

DEVELOPMENT OF AN ADAPTIVE HEAT-TRANSFER CONTROL METHOD AND DEVICE FOR CONCENTRATED SOLAR THERMAL ENERGY SYSTEMS

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Annotation

This paper proposes an adaptive concentrated solar thermal system designed to regulate heat transfer from a solar receiver to a heat exchanger by automatically adjusting the distance between these components. The system consists of square reflective plates, a parabolic reflector, a solar receiver, a movable heat exchanger, a temperature monitoring unit, and an automatic control mechanism. Concentrated solar radiation is converted into thermal energy at the receiver and transferred to a working fluid through the heat exchanger. The collected heat can subsequently be used for industrial process heating or boiler feedwater preheating in thermal power plants. The proposed approach aims to adapt heat extraction to variations in solar irradiance and receiver temperature. The paper presents the system architecture, governing energy-balance equations, a proposed control algorithm, and a methodology for experimental validation. Particular attention is given to the relationship between exchanger position and heat-transfer intensity. The proposed device requires numerical modelling and experimental testing to establish its performance, operational safety, and potential energy-saving benefits.

Keywords

concentrated solar energy, parabolic reflector, solar receiver, movable heat exchanger, adaptive control, thermal energy, heat transfer, boiler feedwater preheating.

**Quyosh energiyasini konsentratsiyalash tizimlarida issiqlik uzatishni adaptiv
boshqarish usuli va qurilmasini ishlab chiqish**

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Annotatsiya

Ushbu maqolada quyosh energiyasini konsentratsiyalash asosida ishlaydigan, quyosh qabul qilgichi va issiqlik almashgich orasidagi masofani avtomatik o'zgartirish orqali issiqlik uzatishni boshqarishga mo'ljallangan tizim taklif etiladi. Tizim kvadrat qaytargich plastinalar, parabolik qaytargich, quyosh qabul qilgichi, harakatlanuvchi issiqlik almashgich, harorat datchiklari va avtomatik boshqaruv mexanizmidan tashkil topadi. Konsentratsiyalangan quyosh nurlanishi qabul qilgichda issiqlik energiyasiga aylantirilib, issiqlik almashgich orqali ishchi muhitga uzatiladi. Olingan issiqlikdan sanoat jarayonlarida yoki issiqlik elektr stansiyalarida qozon ta'minot suvini dastlabki isitishda foydalanish imkoniyati ko'rib chiqiladi. Taklif etilayotgan yondashuv quyosh nurlanishi jadalligi va qabul qilgich haroratining o'zgarishiga mos ravishda issiqlik olish jarayonini boshqarishga qaratilgan. Ishda tizimning konstruktiv tuzilishi, issiqlik balansining matematik ifodalari, avtomatik boshqarish algoritmi va tajribaviy tekshirish metodikasi bayon etilgan. Issiqlik almashgichning joylashuvi bilan issiqlik uzatish jadalligi o'rtasidagi bog'liqlikni aniqlashga alohida e'tibor qaratilgan. Taklif etilgan qurilmaning samaradorligi va energiya tejash imkoniyatlarini aniqlash uchun matematik modellashtirish hamda tajribaviy tadqiqotlar o'tkazish zarurligi asoslangan.

Kalit so'zlar: quyosh energiyasi, quyosh energiyasini konsentratsiyalash, parabolik qaytargich, quyosh qabul qilgichi, harakatlanuvchi issiqlik almashgich, adaptiv boshqaruv, issiqlik uzatish, issiqlik elektr stansiyasi, qozon ta'minot suvini dastlabki isitish.

1. Introduction

Concentrated solar thermal (CST) systems use reflective surfaces to redirect direct solar radiation toward a receiver, where radiant energy is converted into heat. Depending

on receiver design and the working medium, the resulting thermal energy can be supplied to industrial processes, used for water or steam heating, or integrated into a power-generation cycle [1–4]. Compared with photovoltaic conversion, a solar thermal system can deliver heat directly and may be combined with thermal storage when suitable system components are included [2,3].

