

Thinner Walls, Slower Flow: CFD Design of a Cavity-Receiver Heat Plate for a Solar Fresh Water Generator Serving Coastal Communities

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ABSTRACT

Coastal communities in Indonesia face a persistent shortage of potable water, since abrasion renders groundwater brackish and piped supply networks do not reach many settlements. A solar-driven fresh water generator offers a decentralised remedy, and the thermal performance of such a device is governed principally by the design of its heat receiver. This study determines the cavity-receiver heat plate configuration that maximises the overall heat transfer coefficient in a small parabolic dish system, using computational fluid dynamics simulation in ANSYS Fluent to compare two designs differing in wall thickness and working-fluid velocity. Model 1 combined a wall thickness of 1 mm with a flow velocity of 0.05 m/s; Model 2 combined 2 mm with 0.15 m/s. Water was adopted as the working fluid, with temperature-dependent specific heat, density, and dynamic viscosity represented by polynomial functions. Simulation showed that Model 1 produced a uniform temperature distribution across the inner plate surface and attained the higher outlet temperature, whereas Model 2 concentrated heat at a single region and remained below 40 °C. Model 1 also exhibited the lower internal pressure and a pronounced pressure drop across the plate outlet, conditions associated with more effective absorption of concentrated radiation. The study concludes that the thinner wall reduces conductive resistance while the lower velocity lengthens residence time, and that these two effects act in the same direction. The recommended configuration is therefore a 1 mm inverted cavity operating at 0.05 m/s, which the simulation indicates can raise the working fluid to 54 °C.

INTRODUCTION

Communities settled along the Indonesian coastline face a fundamental constraint upon daily life: the limited availability of fresh water. Coastal abrasion permits the intrusion of saline water into shallow aquifers, rendering groundwater unfit for consumption, and many such settlements lie beyond the reach of reticulated supply networks. The consequence is a dependence upon purchased or transported water that imposes both a financial burden and a logistical vulnerability. A device capable of converting brackish water into potable water at the point of need would therefore address a genuine deficiency, provided that it can be operated without a grid electricity connection.

Solar energy offers the obvious source. Indonesia receives substantial direct normal irradiance throughout the year, and solar-driven desalination has attracted sustained research attention as a means of addressing water scarcity in precisely the settings where conventional infrastructure is absent (Kumar et al., 2024; Madhuri et al., 2025). Hoque et al. (2019) demonstrated the applicability of solar stills to saline water desalination for low-income coastal areas specifically, and subsequent work has examined means of enhancing their output through porous media and feed preheating (Abd Elbar & Hassan, 2020) and through optimisation of film thickness and interfacial transfer (de Paula & Ismail, 2021; Wang et al., 2023).

Among the available solar thermal technologies, concentrated solar power employing a parabolic dish concentrator is well suited to small-scale deployment. The dish focuses incident radiation onto a receiver mounted at the focal point, and the temperature attainable at that point substantially exceeds what a flat-plate collector can achieve for the same aperture. Design analysis of dish technologies has established the principal specifications governing their performance across applications (Hafez et al., 2017), and low-cost mechanical designs suitable for constrained budgets have been developed and demonstrated (Hijazi et al., 2016). Recent reviews document continuing advances in receiver design and heat loss reduction for such systems (Abed et al., 2024).

Within a dish system the receiver constitutes the critical component, since it determines the proportion of concentrated radiation that is converted into useful thermal energy in the working fluid. Cavity geometries are generally preferred to external absorbers because the enclosure traps re-radiated energy and increases the effective absorptance of the irradiated surface. A substantial body of work has examined the influence of cavity geometry upon optical and thermal performance, comparing cubical, cylindrical, spherical, conical, and hyperbolic configurations (Loni et al., 2018; Si-Quan et al., 2019; Daabo et al., 2016; Mandal et al., 2024), and investigating the effect of aspect ratio experimentally (Venkatachalam & Cheralathan, 2019).

Two design parameters have received comparatively less attention than geometry, notwithstanding their direct bearing upon the heat transfer coefficient. The first is the wall thickness of the absorber plate, which governs the conductive resistance between the irradiated surface and the working fluid. The second is the velocity of the working fluid within the cavity, which governs both the convective coefficient at the wall and the residence time available for energy

transfer. These parameters act in opposition in some respects and in concert in others, and their combined effect upon the overall heat transfer coefficient is not readily predicted analytically.

