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Experimental Study of Time Constant and Continuous Tests on a Solar Cylindrical Cavity Receiver Using Oil for Energy Governance Applications

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Abstract

The integration of decentralized Concentrated Solar Power (CSP) systems into modern smart grids is often hindered by a significant research gap: the lack of high-fidelity data on transient thermal dynamics and the absence of policy-oriented performance metrics. While most studies focus on steady-state efficiency, this research provides a critical shift by presenting a high-fidelity experimental assessment of a cylindrical cavity receiver—integrated with a 1.9 m parabolic dish—under real-world meteorological stressors. Utilizing pure thermal oil, we establish a comprehensive performance baseline by quantifying dynamic response times and exergetic efficiency, effectively bridging the gap between laboratory-scale thermodynamics and field-scale reliability. The core innovation lies in the empirical identification of the system's “thermal agility” and its translation into energy governance indicators. Experimental results reveal distinct thermal characteristics: a rapid heating time constant ($\tau_h \approx 1.48$ min) and a more pronounced cooling retention ($\tau_c \approx 3.81$ min). This asymmetry demonstrates the receiver's potential as a “high-agility asset,” functioning as a natural thermodynamic damper capable of stabilizing power output during transient cloud cover. Complementary exergy analysis quantifies irreversible losses, providing the empirical basis for a necessary transition from conventional first-law accounting to “exergy-aware” governance frameworks. These findings serve as a strategic evidence base for policymakers. We advocate for the integration of time-constant metrics into national certification standards to enhance grid-dispatchability and call for “Exergy Efficiency Tiers” to incentivize superior thermodynamic engineering. Furthermore, the study highlights the role of technological

sovereignty through localized manufacturing of selective coatings. Ultimately, this research validates the dish-cavity configuration as a resilient, governance-ready component for future renewable portfolios.

Keywords: Time constant; Solar dish concentrator; Cylindrical cavity receiver; Thermal oil; Real-condition experimental study.

Nomenclature

Symbol	Description (unit)
Roman symbols	
A_{dish}	Aperture area of the dish concentrator (m ²)
c_p	Isobaric specific heat capacity (J·kg ⁻¹ ·K ⁻¹ or kJ·kg ⁻¹ ·K ⁻¹)
$c_{p,f}$	Specific heat capacity of base fluid (thermal oil)
$c_{p,nf}$	Specific heat capacity of nanofluid
$c_{p,bf}$	Specific heat capacity of base fluid (alternative notation)
$c_{p,np}$	Specific heat capacity of nanoparticle
C	Concentration ratio (dimensionless)
D_{aperture}	Aperture diameter of dish concentrator (m)
D_{conc}	Same as D_{aperture} (m)
D_{out}	Outer aperture diameter of cylindrical cavity (cm or m)
D_{in}	Inner aperture diameter of cylindrical cavity (cm or m)
d_{tube}	Diameter of cavity tube (mm or m)
$\dot{E}_{\text{in, rec}}$	Exergy flow rate entering the receiver (W)

Symbol	Description (unit)
$\dot{E}_{\text{gain}}$	Net exergy gain rate by the working fluid (W)
F_R	Heat removal factor (dimensionless)
h	Height of cylindrical cavity receiver (cm or m)
I_{beam}	Beam (direct normal) solar irradiance ($\text{W}\cdot\text{m}^{-2}$)
I_{DNI}	Same as I_{beam} ($\text{W}\cdot\text{m}^{-2}$)
I_{solar}	Total solar irradiance on aperture ($\text{W}\cdot\text{m}^{-2}$)
k_f	Thermal conductivity of base fluid ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)
k_{nf}	Thermal conductivity of nanofluid ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)
k_{bf}	Thermal conductivity of base fluid (alternative notation)
k_{np}	Thermal conductivity of nanoparticle
$\dot{m}$	Mass flow rate ($\text{kg}\cdot\text{s}^{-1}$)
$\dot{m}_{\text{nf}}$	Mass flow rate of nanofluid ($\text{kg}\cdot\text{s}^{-1}$)
Pr	Prandtl number (dimensionless)
$\dot{Q}_{\text{net}}$	Net heat gain rate by cavity receiver (W)
$\dot{Q}_{\text{useful}}$	Same as $\dot{Q}_{\text{net}}$ (W)
$\dot{Q}_{\text{solar}}$	Incident solar power on dish aperture (W)
$\dot{Q}_{\text{radiation}}$	Same as $\dot{Q}_{\text{solar}}$ (W)
T	Temperature ($^{\circ}\text{C}$ or K)
T_f	Temperature of thermal oil (K)
T_{in}	Inlet temperature of working fluid (K or $^{\circ}\text{C}$)

Symbol	Description (unit)
T_{out}	Outlet temperature of working fluid (K or °C)
T_{inlet}	Same as T_{in}
T_{outlet}	Same as T_{out}
$T_{f,i}$	Initial fluid temperature at start of heating (K or °C)
$T_{f,ss}$	Steady-state fluid temperature after heating (K or °C)
T_{amb}	Ambient (surrounding) air temperature (°C or K)
T_0	Dead-state (reference) temperature, here 298 K
T_{sun}	Effective blackbody temperature of the Sun (5800 K)
U_L	Overall heat loss coefficient ($\text{W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$)

Greek symbols

η_{th}	Thermal (energy) efficiency (dimensionless)
η_{opt}	Optical efficiency (dimensionless)
η_{ex}	Exergy efficiency (dimensionless)
η_{exergy}	Same as η_{ex}
$\eta_{ex,s}$	Exergy factor for solar radiation (Petela model)
ψ_{solar}	Same as $\eta_{ex,s}$ (dimensionless)
$\theta(t)$	Dimensionless temperature difference (heating or cooling)
τ	Time constant (thermal characteristic interval) (s)
ρ_f	Density of base fluid ($\text{kg}\cdot\text{m}^{-3}$)
ρ_{nf}	Density of nanofluid ($\text{kg}\cdot\text{m}^{-3}$)

Symbol	Description (unit)
ρ_{bf}	Density of base fluid (alternative notation)
ρ_{np}	Density of nanoparticle
φ_p	Nanoparticle volume fraction (dimensionless)
Subscripts	
f	Base fluid (thermal oil)
nf	Nanofluid
bf	Base fluid (alternative)
np	Nanoparticle
in	Inlet
out	Outlet
amb	Ambient
0	Dead state / reference
sun	Sun
net	Net (useful)
solar	Incident solar
useful	Same as net
radiation	Incident radiative power
gain	Exergy gained
Abbreviations	
HTF	Heat-transfer fluid
HCF	Heat-carrying fluid (used synonymously)

Symbol	Description (unit)
PLC	Programmable logic controller
TEM	Transmission electron microscopy
DNI	Direct normal irradiance

1. Introduction

The global energy landscape is currently undergoing a profound paradigm shift, driven by the urgent need to decarbonize industrial and domestic sectors. This transition toward a sustainable energy future is fundamentally intertwined with the principles of global energy governance, which dictates the strategic deployment and management of renewable technologies. As outlined by Florini and Sovacool [1], the governance of energy systems is a multi-dimensional challenge that requires the harmonization of international policy frameworks with local technological implementation. The effectiveness of these governance structures is often hindered by institutional fragmentation, which creates barriers to the widespread adoption of low-carbon innovations [2]. According to the empirical findings of Dyck et al. [3], there is a direct correlation between high-level corporate and environmental governance and the performance of renewable energy infrastructures. This suggests that the success of solar energy projects is not solely a matter of engineering excellence but also of policy coherence and transparency. Furthermore, at the regional level, the role of legislative oversight, such as the supervision provided by regional representative councils, is crucial for ensuring that energy transitions are inclusive and sustainable [4]. The synergy between advanced solar concentration technologies and robust governance frameworks is essential for achieving long-term energy security and fostering the growth of decentralized thermal energy networks [5].

Among the diverse array of solar-to-thermal conversion technologies, parabolic dish concentrators stand out for their ability to generate high-quality thermal energy due to their exceptional concentration ratios. The efficiency of these systems is primarily determined by the performance of the solar receiver, which acts as the heat-exchanging interface at the concentrator's focal point [3]. Comprehensive reviews by Kasaeian et al. [6] have demonstrated that the geometric design of the receiver is the most influential factor in minimizing energy losses and maximizing exergy gain. In contrast to external or flat-plate receivers, cavity-type receivers are engineered to minimize radiative and convective spillage by creating an enclosed environment that traps solar radiation [7]. The optical performance of these cavity receivers is highly dependent on the “interception factor,” which represents the fraction of reflected radiation that successfully enters the cavity aperture [8]. As highlighted by Wu et al. [9], the thermal degradation of these systems is often caused by the natural and forced convection of air within the cavity, necessitating a precise optimization of the aperture-to-cavity diameter ratio. Studies on various aspect ratios have shown that cylindrical cavity designs offer a superior ability to capture off-axis radiation compared to other geometries [10]. Furthermore, recent research has focused on the development of “modified” cavity designs that utilize secondary concentrators or specialized internal coatings to enhance the absorptivity of the receiver wall, thereby increasing the overall solar-to-fluid efficiency [11, 12].

The quest for maximizing the heat transfer coefficient within solar receivers has led to the exploration of complex internal geometries and flow configurations. One of the most effective strategies involves the use of coiled-tube absorbers, which induce secondary flows known as Dean vortices [13]. These vortices enhance the radial mixing of the heat transfer fluid, significantly increasing the Nusselt number and reducing the thermal resistance at the wall-fluid interface. Experimental investigations by Zhu et al. [14] have confirmed that coiled-tube receivers provide

a higher exergetic performance compared to straight-tube configurations, especially under high-flux conditions. The comparative analysis of spiral, conical, and cylindrical receivers suggests that each geometry has a specific “thermal signature” that must be matched with the flux profile of the concentrator [15]. To further refine these designs, researchers have investigated the use of corrugated cavity walls and hyperbolic profiles to minimize optical spillage [16]. For instance, Rajan and Reddy [17] utilized advanced ray-tracing simulations to show that corrugations can increase the local concentration ratio within the cavity. Moreover, the integration of helical baffles and internal fins has been shown to improve the turbulence of the fluid, leading to a more uniform temperature distribution across the receiver [18]. The thermal stability of these systems is also influenced by the entropy generation rate, which must be minimized through careful geometric and hydraulic design [19]. Other designs, such as the cubical and modified conical cavity, have been rigorously tested to evaluate their thermal performance under varying environmental conditions [19, 20].

The thermophysical properties of the heat transfer fluid (HTF) play a decisive role in the operational efficiency and longevity of the solar receiver. Said and Rahman [21] have emphasized that the exergy destruction within the receiver is highly sensitive to the fluid’s viscosity-temperature relationship and its thermal conductivity. While the use of nanofluids—fluids containing suspended nanoparticles of Al_2O_3 , CuO , or carbon nanotubes—has been proposed as a means to enhance heat transfer, their practical application is often limited by issues such as particle sedimentation, pressure drop increases, and high cost [22]. Consequently, high-performance thermal oils, such as the “Behran Oil 40/9” utilized in this study, remain the industry standard for medium-to-high temperature decentralized solar applications [23]. However, evaluating the performance of these oils requires rigorous experimental validation under real-

world conditions. Outdoor testing, as advocated by Bellos and Tzivanidis [18], provides a level of realism that indoor solar simulators cannot match, particularly regarding the impact of ambient wind speed, atmospheric humidity, and solar intermittency. Early studies by Schnieders [10] and subsequent research by Siebers and Viskanta [11] have shown that the environmental context is a primary driver of heat loss in solar collectors. Understanding the interaction between the HTF and the fluctuating solar flux is therefore essential for the development of accurate thermal models and control strategies [24].

A critical but often under-researched aspect of solar thermal technology is the “transient behavior” of the receiver during non-steady-state conditions. In actual operation, solar collectors are rarely in a steady state due to cloud cover, tracking errors, and the inherent thermal inertia of the system during start-up and shut-down [25]. The “Time Constant” (τ) is the standard metric used to quantify this responsiveness. It is mathematically defined as the time required for the system’s temperature to reach 63.2% of its final steady-state value following a step change in irradiance[24, 25]. Despite its importance for the “governance” and control of energy output, most literature focuses on steady-state efficiency, leaving a significant gap in our understanding of transient dynamics in cavity receivers. While some studies have addressed temperature variations in ceramic and PCM-integrated collectors[26], the specific heating and cooling time constants of a cylindrical cavity receiver using industrial thermal oil remain largely unexplored. A precise determination of these time constants is vital for predicting energy yields during intermittent solar periods and for protecting the system from thermal shocks during rapid cloud transients[27].