A key operational challenge is the variability of solar irradiance. Passing clouds, changes in solar angle, reflector soiling, and seasonal conditions alter the heat absorbed by the receiver. If heat extraction does not respond to these changes, the receiver may experience excessive temperature, unnecessary thermal losses, or unstable outlet-fluid temperature. Conventional fixed-geometry arrangements do not necessarily adapt the thermal coupling between the receiver and the heat exchanger to the instantaneous operating state.

This study proposes an adaptive mechanism in which the relative distance between the receiver and a movable heat exchanger is adjusted using temperature and irradiance measurements. The central hypothesis is that a controlled change in geometry can regulate the effective heat-transfer rate and help maintain a selected receiver-temperature range. The concept is intended as a controllable thermal interface rather than a replacement for established receiver designs. Its performance must be quantified through modelling and experiments before any efficiency or energy-saving claim can be confirmed.

2. System architecture and operating principle

The proposed device comprises: (i) square reflective plates that direct incident radiation toward a parabolic reflector or focal region; (ii) a parabolic reflector; (iii) a solar receiver with an absorbing surface; (iv) a heat exchanger mounted on a linear actuator; (v) receiver and fluid temperature sensors; (vi) a solar-irradiance sensor; and (vii) a controller with actuator drive and safety interlocks. The exact optical arrangement

and the function of the square plates must be fixed during prototype design to avoid shading and unintended focal displacement.

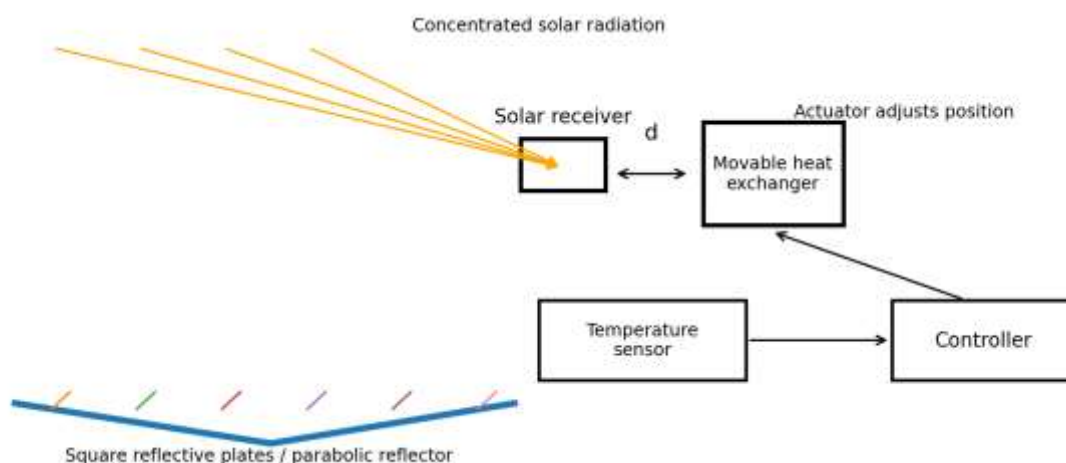


Figure 1. Conceptual arrangement of the adaptive concentrated solar thermal system.

Solar radiation is concentrated on the receiver, which absorbs part of the incident optical power. Heat is then transferred to a working fluid through the exchanger. In the proposed configuration, the exchanger position d is adjustable within a mechanically defined range. A temperature controller commands the actuator to move the exchanger closer to or farther from the receiver, according to a calibrated relationship between position, receiver temperature, irradiance, and measured heat delivery.

The movable assembly should include mechanical end stops, a position encoder, thermal shielding, and a fail-safe position. The control logic must not rely on distance alone: receiver temperature, fluid inlet temperature, flow rate, and irradiance are required to distinguish a genuine change in heat-transfer conditions from sensor drift or fluid-flow interruption. If a high-high temperature threshold is reached, the system should move to its predefined safe state and, where necessary, defocus or interrupt the solar input.