This study accordingly determines, by computational fluid dynamics, the combination of wall thickness and working-fluid velocity that maximises the overall heat transfer coefficient of a cavity-receiver heat plate intended for a simple solar fresh water generator. Two objectives are pursued: to produce a heat plate design suitable for service as the heat receiver of such a device, and to establish the reliability implications of material thickness for maximising absorbed solar energy. The contribution lies in isolating the joint effect of thickness and velocity, which the cavity geometry literature has largely treated as secondary to shape.

LITERATURE REVIEW

Concentrated Solar Power and the Parabolic Dish

Concentrated solar power differs fundamentally from photovoltaic conversion. Whereas photovoltaic cells convert incident photons directly into electrical current, concentrated solar power employs reflective surfaces to focus radiation onto a receiver, generating high-temperature heat that may be used directly or converted subsequently. The parabolic dish configuration achieves the highest concentration ratio among the principal architectures, and can generate output at temperatures well above those accessible to trough or Fresnel systems. Schiel and Keck documented the development of dish systems for power generation, and Sandoval et al. (2019) modelled the thermal behaviour of a dish-Stirling installation, illustrating the range of applications the architecture supports.

Assessments of deployment potential indicate that the technology is well matched to tropical latitudes. Yushchenko et al. (2018) conducted a geographic assessment of photovoltaic and concentrated solar power generation potential in West Africa, and Ling-zhi et al. (2018) examined the economic performance of the concentrated solar power industry in China. Turrini et al. (2018) demonstrated an innovative small-scale prototype integrating a dish concentrator with molten salt storage, establishing that the architecture is viable at modest scale and not only in utility installations. This scalability is essential to the present application, in which the device must serve a village rather than a grid.

Cavity Receiver Design

The receiver converts concentrated radiation into thermal energy within the working fluid, and its design governs the efficiency of the system as a whole. Cavity receivers enclose the absorbing surface within a partially closed volume, which reduces radiative and convective loss relative to an exposed absorber and permits the irradiated area to be more fully exploited. Bellos et al. (2019) conducted an optical and thermal analysis of several cavity receiver designs for dish concentrators and quantified the trade-offs among them, while Kanatani et al. (2017) developed a model of a cavity receiver employing coiled tubes, a configuration that increases the heat transfer area within a given envelope.

Geometry has been the dominant variable in this literature. Loni et al. (2018) compared cubical and cylindrical cavity receivers experimentally and numerically using thermal oil as the working fluid, and Si-Quan et al. (2019) examined the optical and thermodynamic characteristics of a spherical cavity numerically. Daabo et al. (2016) assessed the effect of receiver geometry upon optical performance in small-scale dish applications, and Mandal et al. (2024) investigated a hyperbolic cavity coupled to a secondary reflector. Yan et al. (2018) approached the problem from the concentrator side, optimising a discrete dish to achieve uniform flux distribution upon the cavity receiver, and Pratik et al. (2024) conducted a numerical investigation to optimise a modified cavity receiver for enhanced thermal performance.

Aspect ratio has also been examined directly. Venkatachalam and Cheralathan (2019) studied experimentally the effect of aspect ratio upon the thermal performance of a cavity receiver for a dish concentrator and reported that receiver surface temperature declines as aspect ratio increases, while thermal performance does not vary monotonically with that parameter. Roostaei and Ameri (2019) considered the corresponding problem for trapezoidal cavity receivers in linear Fresnel fields, relating cavity dimension to heat loss. The recurring finding across this body of work is that reducing receiver surface temperature is not by itself sufficient to improve thermal performance, since the useful output depends upon the temperature attained by the working fluid rather than by the absorber.

Working Fluid and Transfer Enhancement

The choice and management of the working fluid conditions the effectiveness of any receiver design. Loni et al. (2018) employed thermal oil, which permits higher operating temperatures than water but introduces cost and handling considerations inappropriate to a village-scale device. Water, by contrast, is available at the point of use and requires no special handling, at the cost of a lower attainable temperature and the need to represent its temperature-dependent properties accurately in simulation. Sheeba et al. (2020) characterised the heat transfer and flow behaviour of a conical coil heat exchanger, a configuration analogous to the coiled arrangement within a cavity.