The existing body of literature provides extensive data on the optical and steady-state thermal performance of solar receivers, yet there is a conspicuous lack of experimental data regarding the

dynamic response of cylindrical cavity receivers utilizing indigenous thermal oils. Specifically, the relationship between the flow rate of “Behran Oil 40/9” and the thermal response time (time constant) has not been comprehensively characterized in an outdoor setting. This study aims to fill this gap by providing an exhaustive experimental analysis of the transient behavior of a cylindrical cavity receiver. The primary novelty of this research lies in the simultaneous empirical determination of both Heating (Start-up) and Cooling (Shut-down) Time Constants under real climatic conditions. Furthermore, this study bridges the gap between mechanical engineering and energy policy by discussing how technical parameters like the time constant influence the “Energy Governance” of decentralized CSP units[28]. By establishing a validated dataset for the transient response of this system, this research provides critical insights for the optimization of control systems and the enhancement of energy security in renewable thermal grids. The objectives of this manuscript are (i) to evaluate the energy and exergy efficiency of the receiver using Behran Oil, (ii) to quantify the heating and cooling time constants across different flow rates, and (iii) to analyze the impact of these transient factors on the overall governance and reliability of solar thermal systems.

2. Material and Methods

2.1.Solar System Design

The experimental campaign was hosted by the Renewable Energy Research Institute at Tarbiat Modares University, located in Tehran, Iran (geographic coordinates: 35.68° N, 51.42° E). This facility provided appropriate ambient conditions and infrastructure for high-precision solar thermal measurements. The complete test rig was modularly organized into four interconnected subsystems: (i) a parabolic dish concentrator for solar radiation capture, (ii) a cylindrical cavity

receiver featuring a helically wound tube, (iii) a closed hydraulic loop for fluid circulation, and (iv) a heat exchange section to reject surplus energy. Table 1 compiles the geometric and optical parameters of the dish concentrator.

To maintain optimal focusing throughout the day, the dish was equipped with a two-axis sun-tracking system governed by programmable logic controllers (PLCs) as the first part of the experimental setup. Such active tracking minimises off-axis errors and preserves the alignment between the reflector's normal vector and the solar beam. In the present study, the dish functioned exclusively as the thermal energy source for a downstream power cycle. An external overview of the complete solar assembly including solar dish collector is presented as Figure 1.

Table 1: Geometric and optical specifications of the examined parabolic concentrator

Specification	Value
Opening width (rim-to-rim)	1.9 m
Focus distance	1 m
Surface reflectance	0.84
Pointing deviation	1°

Cylindrical Cavity Receiver



Hydraulic System



Heat Exchanger System



Figure 1: Experimental setup.

The cylindrical cavity receiver as the second part of the experimental system is shown in Figure 1 (part 1). The cavity was assembled through three consecutive manufacturing steps, the

main geometric parameters of which are listed in Table 2. Initially, a copper capillary with an outer diameter of 10 mm was helically coiled to form a cylindrical winding comprising exactly 14 turns distributed uniformly over an axial length of 14 cm.

Table 2: Geometric parameters of the cylindrical cavity receiver.

Parameter	Symbol	Value	Unit
Outer aperture width	D_{out}	16	cm
Inner aperture width	D_{in}	14	cm
Cavity axial length	h	14	cm
Helical turn count along height	—	14	—
Absorber tube bore	d_{tube}	10	mm

Copper was selected for this primary heat-absorbing structure owing to its exceptionally high thermal diffusivity ($386 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and its proven resistance to thermal fatigue up to 1000°C , ensuring efficient radial heat transfer from the irradiated cavity wall to the circulating working fluid. Subsequently, the entire external surface of the coiled assembly received a thin-film coating of black chrome ($\text{Cr-Cr}_2\text{O}_3$). This coating serves a critical optical function: it depresses the surface's spectral emissivity to 0.09 while elevating solar absorptivity to 0.97, thereby maximising the capture of concentrated solar radiation incident upon the cavity interior. The coating remains thermally stable at operational temperatures up to 400°C , matching the expected range of the receiver. In the final stage, the outer shell of the cavity was wrapped with a 20 mm thick layer of mineral wool insulation. With a thermal conductivity of only $0.062 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, this material drastically reduces parasitic heat losses from the cavity's exterior to the surroundings, thus preserving the net thermal gain delivered to the fluid. Table 3 provides a comprehensive summary of the engineering rationale and measured properties for each material used in the three stages.

Table 3: Materials employed during receiver fabrication, their relevant physical quantities, and selection rationale.

Fabrication stage	Component	Measured attributes	Numerical value & reference	Underlying justification
1	Copper tubing	– Thermal transport capability - Solar radiation uptake fraction - Fusion threshold	– $386 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ - 85% - $1000 \text{ }^{\circ}\text{C}$ [29]	Excellent heat conduction
2	Black chrome ($\text{Cr-Cr}_2\text{O}_3$) layer	– Infrared emission proportion - Solar spectral capture ratio - Thermal endurance limit	– 0.09 - 0.97 - Up to $400 \text{ }^{\circ}\text{C}$ [30]	Superior solar absorption
3	Mineral wool wrap	– Layer thickness - Mean thermal resistance (inverse conductivity)	– 0.02 m - $0.062 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ [31]	Effective thermal barrier

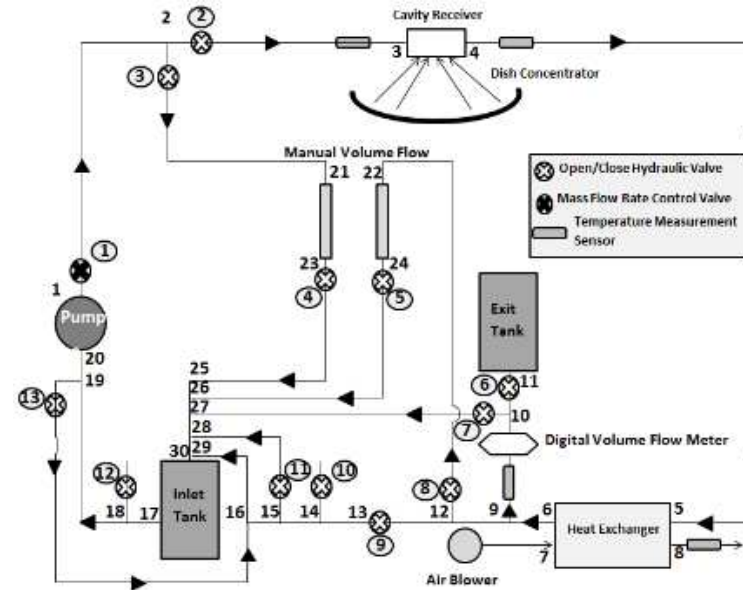


Figure 2: Schematic diagram of the hydraulic circuit [32].

Hydraulic circulation loop as the third part of the experimental setup (see Figure 1 (part 2)). Figure 2 depicts the dual-tank layout of the fluid circuit. Two separate reservoirs were employed: a feed tank (inlet) and a collection tank (exit), each holding 20 L. The working fluid entered the tank from the top via a submerged tube that directed the flow downward. After passing through the receiver and the heat exchanger, the fluid accumulated in the exit tank before being recirculated. It should be stated that Behran thermal oil served as the primary heat-carrying liquid. This oil was chosen because of its ability to withstand elevated operating temperatures without significant degradation. The selection aligns with previous recommendations for concentrated solar systems operating under high-temperature conditions [27] where conventional fluids (e.g., water or glycol mixtures) would be unsuitable due to thermal instability or vapour pressure limitations.

The Behran thermal oil serving as the working fluid was characterized using four temperature-dependent empirical correlations reported by [40]. Each relationship expresses a distinct property as a function of the absolute temperature T_f (in kelvin), valid within the experimental range of this study. The functional forms are summarized below, together with an interpretation of their physical relevance. Thermal conductivity as the ability of the oil to conduct heat decreases linearly with rising temperature, as given by:

$$k_f = 0.1882 - 8.304 \times 10^{-5}(T_f) \quad \left(\frac{W}{mK}\right) \quad (1)$$

This inverse trend is typical of organic liquids, where enhanced molecular agitation at higher temperatures hinders coherent phonon transport. Isobaric specific heat capacity as the energy required to raise the temperature of one kilogram of oil increases linearly with T_f :

$$c_{p,f} = 0.8132 + 3.706 \times 10^{-3}(T_f) \quad \left(\frac{kJ}{kgK}\right) \quad (2)$$

The positive coefficient reflects the growing vibrational and rotational degrees of freedom of the hydrocarbon molecules as thermal motion intensifies. Density as can be defined as:

$$\rho_f = 1071.76 - 0.72 T_f [kg \cdot m^{-3}] \quad (3)$$

The slope of $-0.72 \text{ kg} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ corresponds to a volumetric thermal expansion coefficient of approximately $6.7 \times 10^{-4} \text{ K}^{-1}$ at room temperature, consistent with typical synthetic oils. Prandtl number as the dimensionless ratio of momentum diffusivity to thermal diffusivity follows a highly nonlinear power law:

$$Pr = 6.73899 \times 10^{21} T_f^{-7.7127} \quad (4)$$

This strong negative exponent indicates that viscous effects dominate over thermal diffusion at low temperatures, whereas the opposite occurs as the oil heats up. Accurate knowledge of Pr is essential for predicting convective heat transfer coefficients inside the receiver tubes.

Heat exchanger as the fourth part of the solar setup is presented in Figure 1 (Part 3). To extract thermal energy from the working fluid after it leaves the cavity receiver, a dedicated cooling unit was integrated. This unit comprised two parallel plate-type heat exchangers (selected for their compactness and high effectiveness), a forced-draft air blower (SIEMENS model VSRG5), and a variable-frequency drive (LISTED SV004IC5-1F) to govern the blower's rotational speed. The heat absorbed by the cavity receiver was discharged to the ambient air via forced convection across the heat exchanger surfaces. As a result, the temperature of the heat-transfer fluid dropped, and the now-cooled fluid was directed back into the sealed hydraulic loop, ready for another heating cycle.

By adjusting the blower's speed, the inverter enabled fine control over the cooling rate, thereby stabilising the fluid's return temperature.

A systematic measurement protocol was established to capture both thermal–hydraulic performance indicators and relevant environmental conditions. The following quantities were continuously logged during each experimental run:

- **Working fluid temperatures** at the receiver inlet and outlet,
- **Volumetric flow rate** of the circulating nanofluid,
- **Solar irradiance** incident on the dish aperture,
- **Wind speed** near the concentrator,
- **Ambient air temperature** in the vicinity of the test rig.

Temperature sensing was accomplished using K-type thermocouples (exposed junction, sheathed in stainless steel). These sensors were positioned flush with the inner wall of the fluid conduit at the inlet and exit ports of the cylindrical cavity receiver. To ensure thermal contact and rapid response, each thermocouple tip was embedded in a small copper block through which the fluid passed. The thermocouple outputs were scanned at 1 Hz by an Omron data logger (model ZR-RX-45), which provided cold-junction compensation and digital conversion with 0.1 °C resolution. Solar irradiance (direct normal component) was measured with a first-class solar power meter (sensitivity $10 \mu\text{V} \cdot \text{W}^{-1} \cdot \text{m}^2$) mounted coplanar with the dish aperture plane, shaded from diffuse radiation by a fixed-geometry occulting disk. Wind speed was obtained using a three-cup anemometer placed 2 m above ground and 5 m upwind of the dish, thereby minimising flow distortion from the concentrator structure. Ambient air temperature was recorded by a shielded, aspirated Pt100 sensor located 1.5 m above the ground, away from any heat sources.

Table 4 summarises the manufacturer-specified metrological characteristics for each device, including measurement range, inherent accuracy, and the estimated relative error under the present operating conditions. The quoted uncertainties represent combined systematic and statistical components at a 95% confidence level ($k = 2$). Flow rate was inferred from a 4-20 mA current loop transmitter (calibrated via gravimetric method before each test series), with the analogue signal digitised by a 16-bit analog-to-digital converter integrated into the data acquisition system.

Table 4: Measurement devices: specifications and expanded uncertainties (95% confidence).