3. Methodology and mathematical model

3.1. Optical and receiver energy balance

A first-order estimate of the solar power absorbed by the receiver is:

$$\dot{Q}_{\text{abs}} = \text{DNI} \cdot A_{\text{ap}} \cdot C_{\text{opt}} \cdot \alpha_{\text{abs}} \quad (1)$$

where DNI is direct normal irradiance (W/m^2), A_{ap} is the effective aperture area (m^2), C_{opt} is the aggregate optical efficiency (dimensionless), and α_{abs} is the receiver absorptance. If concentration ratio is modelled explicitly, it should be incorporated consistently into the optical-flux distribution rather than double-counted in this power balance.

The transient receiver energy balance can be written as:

$$m_r c_r (dT_r/dt) = \dot{Q}_{\text{abs}} - \dot{Q}_{\text{hx(d)}} - \dot{Q}_{\text{loss}}(T_r, T_a) \quad (2)$$

Here, m_r and c_r are the receiver thermal mass and specific heat capacity, T_r is receiver temperature, $\dot{Q}_{\text{hx}}$ is heat transferred to the exchanger, and $\dot{Q}_{\text{loss}}$ represents convective, radiative, and conductive losses. A practical loss model may use:

$$\dot{Q}_{\text{loss}} = h_a A_r (T_r - T_a) + \varepsilon \sigma A_r (T_r^4 - T_a^4) + \dot{Q}_{\text{cond}} \quad (3)$$

where h_a is the effective convective heat-transfer coefficient, A_r is the exposed receiver area, T_a is ambient temperature, ε is effective emissivity, σ is the Stefan–Boltzmann constant, and $\dot{Q}_{\text{cond}}$ accounts for conductive losses. Absolute temperatures must be used in the radiation term.

3.2. Heat exchanger model and position dependence

For a liquid working fluid, the useful heat rate measured on the fluid side is:

$$\dot{Q}_{\text{fluid}} = \dot{m} c_p (T_{\text{out}} - T_{\text{in}}) \quad (4)$$

where $\dot{m}$ is mass flow rate (kg/s), c_p is specific heat capacity ($\text{J}/(\text{kg} \cdot \text{K})$), and T_{in} and T_{out} are inlet and outlet temperatures. The measured fluid-side heat rate is the preferred experimental metric because it quantifies heat actually delivered to the process.

The exchanger heat-transfer rate may also be represented by the conventional effectiveness–NTU relation:

$$\dot{Q}_{hx} = \varepsilon_{hx} C_{\min} (T_{r,eq} - T_{in}), \quad NTU = UA(d)/C_{\min} \quad (5)$$

where ε_{hx} is exchanger effectiveness, $C_{\min}$ is the smaller heat-capacity rate, $T_{r,eq}$ is an effective hot-side temperature, U is the overall heat-transfer coefficient, and A is the effective exchange area. In this concept, distance d can affect the effective thermal coupling, view factor, convective interaction, or contact geometry depending on the physical construction. Therefore, the function $UA(d)$ must be identified experimentally; it should not be assumed to follow a universal inverse-square law.

The control objective is to maintain the receiver near a target temperature while maximizing useful heat delivery within safe limits. A simple proportional–integral controller can be expressed as:

$$u(t) = K_p e(t) + K_i \int e(t) dt, \quad e(t) = T_r(t) - T_{set} \quad (6)$$

The actuator command u is converted into a bounded position setpoint d . The sign of the control action must be determined during commissioning: if moving the exchanger closer increases heat extraction, a high receiver temperature should generally command a smaller distance. Integral anti-windup and a deadband are recommended to prevent oscillation and excessive actuator movement.

