad (1)$$

$$q = Q_c / A_c \quad (2)$$

$$\sigma = 17/H \quad (3)$$

$$q_{17} = \sigma q \quad (4)$$

$$\eta = q / H \quad (5)$$

Q_c -total heat delivered by the solar collector,J;

ρ_w -density of water,kg/m³;

c_{pw} -water specific heat capacity,J/(kg·°C);

V_s -volume of water in the insulated tank,m³;

t_e -final temperature at the end of the heating test, °C;

t_b -initial temperature of the heating test, °C;

q -heat gained per unit area,J/m²;

A_c - solar-collecting area,m²;

H -total irradiance during the test period,J/m²;

σ -conversion factor;

η -thermal efficiency,percentage.

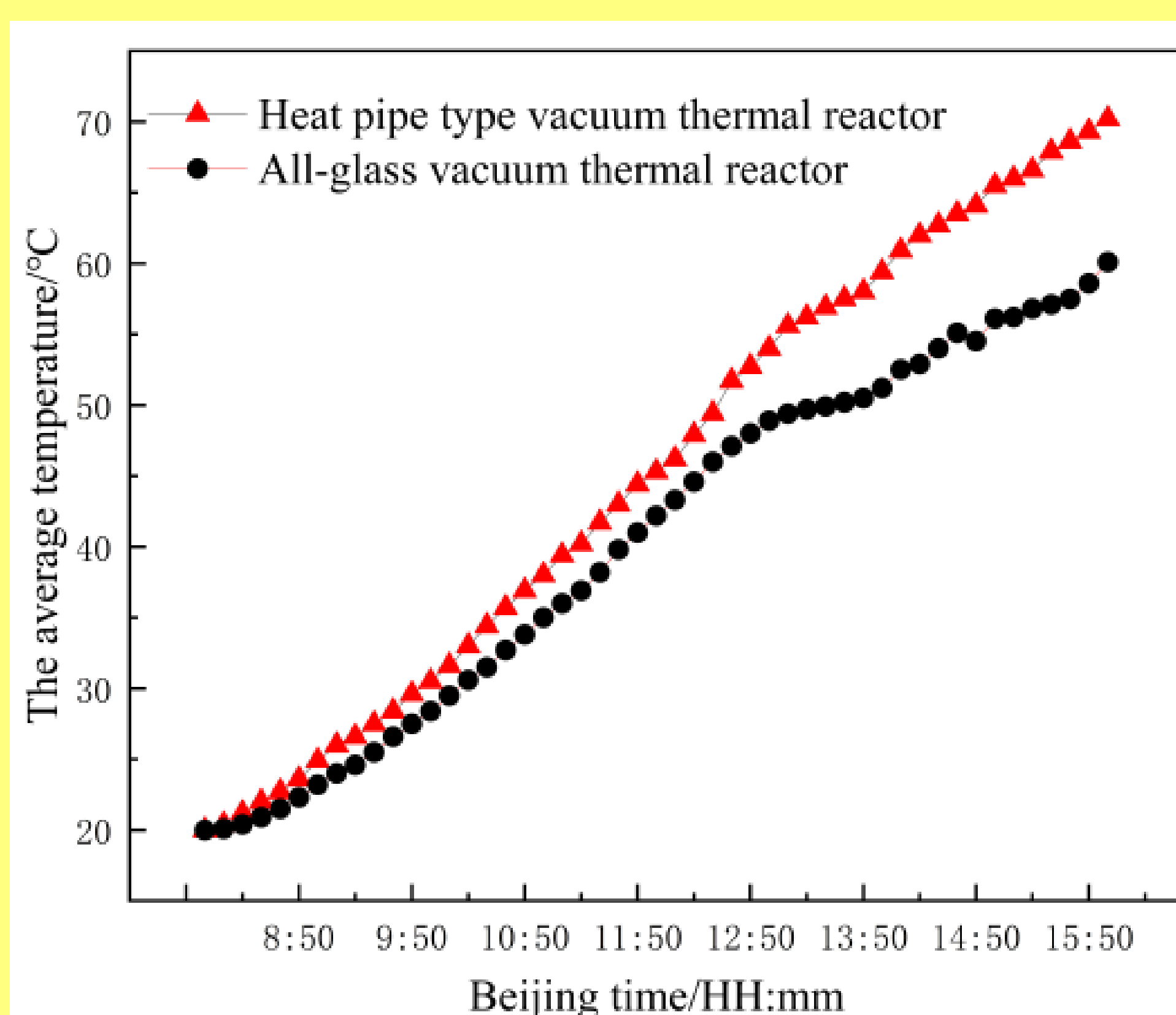


Fig. 3. Average water temperature in the tank varies with temperature.

The experimental group yields $Q_c = 2.45$ MJ, with a corrected q_{17} of 8.85 MJ/m². The control group yields $Q_c = 1.96$ MJ, with a corrected q_{17} of 7.06 MJ/m². Compared with the control group, the experimental group's heat yield increased by 25.3%. The thermal collection efficiencies are 47.6% (experimental) and 38.0% (control), respectively, indicating a 9.6 percentage-point.

Conclusions

This study designs and fabricates a novel heat-pipe concentrating vacuum photothermal reactor, discusses its structural features and operating principles, and conducts outdoor heat-performance experiments under concentrating conditions, using a traditional all-glass vacuum photothermal reactor as the control.

(1)The corrected heat gained under concentrating conditions by the heat-pipe concentrating vacuum photothermal reactor is 8.85 MJ/m², representing a 25.3% improvement over the all-glass reactor's 7.06 MJ/m².

(2)The outlet water temperature reached 78.6 °C in the heat-pipe reactor, 11.8 °C higher than that of the control, resulting in a heat-collection efficiency of 47.6% compared with 38.0% for the control.

(3)The selective absorbing coating of the heat-pipe type concentrated vacuum photothermal reactor is not deposited on the glass tube, the temperature difference between the inner and outer tubes is relatively small, which reduces the risk of tube rupture and coating degradation.

Overall, the heat-pipe vacuum photothermal reactor demonstrates higher solar-thermal collection efficiency and greater system stability. The results reveal a synergistic enhancement arising from the coupling of phase-change heat transfer and the concentrating heat generation effects. This further demonstrates the effectiveness and rationality of the structural and material design of the heat-pipe concentrated vacuum photothermal reactor.

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