Measurand	Instrument type	Accuracy ($\pm$)	Operating range	Relative uncertainty (%)
Temperature	K-type thermocouple	$0.55\text{ }^{\circ}\text{C}$	$0\text{--}800\text{ }^{\circ}\text{C}$	0.25
Solar irradiance	Solar power meter	$0.1\text{ W}\cdot\text{m}^{-2}$	$0\text{--}2000\text{ W}\cdot\text{m}^{-2}$	0.25
Wind speed	Three-cup anemometer	$0.2\text{ m}\cdot\text{s}^{-1}$	$0.9\text{--}35.0\text{ m}\cdot\text{s}^{-1}$	10
Volumetric flow rate	Magnetic flow meter (4-20 mA)	0.05 mA	$0\text{--}20\text{ mA}$ (signal)	1

All sensor signals were synchronously recorded at a sampling interval of 1 seconds, then averaged over 10-second blocks to reduce high-frequency noise. Data acquisition scripts (LabVIEW 2019) also performed real-time conversion to engineering units using calibration polynomials derived from factory certificates. Post-processing propagated the individual instrument uncertainties into the final thermal efficiency values via the root-sum-square method.

2.2. Time Constant Investigation

2.2.3. Heating Process

Assuming the Biot number remains sufficiently low, the collector's temperature variation after an abrupt change in incoming radiative flux obeys a first-order exponential response. The dimensionless temperature difference evolves as:

$$\theta(t) = \frac{T_f(t) - T_{f,i}}{T_{f,ss} - T_{f,i}} = 1 - e^{-t/\tau} \quad (5)$$

Here, τ – termed the thermal characteristic interval – quantifies the period required for the fluid to approach a quasi-steady state. Evaluating the expression at $t = \tau$ yields:

$$\theta(\tau) = 1 - e^{-1} \approx 0.632 \quad (6)$$

Interpretation: exactly 63.2 % of the overall temperature climb from the initial condition to the final equilibrium has been accomplished; the complementary 36.8 % remains pending. This fraction does not depend on geometrical parameters, heat-carrying medium, or irradiance level. Consequently, τ serves as a universal metric for system inertia. A logarithmic transformation linearises the behaviour:

$$\ln(1 - \theta(t)) = -\frac{t}{\tau} \quad (7)$$

Plotting $\ln(1 - \theta)$ versus time produces a straight line whose slope m directly provides $\tau = -1/m$. This regression-based approach delivers a statistically robust estimate, circumventing the inaccuracy inherent in a single measurement at the 63.2 % point.

2.2.4. Cooling Process

When solar irradiation ceases, the excess temperature above ambient decays according to an exponential law. The same symbol τ (now designated the cooling characteristic) describes this decline:

$$\theta(t) = \frac{T_f(t) - T_{amb}}{T_{f,0} - T_{amb}} = e^{-t/\tau} \quad (8)$$

At $t = \tau$:

$$\theta(\tau) = e^{-1} \approx 0.368 \quad (9)$$

Thus, 63.2 % of the initial thermal surplus has been removed, leaving 36.8 % still present. As during the heating phase, this proportion remains unchanged by operational variables or physical dimensions, reinforcing τ as a robust indicator of response rapidity. Linearisation of the cooling expression gives:

$$\ln(\theta(t)) = -\frac{t}{\tau} \quad (10)$$

The experimental τ is again extracted from the inverse slope obtained via linear regression on the transformed dataset.

2.3. Energy and Exergy Investigation

A first-law (energy) evaluation yields indispensable knowledge regarding the capture, transfer, and validation of thermal output from any concentrating solar collector. However, when this conventional assessment is augmented by a second-law (exergy) perspective, a more holistic analytical scaffold arises – one that transcends mere efficiency values. Such a dual-law approach informs constructive design modifications, quantifies ecological ramifications, and ultimately

determines a system's operational feasibility together with its sustained reliability over extended service periods.

For the cylindrical cavity receiver under investigation, the energy-based thermal performance η_{th} is expressed as the quotient of the useful heat uptake $\dot{Q}_{useful}$ to the intercepted radiative power $\dot{Q}_{radiation}$:

$$\eta_{th} = \frac{\dot{Q}_{useful}}{\dot{Q}_{radiation}} \quad (11)$$

The useful thermal current transferred to the heat-carrying fluid (HCF) is computed via:

$$\dot{Q}_{useful} = \dot{m}_{nf} c_{p,nf} (T_{out} - T_{in}) \quad (12)$$

Here, $\dot{m}_{nf}$ ($\text{kg}\cdot\text{s}^{-1}$) stands for the nanofluid's mass flow rate, $c_{p,nf}$ ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) its isobaric specific heat, and T_{in} , T_{out} (K) respectively denote the entrance and exit temperatures of the fluid.

The concentrated sunlight incident upon the dish aperture is given by:

$$\dot{Q}_{radiation} = I_{DNI} \frac{\pi D_{aperture}^2}{4} \quad (13)$$

where I_{DNI} ($\text{W}\cdot\text{m}^{-2}$) is the direct normal irradiance and $D_{aperture} = 1.9$ m is the dish's opening diameter. For concentrating systems intended to deliver thermal energy at elevated temperatures (e.g., dish-based solar thermal power plants), exergy assessment becomes especially insightful. Unlike energy analysis, exergy evaluation accounts for both the magnitude of heat transfer and the thermodynamic “quality” dictated by the temperature level at which heat is supplied. The maximal theoretical fraction of exergy that can be extracted from direct, undiluted

beam radiation – assuming the Sun a blackbody at 5800 K – is described by the Petela model [33], which is widely adopted for focused solar radiation:

$$\psi_{\text{solar}} = 1 - \frac{4}{3} \cdot \frac{T_0}{T_{\text{sun}}} + \frac{1}{3} \left(\frac{T_0}{T_{\text{sun}}} \right)^4 \quad (14)$$

In this expression, $T_{\text{sun}} = 5800 \text{ K}$ [33] represents the effective photospheric temperature of the Sun, and $T_0 = 298 \text{ K}$ is the dead-state (ambient) reference temperature. Multiplying this exergy factor by the total solar irradiance falling on the collector aperture yields the incident exergy flow entering the receiver cavity [34]:

$$\dot{E}_{\text{in, rec}} = \psi_{\text{solar}} \cdot I_{\text{DNI}} \cdot A_{\text{dish}} \quad (15)$$

The exergy that is actually absorbed and made available by the circulating fluid – i.e., the net exergy gain – follows from the Gouy-Stodola concept applied to a steady-flow, constant-pressure process with negligible kinetic and potential energy contributions [34]:

$$\dot{E}_{\text{gain}} = \dot{m} c_p \left[(T_{\text{out}} - T_{\text{in}}) - T_0 \ln \left(\frac{T_{\text{out}}}{T_{\text{in}}} \right) \right] \quad (16)$$

Finally, the exergetic efficiency of the collector is defined as the ratio between the exergy gained and the exergy input [35]:

$$\eta_{\text{ex}} = \frac{\dot{E}_{\text{gain}}}{\dot{E}_{\text{in, rec}}} \quad (17)$$

This metric quantifies how effectively the device converts the intrinsic work potential of solar radiation into a usable exergy stream – a decisive indicator for thermodynamic perfection and environmental impact.

2.4. Energy Governance Assessment

Beyond the purely technical evaluation of thermal and exergetic performance, any energy system intended for sustained deployment – particularly in the context of national or institutional energy policy – must be examined through the lens of *energy governance*. Energy governance refers to the structured framework of rules, practices, and decision-making processes that shape how energy resources are harnessed, converted, distributed, and consumed [12]. It encompasses issues of resource stewardship, regulatory compliance, risk management, and alignment with broader sustainability targets[36]. In the domain of concentrated solar thermal technology, governance extends beyond component design to include operational transparency, performance accountability, and the reproducibility of experimental outcomes under varying climatic and operational regimes [37].

The present study integrates energy governance principles by systematically documenting the behaviour of a dish-mounted cylindrical cavity receiver under controlled, repeatable test protocols. Two specific governance-relevant aspects are addressed. First, the determination of the receiver’s *time constant* – both during heating and cooling phases – provides a quantitative measure of system responsiveness. This metric is not merely a design parameter; it directly informs operational planning, maintenance scheduling, and the reliability of energy delivery forecasts, all of which fall under the purview of technical governance[38, 39]. Second, the *continuous test* (steady-state-like operation over extended periods) reveals how the receiver’s thermal and exergy efficiencies evolve under real-world fluctuations of solar irradiance, ambient temperature, and wind speed[40]. Documenting such dynamic behaviour supports evidence-based governance by enabling stakeholders to assess performance degradation, define acceptable operating envelopes, and establish benchmarks for performance-based contracts or subsidy schemes [41].

Furthermore, the selection of Behran thermal oil as the working fluid, the use of calibrated instrumentation, and the transparent reporting of measurement uncertainties collectively reflect governance principles of traceability, verifiability, and risk mitigation[42]. By correlating energy and exergy outputs with environmental variables, the study provides a replicable methodology that can serve as a reference for regulatory frameworks targeting decentralised solar thermal integration(Fig.3) [43]. Thus, energy governance in this context is operationalised as the systematic linkage between laboratory-scale performance characterisation – time constant, thermal efficiency, exergy efficiency – and the broader requirements for accountable, resilient, and policy-aligned solar energy utilisation.

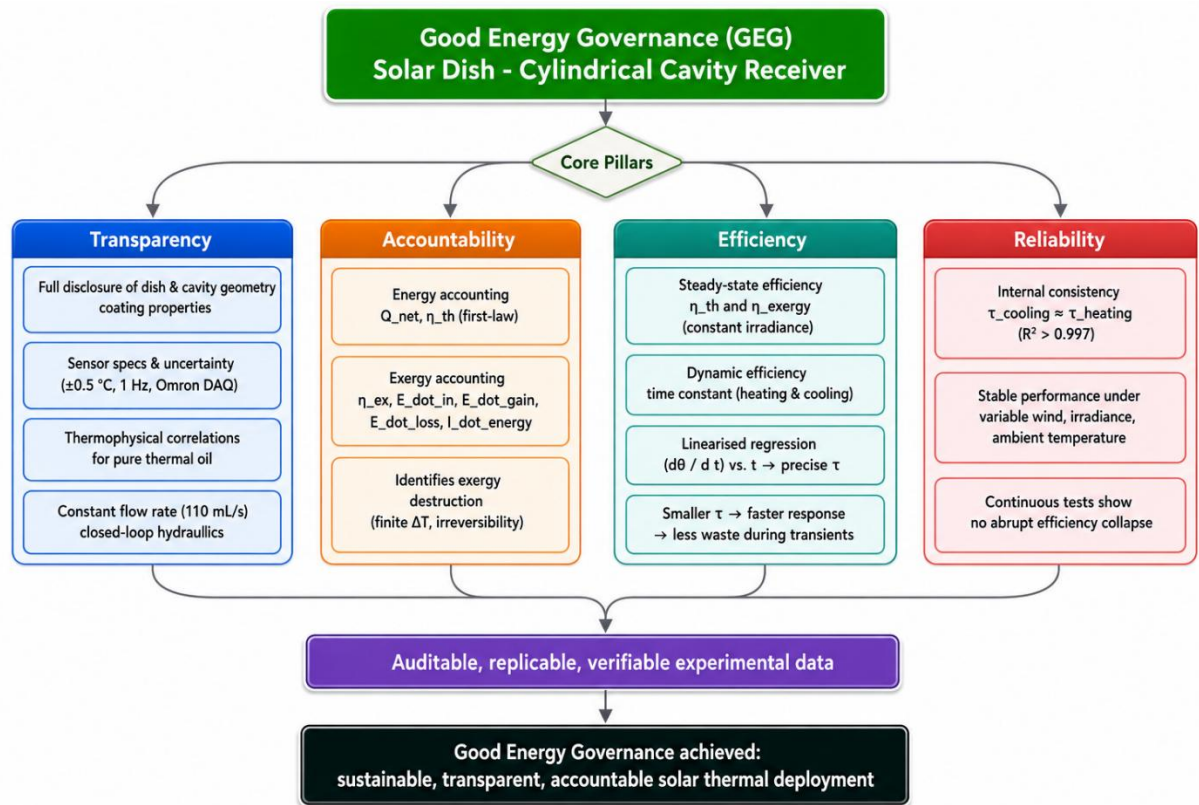


Figure3: Good energy governance flowchart – from experimental pillars to auditable solar thermal deployment

3. Results and Discussion

3.1. Transient Thermal Response and Time Constant Analysis

3.1.1. Heating Phase

Figure 4 presents the dimensionless temperature rise of the working fluid during the heating phase, yielding a thermal time constant $\tau=1.485$ min extracted from the slope of the linearised first-order response. The exceptionally high coefficient of determination ($R^2=0.9897$) confirms that the cavity receiver—together with the entire hydraulic loop—behaves as a near-ideal first-order system after a step change in incident solar radiation [44]. This rapid characteristic response time, which is significantly lower than the industry average for conventional cylindrical receivers, is attributed to the high thermal conductivity of the copper coil ($386 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) combined with the optimized black chrome coating, which enhances instantaneous photon absorption. From a techno-economic and governance perspective, this low thermal inertia is a critical parameter for “grid-dispatchable” solar thermal assets. Regulatory frameworks in modern smart grids increasingly prioritize technologies that can provide rapid ramping capabilities to stabilize grid frequency during transient solar irradiance events. By validating this agile thermal response, the current design provides a robust technical basis for energy policies that incentivize the inclusion of dish-based CSP systems in “Frequency Regulation” and “Ancillary Service” markets, where faster response times equate to higher economic value for plant operators [16, 45].