Flow velocity within the receiver mediates two competing effects. Higher velocity raises the convective heat transfer coefficient at the wall, which favours transfer; but it simultaneously shortens the residence time during which any element of fluid is exposed to the irradiated surface, which opposes it. The net effect upon outlet temperature depends upon which mechanism dominates for the geometry and irradiance in question, and is therefore an empirical matter to be resolved by simulation or experiment rather than by inspection.

Solar Desalination for Coastal Communities

The application motivating this study belongs to a well-established field. Kumar et al. (2024) reviewed solar stills as a response to water scarcity, and Madhuri et al. (2025) situated solar-driven desalination within the broader agenda of climate mitigation and sustainable development. Hoque et al. (2019) addressed the specific case of low-income coastal areas, and Abd Elbar and Hassan (2020) demonstrated enhancement of a hybrid system through porous

material and feed preheating. de Paula and Ismail (2021) established the influence of water film thickness upon heat and mass transfer in an inclined still, and Wang et al. (2023) optimised heat and mass transfer in a passive interfacial configuration. The feed-preheating strategy of Abd Elbar and Hassan (2020) is particularly germane to the present design: their enhancement raised feed temperature ahead of the still itself, a role directly analogous to the 54 °C outlet achieved by the receiver characterised below, and reinforces the positioning of a preheating receiver, rather than a boiling heat source, as the appropriate application for a device operating in this temperature range.

Two observations follow. First, the desalination literature concentrates upon the evaporation stage and the still itself, with the upstream heat source frequently treated as a given. Second, the cavity receiver literature concentrates upon geometry and optical performance, generally with power generation rather than water production as the intended application. The present study addresses the junction between these fields by optimising the receiver specifically for the temperature range and scale relevant to a village fresh water generator.

Research Gap

The reviewed literature establishes that cavity geometry, aspect ratio, and concentrator flux uniformity have each been examined systematically. It does not establish the joint effect of absorber wall thickness and working-fluid velocity upon the overall heat transfer coefficient, notwithstanding that these are the two parameters most readily varied by a fabricator working with limited resources. The present study addresses that gap through comparative CFD simulation of two configurations differing in both parameters.

METHODOLOGY

System Configuration and Mathematical Model

The system comprises a parabolic dish concentrator focusing direct normal irradiance onto an inverted cavity receiver, within which the heat plate carries the working fluid. The energy captured by the collector aperture is determined by the product of aperture area and direct solar irradiance. The useful heat produced by the collector follows from the mass flow rate, the specific heat of the working fluid, and the temperature rise between inlet and outlet. Thermal efficiency is expressed as the ratio of net useful heat to incident irradiance, and optical efficiency as the ratio of radiation absorbed by the coil to radiation incident upon the aperture.

The heat transfer coefficient of the flowing fluid is computed from the useful heat, the heat transfer area, and the difference between the receiver surface temperature and the mean fluid temperature, the latter taken as the arithmetic mean of inlet and outlet values. The energy balance of the system under transient heating is expressed through the fluid mass, volume, and specific heat under the assumption of initially uniform conditions. Radiative loss from the receiver is evaluated under steady-state conditions from the absorber outer diameter, surface emissivity, and the Stefan-Boltzmann constant, radiation being the dominant loss mechanism at the temperatures concerned.

Working Fluid Properties

Water was adopted as the working fluid on the grounds of availability, safety, and appropriateness to the intended application. Because the thermophysical properties of water vary appreciably across the operating range, each was represented by a polynomial function of temperature obtained by regression. Specific heat capacity and density were represented across the range 285.15 K to 698.15 K. Dynamic viscosity was represented by two separate polynomials, one valid from 285.15 K to 373.15 K and a second from 373.15 K to 698.15 K, in order to capture the change in behaviour across the boiling point at atmospheric pressure.

Simulation Design

Two heat plate models were defined, differing simultaneously in wall thickness and working-fluid velocity. Model 1 combined a wall thickness of 1 mm with a flow velocity of 0.05 m/s. Model 2 combined a wall thickness of 2 mm with a flow velocity of 0.15 m/s. The heat plate adopted an angular geometry intended to maximise transfer from the concentrating element. Geometry preparation, meshing with verification of mesh quality, and solution were performed within a computational fluid dynamics environment (ANSYS Fluent), with boundary conditions derived from site irradiance data for the study location. The complete workflow is represented in Figure 1.