3.3. Adaptive control sequence

The proposed algorithm follows six steps: (1) sample DNI, receiver temperature, fluid inlet/outlet temperatures, flow rate, and exchanger position; (2) validate the sensors and confirm minimum fluid flow; (3) calculate $\dot{Q}_{fluid}$ and the receiver temperature error; (4) estimate the current operating state using a calibrated model or lookup table; (5) update the position command with rate limits and upper/lower travel constraints; and (6) check safety thresholds before applying the command. A short moving average may

reduce sensor noise, but its time constant should remain small relative to the receiver's thermal response.

For a first prototype, a lookup table $d^* = f(T_r, \text{DNI}, \dot{m})$ may be more robust than a complex predictive controller. Once sufficient dynamic data are collected, the lookup table can be compared with model-predictive control or gain-scheduled PI control. The design should also include a safe response to loss of flow, temperature-sensor failure, actuator stall, and rapid irradiance changes.

4. Illustrative calculations and discussion

To demonstrate the proposed analysis method, an illustrative receiver with $A_{ap} = 4.0 \text{ m}^2$, $\text{DNI} = 800 \text{ W/m}^2$, aggregate optical efficiency $C_{opt} = 0.70$, and absorptance $\alpha_{abs} = 0.92$ is considered. The estimated absorbed power is $\dot{Q}_{abs} = 800 \times 4.0 \times 0.70 \times 0.92 = 2,060.8 \text{ W}$, or approximately 2.06 kW. This is an example calculation, not a measured output. Actual results depend on aperture geometry, optical intercept factor, tracking accuracy, reflectivity, receiver coating, and thermal losses.

For water flow at $\dot{m} = 0.03 \text{ kg/s}$, $c_p = 4,180 \text{ J/(kg}\cdot\text{K)}$, and a measured temperature rise of 12 K, the fluid-side useful heat rate would be $\dot{Q}_{fluid} = 0.03 \times 4,180 \times 12 = 1,504.8 \text{ W}$. This example shows why both receiver-side energy balance and fluid-side calorimetry should be recorded: their difference can be used to estimate thermal losses and measurement uncertainty.

Figure 2 presents a deliberately illustrative relationship between exchanger position and heat-transfer rate for three irradiance levels. The bell-shaped curves are a hypothesis for a geometry in which both very small and very large gaps can reduce effective heat transfer. They are not obtained from an experiment or validated simulation. The real curve could have a different shape depending on whether the exchanger is in contact with the receiver, coupled by radiation, or connected through a fluid passage.