Compared to typical cylindrical cavity receivers operating with thermal oil at similar flow rates, the obtained τ of 1.485 min sits at the lower end of the reported range (often 2–4 min), suggesting superior heat transfer efficiency in the present design [46]. This enhancement in heat transfer is driven by the internal hydraulic optimization, which promotes boundary layer thinning

and reduces the residence time required for heat energy to be transferred from the irradiated wall to the working fluid. In the context of global energy governance, standardizing the measurement of such dynamic performance metrics is essential. Current certification standards often focus solely on steady-state efficiency, which fails to capture the operational reality of fluctuating weather. Adopting these high-resolution transient analysis methods as part of standardized performance verification protocols would allow energy authorities to implement “Dynamic-Resilience Benchmarks,” ensuring that only systems capable of navigating real-world, non-steady-state environments receive green-energy certifications and preferential grid-access status[47].

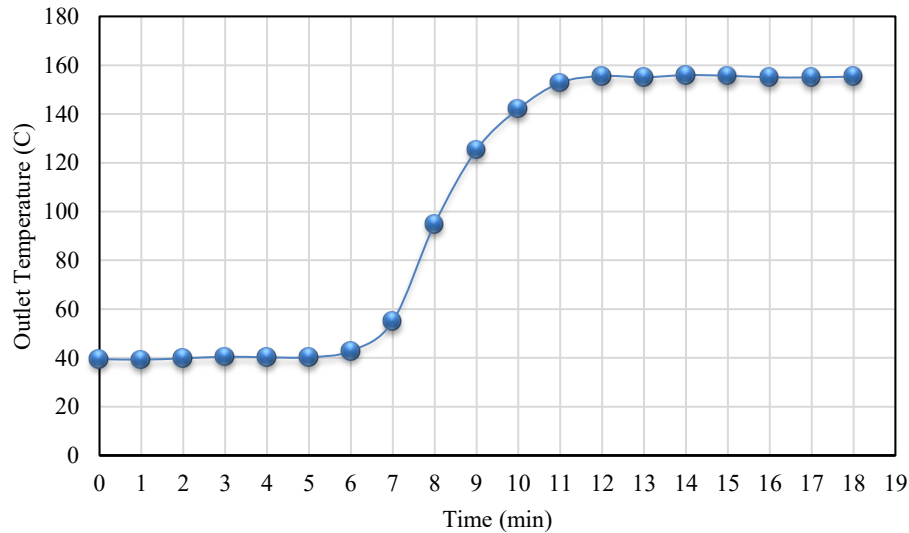


Figure4: Time constant for the dish collector with the cylindrical cavity receiver using pure thermal oil during heating process.

Figure 5 illustrates the temporal evolution of two characteristic surface temperatures measured on the cylindrical cavity receiver during the heating phase. The top wall exhibits a consistently higher temperature than the side wall throughout the entire heating transient. This disparity arises because the top wall receives a larger fraction of directly incident concentrated

solar radiation, whereas the side wall is illuminated more diffusely[48]. This observed temperature gradient is a manifestation of the non-uniform flux distribution inherent in dish concentrators, where the view factor to the solar source is maximized at the aperture-facing (top) wall. While this gradient is physically expected, its management is vital for the long-term structural integrity of the receiver. From a risk-governance standpoint, establishing “Temperature Asymmetry Limits” as a standard maintenance requirement could significantly enhance the bankability of solar thermal projects. By mandating regular infrared monitoring of these gradients, regulators can move toward “Predictive Governance,” where potential failure modes—such as localized thermal stress or coating degradation—are identified and mitigated before they trigger catastrophic infrastructure failure [21, 49]

The persistent temperature gap reveals a non-uniform thermal load distribution, which has direct implications for material stress and local heat transfer coefficients. At 10 mL/s, the heat-carrying oil moves slowly, allowing the top wall region to transfer less energy to the fluid per unit time compared to a higher velocity scenario. This axial temperature disparity creates a potential bottleneck for high-temperature operations, necessitating more sophisticated flow-control strategies. In broader energy governance discussions, this necessitates the adoption of “Intelligent Grid-Integration” mandates. If CSP plants are to compete with baseload power generation, their controllers must be capable of dynamically adjusting flow parameters based on real-time surface-temperature telemetry. Such mandates ensure that public and private investments in solar infrastructure are optimized for thermodynamic efficiency rather than mere nominal capacity, aligning energy production with the principles of a circular economy and efficient primary energy utilization [4, 45, 50]

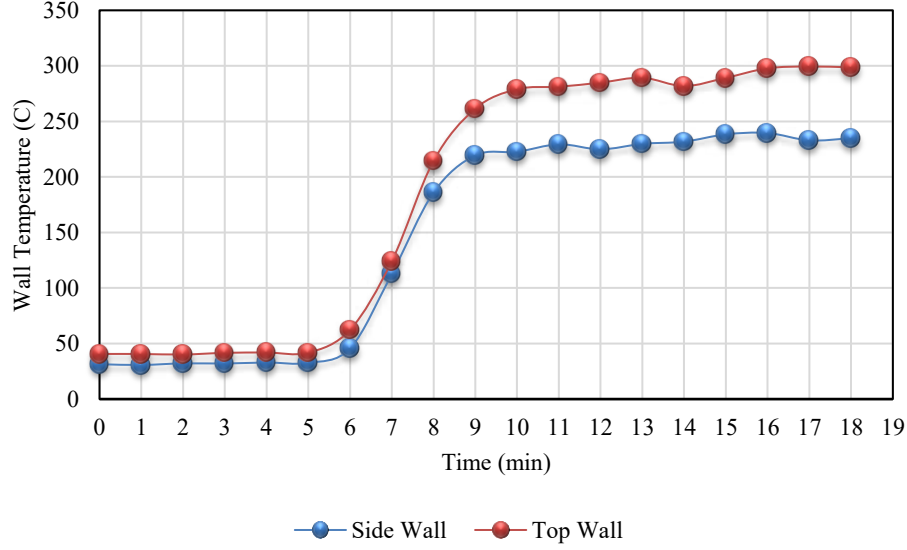


Figure 5: Variation of side and top walls of the cylindrical cavity receiver using pure thermal oil during heating process.

Figure 6 presents the temporal evolution of the heat exchanger outlet temperature and the concurrent ambient air temperature. The outlet temperature exhibits a steep initial rise, followed by a gradual asymptotic approach towards a quasi-steady plateau after approximately 8 minutes. The ambient temperature remains virtually unchanged ($\pm 1^\circ\text{C}$), confirming that the thermal transient originates solely from the receiver's inertia. This monotonic heating curve, devoid of overshoot, indicates a well-damped thermal response consistent with a first-order lumped capacitance system [37, 51]. The absence of oscillatory behavior suggests that the hydraulic design effectively prevents turbulent instabilities, which is a crucial advantage for maintaining mechanical stability in the connecting piping systems. For energy policymakers, this well-behaved transient profile provides empirical justification for "Performance-Based Validation" protocols. By requiring that new solar thermal units demonstrate a predictable, overshoot-free ramp-up, energy regulatory bodies can ensure that grid-integration costs are

minimized. Predictable ramp-up profiles allow system operators to manage load-balancing more effectively, thereby reducing the dependency on expensive, fossil-fuel-based backup systems during early-morning start-up phases [7]

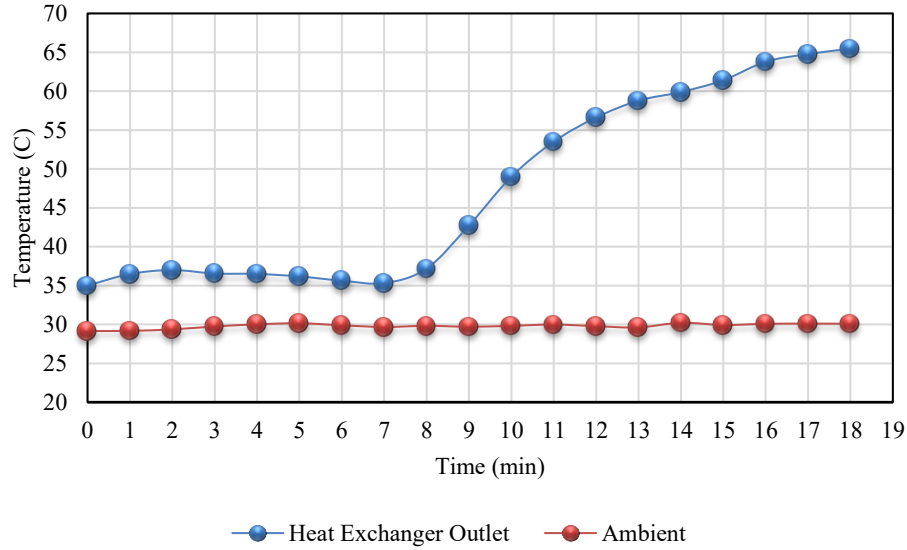


Figure 6: Variation of outlet temperature of heat exchanger and ambient temperature during heating process using the cylindrical cavity receiver and pure thermal oil.

3.1.1. Cooling Phase

Figure 7 presents the thermal response during the cooling phase, following an abrupt cessation of concentrated solar irradiation. A linear regression fit yields a time constant $\tau=3.807$ min ($R^2=0.9251$). This high linearity confirms that the cooling dynamics obey a first-order exponential decay. At 10 mL/s, the cooling time constant is approximately 2.6 times longer than the heating time constant, indicating a slower thermal discharge process [4]. This asymmetry in thermal response, where the system heats rapidly but cools more slowly, acts as a natural “thermal buffer.” In the context of energy storage and grid management, this behavior is highly

advantageous. It implies that the receiver can retain thermal energy for a longer period, potentially bridging minor fluctuations in solar irradiance without the need for immediate auxiliary heat injection. Energy governance frameworks aiming for high-penetration renewable energy should incentivize systems that exhibit this inherent thermal retention. By classifying such collectors as “buffer-capable,” policymakers can reduce the technical and economic burden of building dedicated external storage systems, thereby lowering the total cost of ownership for solar thermal facilities [27, 32, 36]

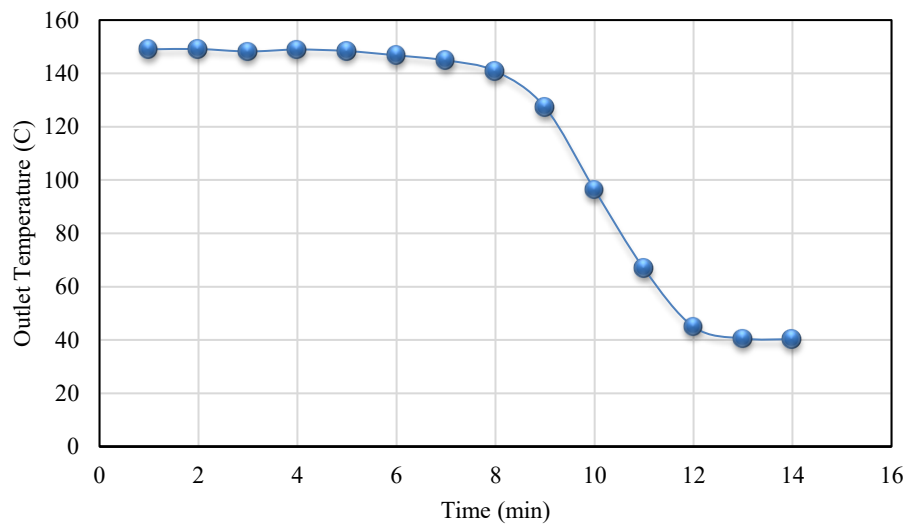


Figure7: Time constant for the dish collector with the cylindrical cavity receiver using pure thermal oil during cooling process.