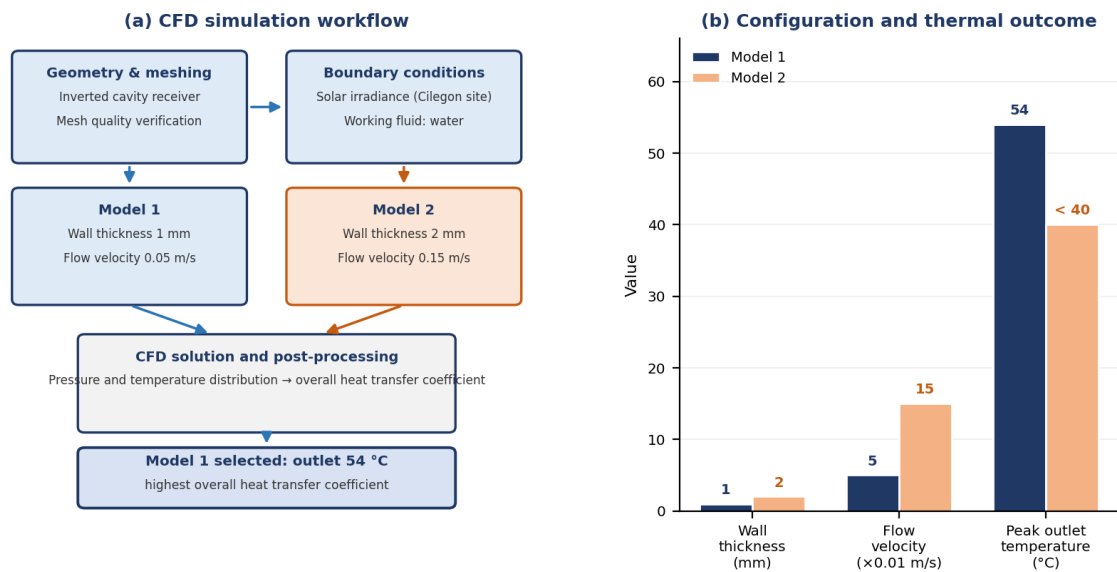


Figure 1. Simulation workflow and comparison of the two heat plate configurations

Post-processing extracted the distribution of pressure and temperature across the plate inlet and outlet for each model. These distributions were then used to evaluate the overall heat transfer coefficient, which constitutes the criterion by which the configurations were compared. It should be noted that the two models differ in both parameters simultaneously rather than in one at a time; the design therefore identifies the superior configuration but does not isolate the independent contribution of thickness and velocity, a limitation addressed in the discussion.

RESEARCH RESULT

Pressure Distribution

The behaviour of the working fluid within the plate is conditioned by the internal pressure field, and the distribution across the plate inlet was examined first. In both models the pressure recorded at the lower region of the plate exceeded that at the upper region. This asymmetry arises because concentrated radiation is incident upon the lower surface of the inlet plate, raising the temperature of the fluid on that side and, through the resulting change in density and volume, its pressure. Pressure at the lower region of the inlet plate ranged from 12.79 to 13.29 kPa, with the highest value recorded for Model 2 operating at the higher flow velocity.

Examination of the plate outlet disclosed a marked difference between the models. Model 2 returned the lowest pressure at the inner surface of the plate, whereas Model 1 returned values clustered closely in the range of 24 to 25 Pa. The pressure profile across the outlet of Model 1 declined substantially, while that of Model 2 remained comparatively flat across a more stable range. This distinction is significant because a pronounced pressure drop across the plate is associated with more effective absorption of the radiation concentrated upon the cavity.

Temperature Distribution

Temperature distribution within the cavity constitutes the principal indicator of heat plate function, and the two models differed both in the magnitude attained and in the uniformity of the field. At the plate inlet, Model 1 exhibited an even distribution of temperature across the inner surface of the plate, whereas in Model 2 the elevated temperature was concentrated at a single region towards the upper part of the plate. The consequence was a higher overall distribution in Model 1, whose inlet reached a maximum of 34 °C.

At the plate outlet the difference was more pronounced. In Model 1 the concentration of temperature lay at the lower part of the plate, whereas Model 2 exhibited two separate concentrations, at the upper and lower parts respectively. Values recorded for Model 2 remained low, below 40 °C, while Model 1 attained the highest temperature observed in the study. Considered together with the pressure results, the temperature field establishes Model 1 as the superior configuration on both criteria. A summary comparison is presented in Table 1.