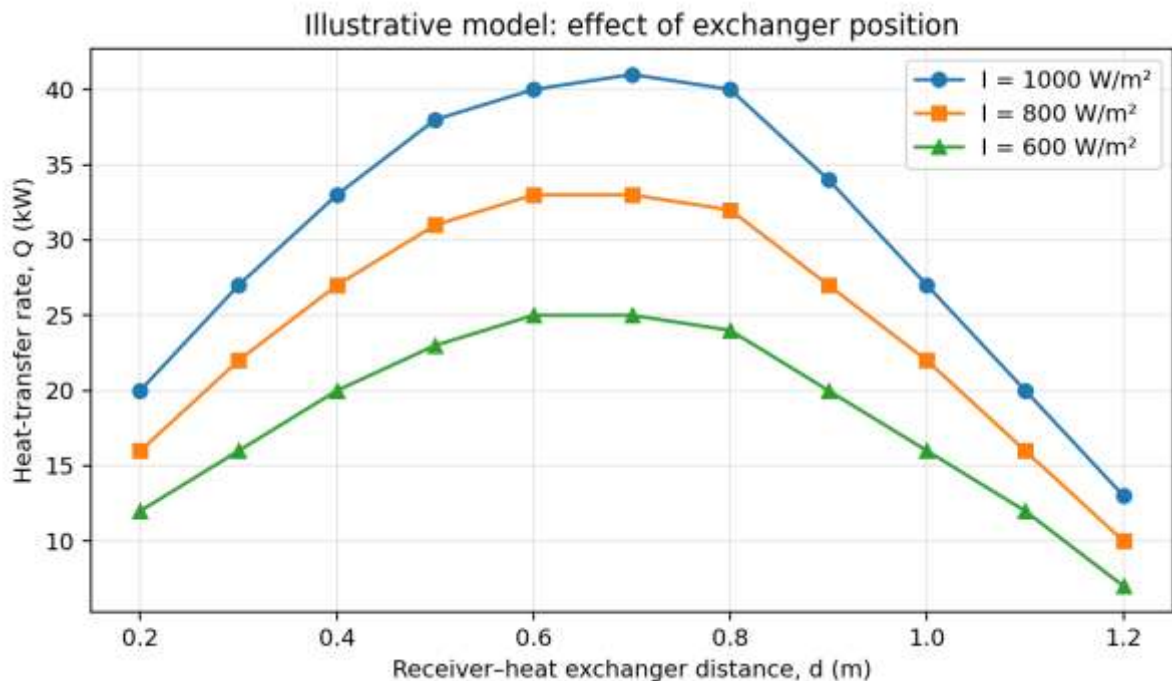


Figure 2. Illustrative, unvalidated model curves showing how exchanger position may influence heat transfer at different irradiance levels.

The graph suggests a testable control principle: determine the operating position that provides the required heat rate without exceeding the receiver-temperature limit, then update that position as irradiance changes. A real controller should optimize a defined objective, for example maximizing $\dot{Q}_{\text{fluid}}$ while constraining $T_r \leq T_{\text{max}}$ and limiting actuator travel. The optimum cannot be claimed from the illustrative graph alone.

5. Experimental validation plan

Validation should proceed in stages. First, calibrate the irradiance sensor, temperature sensors, flow meter, and position encoder. Second, characterize the exchanger at fixed positions under stable irradiance and flow conditions. Third, vary one parameter at a time—position, irradiance, or mass flow rate—and repeat each point to estimate uncertainty. Fourth, compare fixed-position operation with adaptive operation

under a reproducible irradiance profile. A laboratory solar simulator can support repeatable tests; outdoor tests should record DNI and ambient conditions.

At minimum, the data acquisition system should record DNI, T_r , T_{in} , T_{out} , $\dot{m}$, d , actuator power, and timestamps. Suggested evaluation indicators include useful heat rate, receiver peak temperature, tracking error, response time, actuator energy consumption, and the ratio of delivered heat to absorbed solar power. The thermal efficiency can be defined as $\eta_{th} = \dot{Q}_{fluid}/\dot{Q}_{abs}$, provided both terms are measured or estimated on a consistent boundary.

Uncertainty analysis should account for sensor accuracy, calibration drift, flow fluctuations, and temporal mismatch among measurements. Each test point should be repeated, and mean values should be reported with standard deviation or confidence intervals. Safety tests must include blocked flow, sensor disconnection, actuator end-stop activation, and rapid changes in irradiance. Only after these steps can the proposed device's repeatability, durability, and energy-saving potential be evaluated.

6. Conclusion

An adaptive concentrated solar thermal concept has been proposed to regulate heat transfer by adjusting the distance between a solar receiver and a movable heat exchanger. The paper defines the system components, receiver energy balance, fluid-side heat measurement, exchanger model, and a preliminary feedback-control strategy. The concept may be relevant to industrial process heating and boiler feedwater preheating where a controllable source of solar heat can reduce demand on conventional heat supply. The main research contribution is the proposed use of exchanger position as a controllable variable, combined with temperature and irradiance feedback. However, the relationship between distance and heat transfer depends on the actual thermal coupling mechanism and must be experimentally identified. The illustrative curves and calculations are intended to guide test planning, not to demonstrate achieved

performance. Future work should develop a safe prototype, determine the function UA(d), compare fixed and adaptive modes, quantify uncertainty, and assess net energy benefits after actuator consumption is included.

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