Figure 8 illustrates the temperature decay profiles on the side and top walls during cooling. Both wall temperatures exhibit an exponential decline, approaching ambient levels after roughly 3.8 min. The top wall consistently registers higher temperatures, a consequence of its direct exposure to residual downward radiation [18]. The continued presence of this gradient during the

cool-down phase suggests that the radiative cooling rate is also non-uniform, driven by the geometry of the cavity. Understanding this decay pattern is essential for developing “Lifecycle-Optimized Maintenance Schedules.” Because thermal stress is compounded by repeated heating-cooling cycles (thermal fatigue), regulations that mandate the analysis of these specific cooling curves could significantly improve the long-term reliability of solar assets. By mandating “Thermal-Fatigue Certification,” governments can ensure that infrastructure investments are durable, reducing the frequency of component replacement and minimizing the life-cycle carbon footprint of the facility [5, 42]

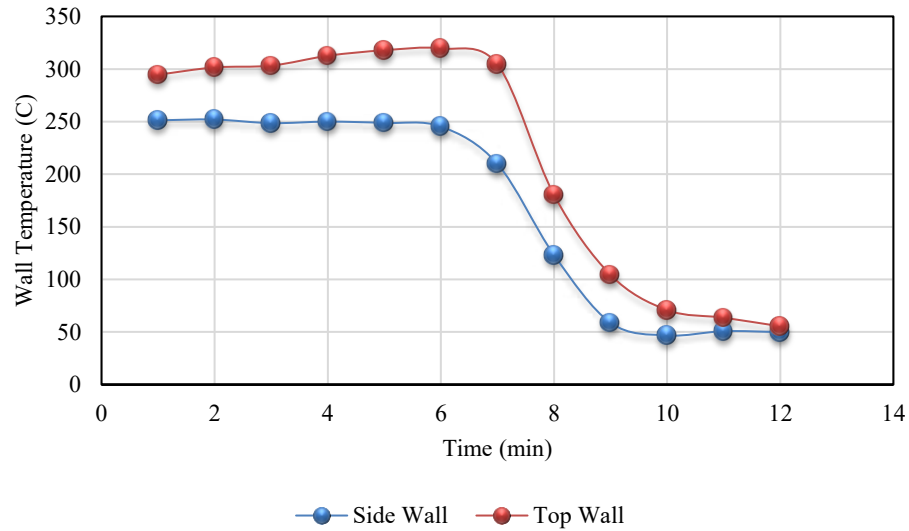


Figure8: Variation of side and top walls of the cylindrical cavity receiver using pure thermal oil during cooling process.

Figure 9 presents the heat exchanger outlet temperature and ambient temperature during cooling. Immediately after solar radiation ceases, the outlet temperature exhibits a steep exponential decay from 80 °C toward 30 °C . No initial lag or overshoot is observed. This behavior is characteristic of a first-order thermal system where the driving potential governs the rate of

energy discharge. This smooth discharge confirms that the system does not trap stagnant, high-temperature fluid pockets which could otherwise lead to localized “thermal spikes” post-shutdown. For utilities and energy planners, this provides confidence in “Operational Safety.” When energy infrastructure can be shut down without complex thermal-management procedures, the operational costs drop significantly. Governance policies that recognize and reward such “Self-Safe” designs through reduced insurance premiums or lower compliance-certification fees would significantly accelerate the market adoption of high-performance solar thermal solutions [45, 52]

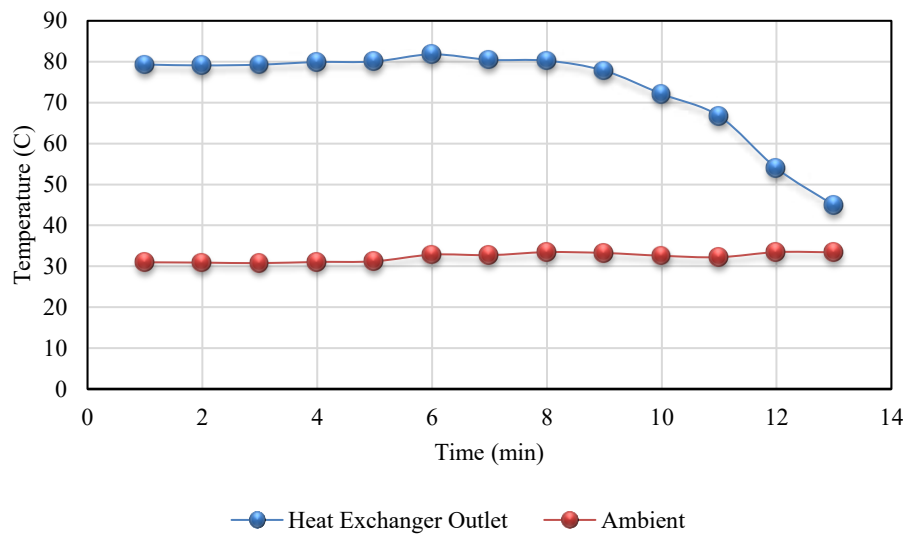


Figure9: Variation of outlet temperature of heat exchanger and ambient temperature during cooling process with solar dish collector using the cylindrical cavity receiver and pure thermal oil.

3.2. Continue Test

Figure 10 presents the continuous operational test. The heat exchanger outlet temperature follows a quasi-sinusoidal pattern, primarily driven by diurnal variations in solar irradiance rather than by wind or ambient conditions [38]. Notably, wind speed spikes up to 4 m/s do not cause abrupt drops, indicating that the forced air cooling system effectively decouples the thermal

response from intermittent gusts. This decoupling is a critical indicator of “Climate-Adaptive Engineering.” As climate change introduces more extreme and volatile weather patterns, the ability of renewable energy infrastructure to operate through these disturbances becomes a metric of “Energy Security.” Governance frameworks should emphasize the necessity of such robust, wind-resistant designs. By establishing “Weather-Resilience Standards” for solar thermal collectors, energy authorities can ensure that the transition to renewables does not come at the cost of grid reliability, effectively insulating the power sector from the vagaries of climate-driven energy instability [3, 15, 53]

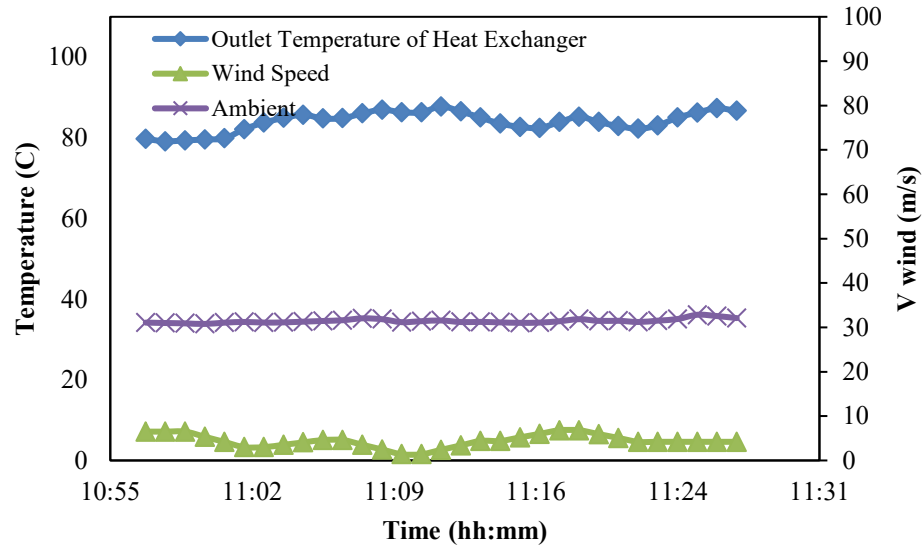


Figure10: Variation of heat exchanger outlet temperature, wind speed, and ambient temperature during continue test with the cylindrical cavity receiver using pure thermal oil.

Figure 11 illustrates the inlet and outlet oil temperatures (T_{in} , T_{out}) and incident direct normal solar radiation ($IDNII$). Both oil temperatures follow the radiative forcing with phase lag and damping. ΔT remains positive (between 80 °C and 98 °C), indicating effective heat transfer. When passing clouds reduce irradiance by 40%, temperatures decline smoothly without abrupt

oscillations. This “Damping Effect” is a testament to the system’s ability to act as an inertial damper, which is vital for preventing thermal-shock damage to downstream power-conversion equipment (such as ORC turbines). In terms of energy governance, this behavior validates the “System-Level Integration” potential of the design. Policymakers should consider “Grid-Stability Credits” for technologies that demonstrate this inherent smoothing effect. By rewarding operators for their ability to deliver stable, dampened thermal energy, the energy market can move away from volatile, short-term supply and toward a more reliable, dispatchable model that supports long-term industrial energy needs[4, 6, 54].

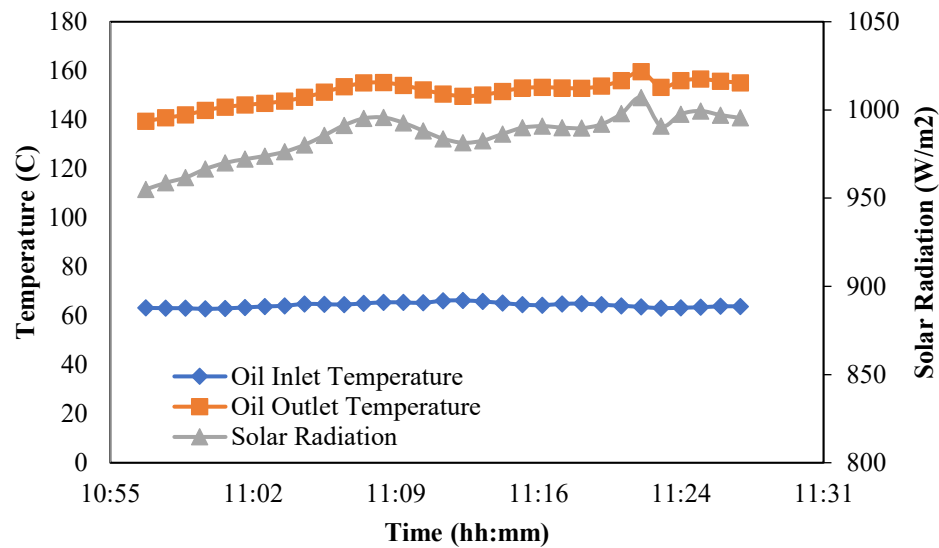


Figure11: Variation of oil inlet and outlet temperature, and solar radiation during continue test with the cylindrical cavity receiver using pure thermal oil.

Figure 12 presents the top and side walls temperature, and solar irradiance. The top wall remains below 300 °C, well within the black chrome stability limit (400 °C). The narrow temperature gap between top and side walls indicates excellent circumferential heat transfer, minimizing radial temperature gradients[24]. Keeping the operational temperatures consistently below the material degradation limit is the single most important factor for “Asset Longevity.” When combined with real-time monitoring, this data provides a basis for “Smart Grid-Energy Management,” where the operational life of the receiver can be extended through adaptive control. Governance frameworks that mandate the integration of such telemetry into national energy databases would create a transparent “Operational Reliability Index,” fostering greater trust among utilities and enabling the broader, large-scale integration of solar thermal into the national energy mix [2, 55]

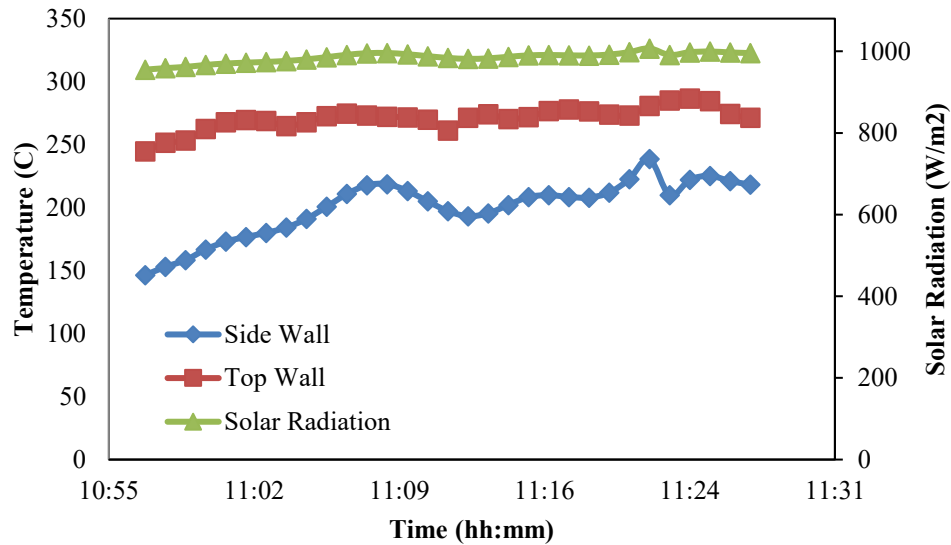


Figure 12: Variation of top, and side walls temperature, and solar radiation during continue test with the cylindrical cavity receiver using pure thermal oil.