Table 1. Configuration and simulated outcome for the two heat plate models.

Parameter	Model 1	Model 2
Cavity geometry	Inverted cavity receiver	Inverted cavity receiver
Wall thickness (mm)	1	2
Working fluid velocity (m/s)	0.05	0.15
Inlet plate pressure, lower region (kPa)	12.79 - 13.29	12.79 - 13.29 (upper end of range)
Outlet plate inner pressure	24 - 25 Pa (clustered)	Lowest recorded; profile comparatively flat
Pressure profile across outlet	Pronounced decline	Comparatively stable
Inlet temperature distribution	Even across inner plate surface	Concentrated at a single upper region
Maximum inlet temperature (deg C)	34	Not reported separately
Outlet temperature concentration	Lower part of plate	Two regions, upper and lower
Peak outlet temperature (deg C)	54	Below 40
Overall heat transfer coefficient	Higher	Lower

Overall Heat Transfer Coefficient

The overall heat transfer coefficient constitutes the decisive indicator for a heat exchanger, since it expresses the capacity of the plate to absorb radiant energy and transfer it to the working fluid. In concentrated solar power systems this coefficient substantially determines the effectiveness of the installation as a whole, and the most favourable cavity configuration is accordingly that which attains the highest value. Evaluation of the pressure and temperature fields established that Model 1, combining a wall thickness of 1 mm with a working fluid velocity of 0.05 m/s, returned the superior coefficient. Under this configuration the working fluid attained a temperature of 54 °C.

DISCUSSION

Why the Thinner Wall and Slower Flow Prevail

The superiority of Model 1 admits a mechanistic explanation in which both varied parameters act in the same direction. Wall thickness governs the conductive resistance between the irradiated outer surface and the working fluid; halving the thickness from 2 mm to 1 mm halves that resistance and permits a greater proportion of the absorbed flux to reach the fluid rather than being stored in, or re-radiated from, the plate material. Flow velocity governs residence time; reducing it from 0.15 m/s to 0.05 m/s triples the interval during which a given fluid element remains exposed to the heated surface, permitting a larger temperature rise per pass.

The countervailing consideration, that lower velocity reduces the convective coefficient at the wall, evidently does not offset these gains at the scale and irradiance concerned. This is consistent with the physical situation: at 0.05 m/s the flow is well within the laminar regime, where the convective coefficient is relatively insensitive to velocity, so that the residence time effect dominates. The finding therefore has a boundary condition attached, namely that it should not be extrapolated to configurations in which the flow would become turbulent.

The uniformity of the temperature field in Model 1, as against the single-point concentration observed in Model 2, carries an additional implication for durability. Concentrated hot spots impose localised thermal stress and, over repeated diurnal cycling, are a plausible precursor to fatigue and eventual failure of the absorber. A design that distributes the absorbed flux evenly is therefore preferable not only on thermal grounds but on reliability grounds, a consideration of particular weight for a device intended for community operation without specialist maintenance support.

Relation to the Cavity Receiver Literature

The finding that receiver surface temperature and useful thermal output are not equivalent measures accords with the experimental result of Venkatachalam and Cheralathan (2019), who observed that a reduction in receiver surface temperature does not by itself indicate improved thermal performance. In the present results the same logic operates: Model 2 concentrated heat at a single region of the plate, which would register as a high local surface temperature, yet delivered a lower outlet temperature to the fluid. The quantity of interest is the energy transferred to the working fluid, not the temperature attained by the absorber.

The pressure findings align with the treatment of cavity receivers as coupled thermal-hydraulic systems rather than purely optical ones. Kanatani et al. (2017) modelled a cavity receiver with coiled tubes in these terms, and Sheeba et al. (2020) characterised the flow and transfer behaviour of an analogous conical coil geometry. The pronounced pressure drop across the outlet in Model 1 indicates a greater conversion of thermal energy within the fluid stream, which is consistent with its higher outlet temperature. Bellos et al. (2019) similarly found that cavity designs must be evaluated on combined optical and thermal criteria rather than either alone.