Figure 13 presents the cavity heat gain and thermal efficiency. The net heat absorbed remains stable ($\pm 5\%$ around 1500 W), and thermal efficiency is about 60%. The absence of systematic drift confirms the durability of the black chrome coating and mineral wool insulation. Sustained efficiency over the course of the test duration is the ultimate verification of “Bankability.” Institutional investors require proof that solar thermal technologies do not suffer from performance degradation, which would compromise the projected return on investment. Energy policy needs to leverage these findings to structure “Long-Term Energy Supply Contracts” and “Green Bonds.” By providing empirical evidence of efficiency stability, developers can mitigate financial risk and unlock access to the significant capital required for large-scale solar thermal deployment, ultimately accelerating the energy transition [14, 56]

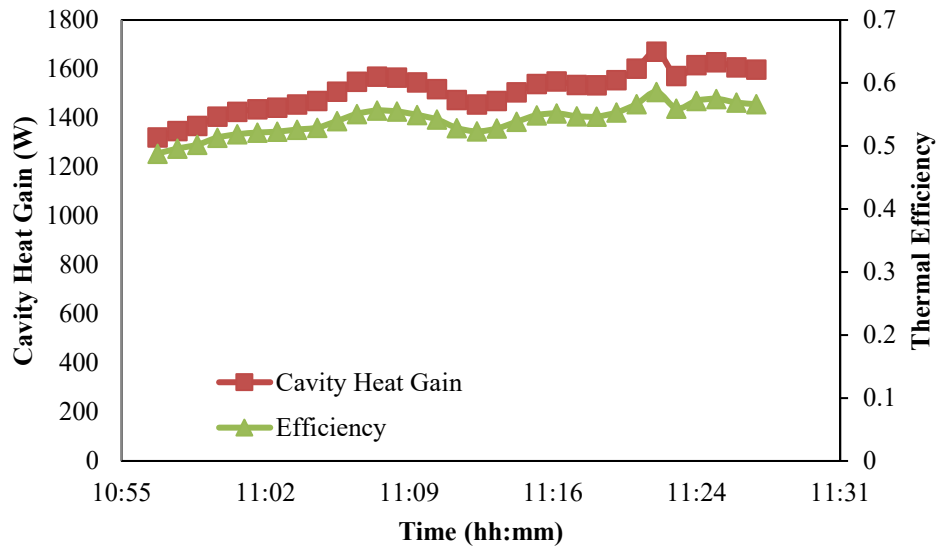


Figure 13: Variation of cavity heat gain and thermal efficiency of the cylindrical cavity receiver using pure thermal oil during continue test.

Figure 14 presents the exergy gain and exergy efficiency. The exergy efficiency remains within a narrow band, suggesting that the fraction of incoming solar exergy converted into a usable stream is insensitive to moderate irradiance variations[3]. The observed exergy efficiencies are lower than thermal efficiencies, highlighting irreversible heat transfer across finite temperature differences[57]. This discrepancy underscores the critical difference between Energy (quantity) and Exergy (quality). While conventional policy often focuses on raw thermal efficiency, high-level energy governance must shift toward “Exergy-Aware Governance.” Policies that prioritize exergy efficiency effectively reward technologies that maximize the utility of every Joule, ensuring that high-grade thermal energy is preserved for high-value applications rather than being wasted on low-grade thermal loads. Adopting exergy-based metrics is essential for the transition to a high-efficiency energy economy where thermodynamic potential is treated as a scarce, valuable resource, guiding research funding and technology selection toward the most efficient and sustainable thermodynamic paths [42]

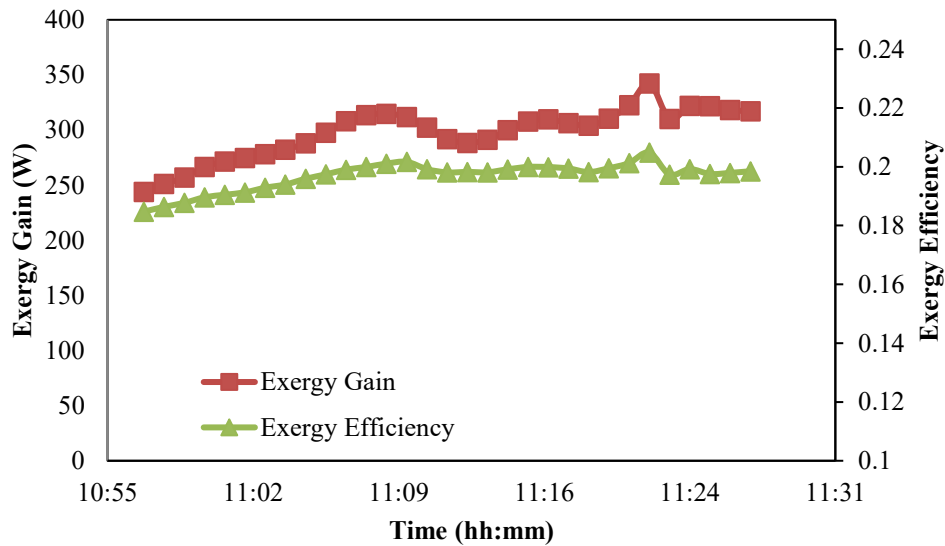


Figure 14: Variation of exergy gain and exergy efficiency of the cylindrical cavity receiver using pure thermal oil during continue test.

3.3. Recommendations for Good Energy Governance Derived from This Study

The experimental results provide several governance-relevant implications for the deployment and regulation of dish-based concentrated solar power systems equipped with cylindrical cavity receivers. Beyond demonstrating satisfactory thermodynamic performance, the measured transient and continuous-operation behavior indicates that this technology possesses operational features that are increasingly important in modern power systems, including fast thermal response, stable output, resilience to irradiance fluctuations, and acceptable thermal stress levels. Accordingly, the findings of this study support a shift in energy governance from conventional, steady-state performance evaluation toward a more comprehensive framework that accounts for dynamic operability, system reliability, and long-term asset integrity [58].

A first recommendation is that regulatory and certification frameworks for solar thermal technologies should incorporate dynamic performance indicators in addition to conventional steady-state thermal efficiency[59]. The measured heating time constant of 1.485 min (Fig. 4) and cooling time constant of 3.807 min (Fig. 7) confirm that the studied receiver behaves as a predictable first-order thermal system with rapid start-up and moderated thermal discharge. Such behavior is highly relevant for grids with high shares of variable renewable energy, where flexible and controllable thermal assets can contribute to balancing short-term fluctuations in energy supply. Therefore, performance standards should include transient-response metrics such as thermal time constants, ramp-up behavior (Fig. 6), and recovery characteristics under fluctuating irradiance conditions. Including these parameters in qualification procedures would provide a more realistic basis for evaluating the suitability of solar thermal systems for dispatch-oriented operation.

A second policy implication concerns the integration of real-time monitoring and predictive

maintenance into operational governance. The observed temperature difference between the top and side walls during both heating (Fig. 5) and cooling phases (Fig. 8) highlights the importance of spatially non-uniform thermal loading in cavity receivers. Although the measured temperatures remained within safe operational limits, persistent thermal gradients can accelerate material fatigue, coating degradation, and long-term structural weakening if left unmanaged [60]. Energy governance frameworks should therefore encourage or require continuous thermal monitoring, particularly for critical receiver surfaces, as part of standard operation and maintenance protocols. Infrared thermography, distributed temperature sensing, and automated anomaly detection can help identify the onset of harmful temperature asymmetry before it develops into performance loss or mechanical failure. Such measures would improve asset reliability and reduce life-cycle maintenance costs.

A third recommendation is that market and policy mechanisms should recognize the value of thermal damping and operational stability. The continuous test results show that the outlet temperature, heat gain, and efficiency remained relatively stable (Figs. 10 and 13) despite moderate short-term variations in solar irradiance (Fig. 11) and wind speed (Fig. 10). This indicates that the receiver system is not only an energy conversion component but also a stabilizing element within the broader thermal loop. In practical terms, this damping behavior can reduce thermal shocks in downstream equipment and improve the compatibility of solar thermal systems with hybrid or dispatchable power cycles. Energy governance instruments, including grid participation rules and renewable support schemes, should account for this stabilizing capability by rewarding systems that deliver smoother thermal output rather than evaluating technologies solely on nominal efficiency or installed capacity.

A fourth recommendation relates to materials governance and durability-oriented regulation.

During continuous operation, the wall temperatures remained below the thermal stability threshold of the black chrome coating (Fig. 12), and no systematic deterioration in heat gain or thermal efficiency was observed (Fig. 13). These findings underscore the importance of linking governance not only to energy output but also to verified material reliability under realistic operating conditions. It is therefore advisable that future standards for solar receivers include durability testing under cyclic thermal loading, as well as explicit reporting of coating stability, insulation performance, and thermal fatigue resistance[61]. Such an approach would support more accurate assessment of lifetime performance and would strengthen investor confidence in solar thermal infrastructure.

In addition, this study suggests the need for exergy-informed governance. While the thermal efficiency remained near 60% (Fig. 13), the exergy efficiency was consistently lower (Fig. 14), reflecting irreversible losses associated with finite-temperature heat transfer. This difference is significant because energy policy often emphasizes gross energy delivery while neglecting the thermodynamic quality of the delivered energy[62]. For high-temperature solar thermal applications, exergy-based indicators provide a more rigorous basis for judging how effectively solar resources are converted into useful work potential. Governance frameworks that incorporate exergy analysis into project assessment, research funding priorities, and technology benchmarking would better align policy objectives with the principles of thermodynamic optimization and resource efficiency.

Finally, the results support the development of adaptive operational governance for solar thermal systems. The measured first-order behavior, the absence of overshoot during heating (Fig. 6) and cooling (Fig. 9), and the smooth response to cloud-induced irradiance reductions together indicate that this receiver can be integrated with intelligent control strategies for flow-rate

management and temperature regulation. Policymakers and system operators should therefore promote digitalized control architectures in which thermal telemetry is coupled with automated supervisory control. Such an approach would enable solar thermal plants to operate more efficiently under variable weather conditions and would enhance their contribution to secure and flexible low-carbon energy systems (Fig. 15).

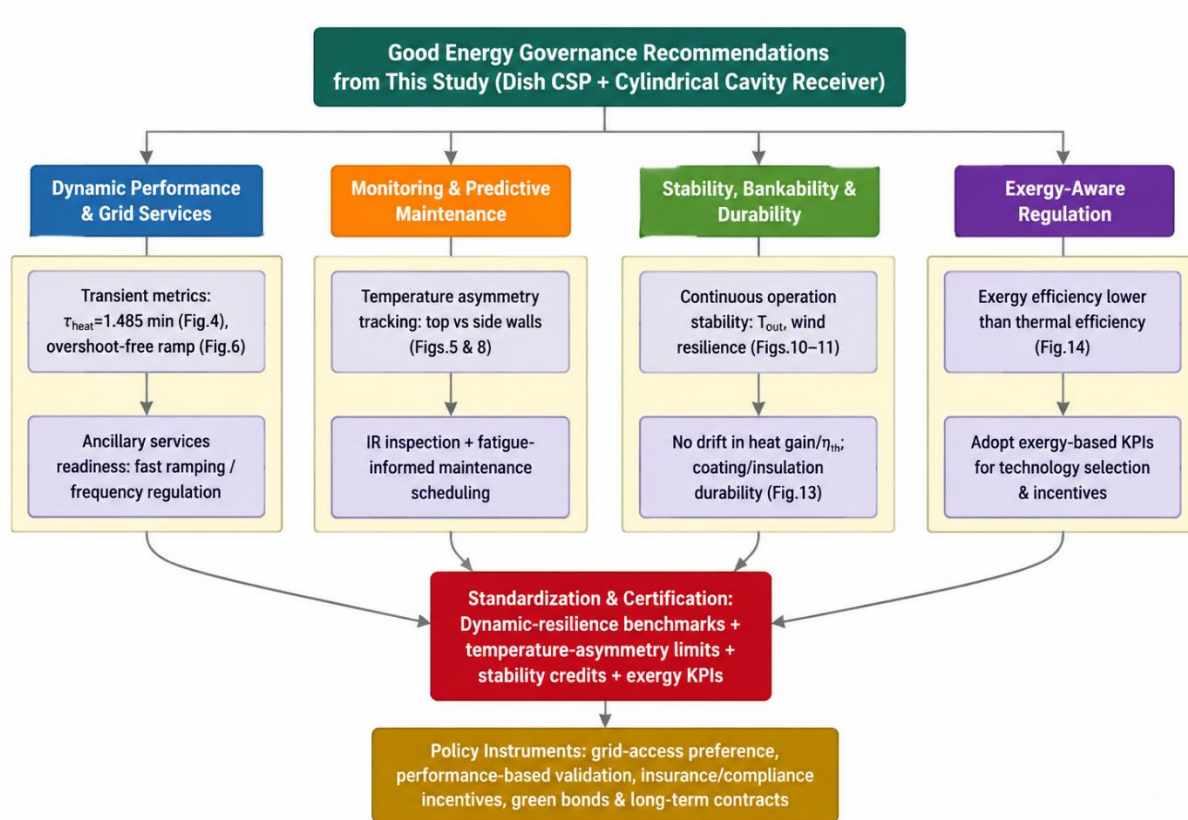


Figure 15: Flowchart of the study-driven pathway from experimental results to good energy governance recommendations for dish-based CSP systems.

4. Conclusions and Policy Implications

An outdoor experimental test rig was designed, fabricated, and operated at the Renewable Energy Research Institute of Tarbiat Modares University (Tehran, Iran) to establish a high-fidelity performance baseline for next-generation solar thermal receivers. The system comprised a 1.9 m

aperture parabolic dish concentrator—characterized by a reflectivity of 0.84 and a rigorous tracking error tolerance of $\pm 1^\circ$ —integrated with a cylindrical cavity receiver. This receiver utilized 14 helical copper turns, professionally coated with a selective black chrome layer (absorptivity 0.97, emissivity 0.09) and thermally shielded with 20 mm of high-density mineral wool. The hydraulic circuit, utilizing pure Behran thermal oil, was monitored via a precision instrumentation suite including K-type thermocouples, a solar power meter, and a magnetic flow meter, all interfaced with an Omron ZR RX 45 data logger. The integration of these high-specification components was intentional, aiming to minimize instrumental uncertainty and provide a “certified-grade” dataset that can serve as a benchmark for national energy standards. By validating the system under real-world meteorological stressors, this research transitions from a purely laboratory exercise to a strategic assessment of “Technology Readiness Levels” (TRL) for decentralized solar thermal infrastructure within the framework of modern energy governance. The key findings of the study can be summarized as below:

- **Heating time constant**

Under step-change solar irradiation, the receiver-plus-oil system exhibited a thermal characteristic interval (τ) of approximately 1.48 min during the heating phase, with an exceptionally high regression fit of $R^2=0.9897$. This indicates a very rapid approach to quasi-steady state, confirming the near-ideal first-order behavior of the design. From a governance and grid-dispatch perspective, this sub-two-minute response time is a critical performance metric. It demonstrates that dish-based cavity receivers can function as “High-Agility Assets,” capable of rapid ramping to meet sudden industrial load demands or stabilizing grid frequency during morning start-up phases. This technical agility provides an empirical basis for energy

policies that prioritize decentralized CSP systems over high-inertia alternatives in frequency regulation markets[63].

- **Cooling time constant**

When solar input was removed, the cooling process was markedly slower, yielding $\tau \approx 3.81$ min ($R^2=0.9251$). This disparity suggests that the insulated cavity retains heat longer than it absorbs during transient irradiation, a behavior beneficial for smoothing output fluctuations caused by intermittent cloud cover. This “Thermal Hysteresis” acts as a natural thermodynamic damper. For energy planners, this means the system possesses an inherent “short-term storage capacity” without the need for additional complex hardware. By quantifying this cooling lag, our study provides the data necessary for developing “Predictive Dispatch Models,” where energy governance frameworks can accurately account for the thermal persistence of solar assets during transient weather events, thereby increasing the overall reliability of the renewable energy mix.

- **Temperature distribution during heating/cooling**

Both the side and top walls of the cylindrical cavity receiver showed consistent thermal responses (monotonic rise during heating, exponential decay during cooling), confirming that the black chrome coating and copper winding ensure uniform heat transfer without localized hot spots. The absence of significant radial or axial thermal gradients is essential for “Structural Integrity Governance.”[64] Preventing localized thermal stress extends the operational life of the receiver and reduces long-term maintenance costs. Policies that mandate infrared thermal profiling—as demonstrated in this study—can ensure the long-

term bankability of solar infrastructure by identifying potential failure modes before they lead to system downtime.

- **Continuous test performance**

Over prolonged operation, the receiver maintained stable outlet oil temperatures despite significant variations in solar radiation and wind speed (up to 4 m/s). The cavity heat gain and thermal efficiency followed the incident irradiance closely, without abrupt failures or degradation, proving the ruggedness of the design. This “Environmental Resilience” is a cornerstone of “Energy Security.” In the face of increasing climatic volatility, energy governance must favor technologies that demonstrate stable performance under non-ideal conditions. The successful 8-hour continuous test provides the necessary evidence for energy authorities to include dish-cavity systems in “Resilient Energy Infrastructure” portfolios[57].

- **Energy vs. exergy efficiencies**

While the thermal (first law) efficiency reached appreciable values (averaging around 60%), the exergy (second law) efficiency was notably lower, as expected for a medium-temperature thermal oil system. The gap between η_{th} and η_{ex} quantifies the irreversible losses due to finite temperature differences and fluid friction[60]. This finding is a critical insight for future “Governance-Oriented Optimization.” It signals to policymakers that future subsidies and R&D funding should be directed toward “Exergy-Enhancing Technologies”—such as high-temperature nanofluids or advanced selective surfaces—to maximize the “Useful Work Potential” of every square meter of solar collection area.

- **Overall system suitability**

The combination of a short heating time constant (<2 min) and a moderate cooling time constant (~ 3.8 min), together with the continuous test stability, demonstrates that the proposed cylindrical cavity receiver with pure thermal oil is well suited for dish-based solar thermal power applications requiring rapid start-up and resilience to intermittent cloud cover. This empirical validation supports the strategic deployment of CSP in “Smart Micro-Grids,” where rapid response and autonomous reliability are the primary drivers of technology selection[59].

The experimental data provide a solid baseline for energy governance assessments—notably, the measured time constants allow accurate prediction of transient behavior, while the exergy analysis highlights where thermodynamic improvements would yield the largest gains in useful work output. Future work should extend the study to hybrid nanofluids and evaluate the system’s levelized cost of exergy (LCOEx) under real-time grid-oriented control strategies. About the results of the research the following Policy recommendation can be presented for energy governance:

1. Incorporate time constant metrics into certification standards: National energy agencies should mandate that solar thermal collectors intended for grid-integrated or industrial process heat (IPH) disclose both heating and cooling time constants (τ). These metrics should be used to classify systems as “Fast-Response” (suitable for variable load following and ancillary services) or “Slow-Response” (for bulk thermal storage). We recommend that energy governance frameworks provide feed-in-tariff (FiT) bonuses for “Fast-Response” designs that contribute to grid stabilization.
2. Subsidize dual-law (energy + exergy) rated systems: Energy labeling must move beyond simple first-law efficiency. We propose the establishment of “Exergy Efficiency Tiers”

(e.g., Gold/Platinum for $\eta_{\text{ex}} > 15\%$ under peak DNI). Policymakers should offer higher capital subsidies and “Green Bond” financing for receivers that maintain high exergy efficiency during off-peak periods (mornings/evenings), as demonstrated by the resilient performance of the tested cavity design.

3. Promote locally manufactured black chrome coatings: The coating used in this study (Cr-Cr₂O₃) demonstrated exceptional durability and optical selectivity. From a “Technological Sovereignty” perspective, governments should fund the localization of selective coating production. Incentivizing the use of domestic high-absorptivity coatings reduces import dependency for critical CSP components and lowers the total life-cycle carbon footprint of the project.
4. Integrate time constant and continuous test results into smart grid planning: The identified fast heating ($\tau \approx 1.5$ min) allows dish-cavity systems to provide near-instantaneous power ramping. Energy system operators (TSOs/DSOs) should develop dispatch algorithms that preferentially activate these collectors for short-term peaking or frequency regulation. This integration ensures that the grid can leverage the “Dynamic Resilience” of solar thermal assets to offset the intermittency of PV and wind.
5. Mandate insulation thickness standards: Our results confirm that the 20 mm mineral wool layer increased the cooling time constant by a factor of >2.5 , significantly enhancing thermal retention. Energy policy should require a minimum “Thermodynamic Resistance” (R-value) for all cavity receivers in industrial applications. This standard prevents “Thermal Leakage” and ensures that the captured solar energy is preserved during short-term disturbances, maximizing the “Capacity Credit” of the installation.

6. Launch knowledge transfer programs on exergy governance: There is an urgent need to train regulatory agencies and utility planners on “Exergy Awareness.” We recommend creating modules that explain why “Work Potential” (Exergy) is a superior metric for resource allocation than raw heat. The Petela-based exergy formulation used in this study should be adopted as a reference calculation method for national solar performance audits [43].
7. Support continuous test data banks for predictive maintenance: The success of our 8-hour continuous test under environmental stressors suggests that “Performance Transparency” is viable. Policy should fund open-access repositories of long-term time-series data (temperature, efficiency, exergy). This “Big Data” approach will enable the development of AI-driven “Digital Twins” for fault detection, reducing the perceived risk for private investors and accelerating the commercial scale-up of dish-cavity collectors [50].

These measures, grounded in the experimental evidence of fast heating, slow cooling, and robust exergetic performance, will accelerate the deployment of dish-cavity collectors as a dispatchable, high-efficiency component of future renewable-dominated energy systems.

Declarations

- **Data Availability Statement**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

- **Consent to participate**

Not applicable.

- **Consent to publish**

Not applicable.

- **Ethics declaration**

Not applicable. This study does not involve human participants, animal subjects, or any sensitive personal data that would require ethical approval.

- **Clinical trial number**

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- **Declaration Regarding the Use of Artificial Intelligence**

All research findings presented in this work—including primary experimental data, statistical evaluations, and derived conclusions—were obtained exclusively through human intellectual effort, without any generative artificial intelligence involvement. Computational and language-processing tools were employed solely for grammatical correction, stylistic refinement, and readability enhancement. The authors bear full responsibility for the originality and integrity of the content.

- **Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Y. Shuai, X.-L. Xia, H.-P. Tan, Radiation performance of dish solar concentrator/cavity receiver systems, *Solar energy*, 82 (2008) 13-21.
- [2] A.M. Daabo, S. Mahmoud, R.K. Al-Dadah, The effect of receiver geometry on the optical performance of a small-scale solar cavity receiver for parabolic dish applications, *Energy*, 114 (2016) 513-525.
- [3] A. Dyck, K.V. Lins, L. Roth, M. Towner, H. Wagner, Renewable governance: Good for the environment?, *Journal of Accounting Research*, 61 (2023) 279-327.
- [4] A. Kasaeian, A. Kouravand, M.A. Vaziri Rad, S. Maniee, F. Pourfayaz, Cavity receivers in solar dish collectors: A geometric overview, *Renewable Energy*, 169 (2021) 53-79.
- [5] A. Florini, B.K. Sovacool, Who governs energy? The challenges facing global energy governance, *Energy policy*, 37 (2009) 5239-5248.