Relative to the wider design literature, the present contribution is narrow but practically consequential. Studies of cavity geometry (Loni et al., 2018; Si-Quan et al., 2019; Daabo et al., 2016; Mandal et al., 2024) and of concentrator flux uniformity (Yan et al., 2018) address parameters that require substantial fabrication capability to vary. Wall thickness and flow rate, by contrast, are within the control of a workshop equipped for sheet metal work and fitted with a simple pump, and the finding that both should be reduced is directly actionable in that setting. Recent reviews of receiver design and heat loss reduction (Abed et al., 2024) situate such incremental parameter optimisation within a broader programme of efficiency improvement.

Implications for the Fresh Water Generator

The outlet temperature of 54 °C attained by Model 1 must be assessed against the requirements of the intended application. This temperature is insufficient to boil water at atmospheric pressure and therefore does not support conventional distillation, but it lies well within the range at which passive solar still designs operate, since these rely upon evaporation from a heated surface followed by condensation rather than upon boiling. de Paula and Ismail (2021) and Wang et al. (2023) both examined heat and mass transfer in configurations operating in this regime. The receiver characterised here is accordingly suited to serve as a preheating or direct-heating element within a still rather than as the heat source for a distillation column.

This positioning is consistent with the evidence on solar desalination for low-resource settings. Hoque et al. (2019) demonstrated the applicability of solar stills to coastal communities with limited means, and Abd Elbar and Hassan (2020) improved output through feed preheating specifically. A dish-concentrated receiver delivering fluid at 54 °C offers precisely such a preheating capability, and its integration with a still represents the natural next stage of development. The reviews of Kumar et al. (2024) and Madhuri et al. (2025) indicate that such hybrid arrangements constitute an active direction within the field.

Limitations

Four limitations qualify these findings. First, and most consequentially, the two models differ simultaneously in wall thickness and flow velocity, so that the study establishes which configuration performs better but cannot apportion the improvement between the two parameters; a factorial design varying each independently is required for that purpose. Second, the results derive from simulation alone and have not been validated against physical measurement, and the CFD predictions are conditional upon the adequacy of the mesh, the turbulence treatment, and the boundary conditions imposed. Third, only two configurations were evaluated, which is insufficient to locate an optimum rather than merely to rank the alternatives tested. Fourth, the simulation assumes steady irradiance and does not represent the diurnal and cloud-driven variability that a deployed device would experience, nor the fouling and scaling that brackish feedwater would produce over time.

CONCLUSIONS AND RECOMMENDATIONS

This study determined by computational fluid dynamics the cavity-receiver heat plate configuration that maximises the overall heat transfer coefficient in a small parabolic dish system intended for a solar fresh water generator. The inverted cavity geometry proved appropriate for a direct-receiver concentrated solar power arrangement. Of the two configurations evaluated, Model 1, combining a wall thickness of 1 mm with a working fluid velocity of 0.05 m/s, returned the superior overall heat transfer coefficient, producing a uniform temperature distribution across the plate and raising the working fluid to 54 °C, whereas Model 2, at 2 mm and 0.15 m/s, concentrated heat at a single region and remained below 40 °C. Both objectives set out in the Introduction are

accordingly met: the 1 mm, 0.05 m/s configuration is recommended as the heat plate design for service in the fresh water generator, and its thinner wall carries no adverse reliability implication for absorbed solar energy, since it is the thinner rather than the thicker plate that maximises useful heat transfer.

Three recommendations follow. First, fabrication of the heat plate should adopt the thinner wall specification and the lower flow velocity, both of which are readily achievable in a workshop setting and neither of which requires specialised materials. Second, the device should be integrated with a passive still configuration rather than a distillation column, since the attainable temperature supports evaporative rather than boiling operation. Third, the uniformity of the temperature field should be treated as a design criterion in its own right, given the implications of localised hot spots for the durability of a device intended for unsupervised community use.

ADVANCED RESEARCH

Four directions for further work are indicated. First, a factorial simulation varying wall thickness and flow velocity independently across a range of levels would permit the separate contribution of each to be quantified and an optimum to be located rather than merely a ranking established. Second, an optical simulation incorporating selective coatings applied to the cavity surface would establish whether absorptance can be raised further without a corresponding increase in re-radiation. Third, experimental validation employing the same variables as the simulation, with attention to reflection behaviour and surface coating, is required before the design is committed to fabrication at scale. Fourth, integration testing with a still, under realistic diurnal irradiance and using genuine brackish feedwater, would establish the water production rate attainable and the rate at which performance degrades through fouling.

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