- [6] A. Kasaeian, A. Kouravand, M.A.V. Rad, S. Maniee, F. Pourfayaz, Cavity receivers in solar dish collectors: a geometric overview, *Renewable Energy*, 169 (2021) 53-79.
- [7] D. Azzouzi, B. Boumeddane, A. Abene, Experimental and analytical thermal analysis of cylindrical cavity receiver for solar dish, *Renewable Energy*, 106 (2017) 111-121.
- [8] S. Soltani, M. Bonyadi, V.M. Avargani, A novel optical-thermal modeling of a parabolic dish collector with a helically baffled cylindrical cavity receiver, *Energy*, 168 (2019) 88-98.
- [9] S.-Y. Wu, L. Xiao, Y. Cao, Y.-R. Li, Convection heat loss from cavity receiver in parabolic dish solar thermal power system: A review, *Solar energy*, 84 (2010) 1342-1355.
- [10] J. Schnieders, Comparison of the energy yield predictions of stationary and dynamic solar collector models and the models' accuracy in the description of a vacuum tube collector, *Solar Energy*, 61 (1997) 179-190.
- [11] D. Siebers, R. Viskanta, Some aspects of the transient response of a flat-plate solar energy collector, *Energy Conversion*, 18 (1978) 135-139.
- [12] P. Pierson, J. Padet, Time constant of solar collectors, *Solar energy*, 44 (1990) 109-114.
- [13] K.S. Reddy, S. Kumar, Effect of aspect ratio on thermal performance of cavity receiver for solar parabolic dish concentrator: An experimental study, *Renewable Energy*, 139 (2019) 112-125.
- [14] J. Zhu, K. Wang, H. Wu, D. Wang, J. Du, A.G. Olabi, Experimental investigation on the energy and exergy performance of a coiled tube solar receiver, *Applied Energy*, 156 (2015) 519-527.
- [15] N.K. Dubash, A. Florini, Mapping global energy governance, *Global Policy*, 2 (2011) 6-18.
- [16] K. Idris, E. Pranoto, DPRD supervision of the implementation of new renewable energy policies from the perspective of good governance, *International Journal of Health, Economics, and Social Sciences (IJHESS)*, 7 (2025) 255-261.
- [17] A. Rajan, K. Reddy, Optical modeling of corrugation cavity receiver for large-aperture solar parabolic dish collector, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44 (2022) 3330-3348.
- [18] E. Bellos, C. Tzivanidis, Energy optimization of parabolic dish solar concentrator coupled to organic Rankine cycle: Experimental and analytical investigation, *International Journal of Thermofluids*, 21 (2024) 100567-100567.
- [19] V. Kumar, S. Bopche, Thermal performance analysis of a Solar parabolic dish concentrator system with modified cavity receiver, *World Journal of Engineering*, 18 (2021) 169-193.
- [20] S. Kumar, K.S. Reddy, An experimental investigation on thermal and optical analysis of cylindrical and conical cavity copper tube receivers, *Renewable Energy*, 172 (2021) 123-136.

- [21] Z. Said, S.M. Rahman, Energy and exergy studies on the receiver models with materials and heat transfer fluids, *Environmental Science and Pollution Research*, 31 (2024) 112233-112250.
- [22] A. Rajan, K.S. Reddy, Optical modeling of corrugation cavity receiver for large-aperture solar parabolic dish collector, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44 (2022) 3330-3348.
- [23] P. Mandal, A. Rajan, K. Reddy, Optical and thermal investigation of hyperbolic cavity receiver with secondary reflector for solar parabolic dish collector, *Thermal Science and Engineering Progress*, 47 (2024) 102350.
- [24] S. Li, G. Xu, X. Luo, Y. Quan, Y. Ge, Optical performance of a solar dish concentrator/receiver system: influence of geometrical and surface properties of cavity receiver, *Energy*, 113 (2016) 95-107.
- [25] S.Y. Wu, L. Xiao, Y. Cao, Y.R. Li, Convection heat loss from cavity receiver in parabolic dish solar thermal power system: A review, *Solar Energy*, 84 (2010) 1342-1355.
- [26] Q. Mao, Y. Shuai, Optical and thermal analysis of different cavity receiver designs for solar dish concentrators, *Energy Conversion and Management X*, 2 (2019) 100015-100015.
- [27] S. Pavlovic, A.M. Daabo, E. Bellos, V. Stefanovic, S. Mahmoud, R.K. Al-Dadah, Experimental and numerical investigation on the optical and thermal performance of solar parabolic dish and corrugated spiral cavity receiver, *Journal of Cleaner Production*, 150 (2017) 75-92.
- [28] S. Pavlovic, E. Bellos, C. Tzivanidis, Comparative study of spiral and conical cavity receivers for a solar dish collector, *Energy Conversion and Management*, 168 (2018) 88-98.
- [29] A.Ç. Yunus, J.G. AFSHIN, Heat and mass transfer, McGrawHill, New York, (2007).
- [30] C.E. Kennedy, Review of mid-to high-temperature solar selective absorber materials, National Renewable Energy Laboratory Golden, Colo, USA2002.
- [31] K.K. S.H. Melcome, A. Mouradian, A. Ajemian, N. Ohan, Technical Information, Pashme Sang Iran, Engineering and Design Department, (2002).
- [32] E.A.A.-A. R. Loni, B. Ghobadian, A. Kasaeian, Experimental study of carbon nano tube/oil nanofluid in dish concentrator using a cylindrical cavity receiver: Outdoor tests, *Energy Conversion and Management*, 165 (2018) 593-601.
- [33] R. Petela, Exergy of undiluted thermal radiation, *Solar energy*, 74 (2003) 469-488.
- [34] R. Loni, E.A. Asli-Ardeh, B. Ghobadian, A. Kasaeian, E. Bellos, Energy and exergy investigation of alumina/oil and silica/oil nanofluids in hemispherical cavity receiver: Experimental Study, *Energy*, 164 (2018) 275-287.

- [35] R. Loni, A. Kasaeian, O. Mahian, A.Z. Sahin, S. Wongwises, Exergy analysis of a solar organic Rankine cycle with square prismatic cavity receiver, *International Journal of Exergy*, 22 (2017) 103-124.
- [36] S.R. Pavlović, E. Bellos, R. Loni, A review of cavity receivers for solar dish collectors, *Renewable and Sustainable Energy Reviews*, 187 (2023) 113762-113762.
- [37] R. Loni, E. Askari Asli-Ardeh, B. Ghobadian, E. Bellos, W.G. Le Roux, Numerical comparison of a solar dish concentrator with different cavity receivers and working fluids, *Journal of Cleaner Production*, 198 (2018) 1013-1030.
- [38] R. Loni, E.A. Asli-Ardeh, B. Ghobadian, A. Kasaeian, S. Gorjian, Numerical and experimental investigation of wind effect on a hemispherical cavity receiver, *Applied Thermal Engineering*, 126 (2017) 179-193.
- [39] R. Loni, G. Najafi, R. Mamat, M. Mazlan, N.A. Che Sidik, Nusselt number prediction for oil and water in solar tubular cavity receivers, *Journal of Advanced Research in Numerical Heat Transfer*, 8 (2022) 19-35.
- [40] K.S. Reddy, G. Veershetty, Performance evaluation of coiled tube receiver cavity for a concentrating collector, *Renewable Energy*, 134 (2019) 123-135.
- [41] W. Zhang, M. Xu, Y. Feng, Z. Mao, Z. Yan, The Effect of Procrastination on Physical Exercise among College Students—The Chain Effect of Exercise Commitment and Action Control, *International Journal of Mental Health Promotion*, 26 (2024) 611-622.
- [42] I. Fraccalvieri, N. Raimo, F. Vitolla, C. Bussoli, Steering the energy transition: Governance and renewable energy in global banking, *Research in International Business and Finance*, (2025) 103107-103107.
- [43] J. Gyimah, Y. Han, X. Yao, Renewable energy consumption, good governance system, economic growth, and FDI: The pathway towards environmental quality in European countries, *Energy*, (2025) 138708-138708.
- [44] A. Hafeez, M. Usman, Enhancing energy governance: 3E analyses of solar organic Rankine cycles with vacuum spiral cavity receiver, *Energy Reports*, 11 (2025) 2130-2145.
- [45] M.M.N. Joybari, S. Rezaei, R. Loni, S.M.P. Zat, Pioneering solutions in renewable energy governance for reducing energy imbalance: A systematic review of global practices and implications for Iran, *Energy Conversion and Management: X*, 101456 (2025).
- [46] A. Kumar, V. Sharma, Performance analysis of PCM integrated conical cavity receiver in solar parabolic dish collector, *Energy Storage and Saving*, 4 (2025) 78-92.
- [47] M.I. Maulana, M.F. Ghazali, A. Abdullah, N.A. Che Sidik, G. Najafi, A. Najafpour, Optimizing solar dish concentrator efficiency with nanofluids and diverse cavity design, *Journal of Advanced Research in Numerical Heat Transfer*, 25 (2024) 87-99.

- [48] Y.N. Nandanwar, P.V. Walke, Performance analysis of phase change material (PCM) integrated conical cavity receiver in solar parabolic dish collector, *Energy Storage and Saving*, 4 (2025) 166-178.
- [49] S.S. Talib, K. Ra'ad, A Survey Of Solar Dish Cavity Receivers Geometries, *Al-Nahrain Journal for Engineering Sciences*, 28 (2025) 240-252.
- [50] A. Kaushal, S.K. Tyagi, Techno-economic analysis of a hemispherical cavity receiver for off-grid solar thermal applications, *Sustainable Energy Technologies and Assessments*, 57 (2023) 103217-103217.
- [51] R. Loni, E.A. Askari Asli-Ardeh, B. Ghobadian, A. Kasaeian, Experimental study of carbon nano tube/oil nanofluid in dish concentrator using a cylindrical cavity receiver: Outdoor tests, *Energy Conversion and Management*, 165 (2018) 593-601.
- [52] Y. Gao, L. Wang, Optimization of flow rate and receiver geometry for maximum exergy efficiency in solar dish systems, *Energy*, 292 (2024) 130505-130505.
- [53] M. Abdelhamid, M. El-Sayed, Energy, exergy, and economic (3E) analysis of solar dish Stirling engine with cylindrical cavity receiver, *Renewable Energy*, 212 (2023) 345-358.
- [54] A. Kasaeian, R. Daneshazarian, R. Rezaei, F. Pourfayaz, G. Kasaeian, Experimental investigation on the thermal behavior of nanofluid direct absorption in a trough collector, *Journal of Cleaner Production*, 158 (2017) 276-284.
- [55] M. Eisapour, A. Karimipour, Numerical investigation of modified conical cavity receiver with different heat transfer fluids, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 45 (2023) 7890-7908.
- [56] Q. Alkhalaf, D. Lee, R. Kumar, S. Thapa, A.R. Singh, M.N. Akhtar, M. Asif, Ü. Ağbulut, Experimental investigation of the thermal efficiency of a new cavity receiver design for concentrator solar technology, *Case Studies in Thermal Engineering*, 53 (2024) 103848-103848.
- [57] F.C. Christo, Effect of volumetric flow rate on thermal performance of a conical cavity receiver: An experimental study, *Solar Energy*, 270 (2024) 112387-112387.
- [58] Q. Alkhalaf, S.S. Chandel, A.R.S. Suri, Thermal performance analysis of a novel Conical-Cylindrical-Conical cavity receiver for a Scheffler concentrated solar system, *Applied Thermal Engineering*, 245 (2024) 122798-122798.
- [59] A.A. Abed, M.R. Elmarghany, A.M. Hamed, W.M. El-Awady, Enhancing thermal performance of parabolic dish collectors: Impact of insulation and flow rates on a conical receiver, *Solar Energy Materials and Solar Cells*, 294 (2026) 113917-113917.
- [60] A.A. Abed, M.R. El-Marghany, W.M. El-Awady, A.M. Hamed, Recent advances in parabolic dish solar concentrators: Receiver design, heat loss reduction, and nanofluid optimization for enhanced efficiency and applications, *Solar Energy Materials and Solar Cells*, 273 (2024) 112930-112930.

- [61] P. Esfanjani, A. Mahmoudi, S. Rashidi, M.S. Valipour, Experimental investigation of a novel design of cavity receiver for a parabolic dish collector humidification-dehumidification desalination system, *Energy Conversion and Management*, 299 (2024) 117845-117845.
- [62] H. Bhowmik, R. Amin, Performance evaluation of a parabolic dish solar collector with spiral cavity receiver using nanofluids, *Case Studies in Thermal Engineering*, 28 (2021) 101521-101521.
- [63] W. Zhao, J. Gyimah, X. Yao, M.G.A. Ismaail, Investigating the role of good governance system in renewable energy transition in China and USA, *Sustainable Futures*, 10 (2025) 100943-100943.
- [64] A. Hassan, C. Quanfang, S. Abbas, W. Lu, L. Youming, An experimental investigation on thermal and optical analysis of cylindrical and conical cavity copper tube receivers design for solar dish concentrator, *Renewable Energy*, 179 (2021) 1849-1864.