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Numerical Simulation and Experimental Validation of Heat Transfer Through a CFRP Heating Flatbed with a Sand Thermal Buffer

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ABSTRACT

Stable conductive heating is required to reproduce desert basking conditions for captive *Uromastix aegyptia*, but conventional platforms may be heavy and thermally non-uniform. This study aimed to determine a suitable sand-buffer thickness for a lightweight carbon-fibre-reinforced polymer (CFRP) heating flatbed and experimentally validate the predicted surface temperature. A steady-state SOLIDWORKS Simulation model represented CFRP as orthotropic and dry sand as isotropic silicon dioxide. The measured heater condition was 77.4 °C; ambient temperature, convection coefficient, emissivity, and view factor were 298.9 K, 1.79 W/(m²·K), 0.9, and 0.5, respectively. Iterative modelling selected a 50 mm sand layer and predicted a surface temperature of 54.90 °C. The prototype was evaluated by infrared thermography at six intervals over 240 min in three trials. At 240 min, the mean centre temperature was 55.53 °C. The absolute difference from the prediction was 0.63 °C and the relative deviation was 1.15%, below the predefined 5% criterion. The final spatial maximum of 58.57 °C shows that centre-temperature agreement must be considered together with surface uniformity. The CFRP-sand configuration therefore produced a stable conductive surface, and the model provides a practical basis for preliminary thickness selection under the tested conditions.

1. Introduction

Desert reptiles depend on external heat sources to regulate physiological functions. A previous heating-flatbed experiment identified 50-55 °C as an effective conductive basking range for captive *Uromastix aegyptia* under tropical conditions [1]. Body-surface temperature and body length are also associated with thermoregulatory behaviour in lizards [2]. Temperature further affects thermal biology and locomotor performance in extreme-desert species [3]. These findings show that a basking system must provide both an appropriate target temperature and a stable spatial distribution.

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Reproducing this thermal environment in Malaysia is difficult because moderate ambient temperature is accompanied by high humidity. Long-term climatic warming can alter the thermal opportunities available for lizard thermoregulation [4]. At the substrate scale, experimental work shows that heat transfer in granular material depends on packing and inter-particle contact [5]. Measurements made specifically on sands likewise demonstrate that density, mineral composition, and pore structure influence effective thermal conductivity [6]. Consequently, sand depth cannot be selected from heater temperature alone.

Conventional radiant lamps can create steep local temperature gradients, whereas concrete platforms add thermal mass but reduce portability. Heating can also alter bond behaviour in CFRP-wrapped concrete systems, illustrating the need to consider thermal durability in hybrid structures [7]. Carbon-fibre-reinforced polymer (CFRP) offers high specific stiffness and architecture-dependent properties [8]. Direct measurements of carbon/epoxy composites confirm that thermal conductivity is tensorial and differs markedly between in-plane and through-thickness directions [9]. Multiscale modelling further shows that fibre arrangement and matrix properties control the effective thermal response [10]. Analytic modelling of orthotropic network heaters demonstrates how directional conduction can distribute heat laterally [11].

Sand contributes heat capacity and provides a natural contact surface. Its use in solar-thermal technologies demonstrates the suitability of granular media for sensible-heat storage [12]. Environmental boundary conditions also influence natural-convection heat-transfer coefficients and therefore affect predicted surface temperature [13]. Although these studies clarify the separate behaviour of CFRP, sand, heaters, and ambient heat loss, validation data remain limited for a CFRP casing combined with a thick sand buffer and an embedded electric plate for tropical captive husbandry. This study addresses that gap by determining a sand thickness that produces a 50-55 °C surface and experimentally validating the numerical prediction. Specifically, the study defines a measured heater boundary condition, predicts steady-state heat transfer through the CFRP-sand assembly, quantifies the transient response over 240 min, and calculates the final simulation deviation. The resulting workflow provides a practical basis for designing lightweight, portable basking systems while identifying spatial non-uniformity that must be addressed for safe operation.

2. Methodology

2.1 Heating System and Boundary Characterisation

The Dhabb Environment Heat-Activated Base (DEHAB) consisted of a CFRP casing, an electric QC_NCB01-3A heating plate, and a quartz-rich granular sand layer. Before numerical modelling, the heating plate was operated in P1 mode and mapped using a UNI-T UTi120S infrared thermal imager. The right, middle, and left heating segments were each imaged three times. Across the mapped surface, the measured minimum and maximum temperatures were 74.7 and 80.3 °C, respectively, and the mean centre temperature was 78.2 °C. The numerical model used 77.4 °C as the prescribed heater boundary, consistent with the representative operating range measured during characterisation, as illustrated in Figure 1.

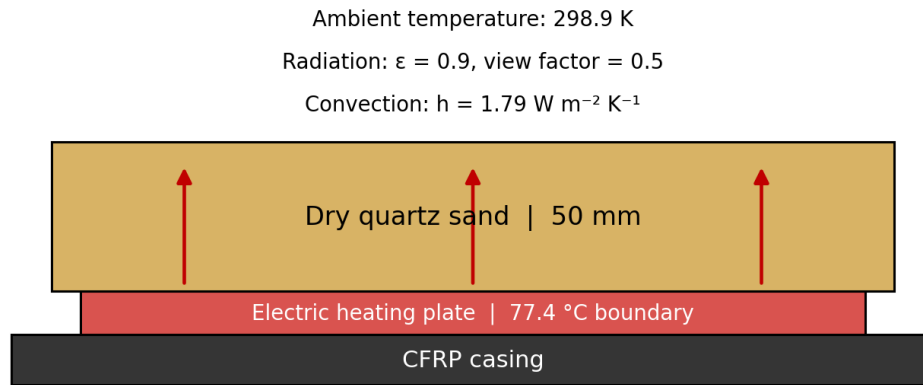


Fig. 1. Thermal model and principal boundary conditions

2.2 Numerical Heat-Transfer Model

The three-dimensional assembly was constructed in SOLIDWORKS and analysed with the thermal module of SOLIDWORKS Simulation. The CFRP casing was treated as an orthotropic continuum, whereas the sand was represented as isotropic silicon dioxide (SiO_2). The assigned thermophysical properties are listed in Table 1. These values define the numerical inputs and are interpreted as effective bulk properties for the tested configuration.

Table 1

Thermophysical properties assigned in the numerical model

Material	Property	Value
CFRP	In-plane thermal conductivity	4.18 W/(m·K)
CFRP	Through-plane thermal conductivity	0.68 W/(m·K)
CFRP	Density	1780 kg/m ³
Sand (SiO_2)	Thermal conductivity	0.35 W/(m·K)
Sand (SiO_2)	Specific heat capacity	800 J/(kg·K)
Sand (SiO_2)	Density	1700 kg/m ³

The lower heater interface was prescribed at 77.4 °C. Heat loss from the exposed upper surface was represented by natural convection to an ambient temperature of 298.9 K using a heat-transfer coefficient of 1.79 W/(m²·K) [13]. Surface-to-ambient radiation used an emissivity of 0.9 and a view factor of 0.5. Perfect thermal contact was implicitly assumed between adjoining components; interfacial contact resistance and moisture transport were not independently modelled. The sand thickness was changed iteratively until the exposed surface approached the required 50–55 °C range. The selected configuration contained a uniform 50 mm sand layer, as illustrated in Figure 2.

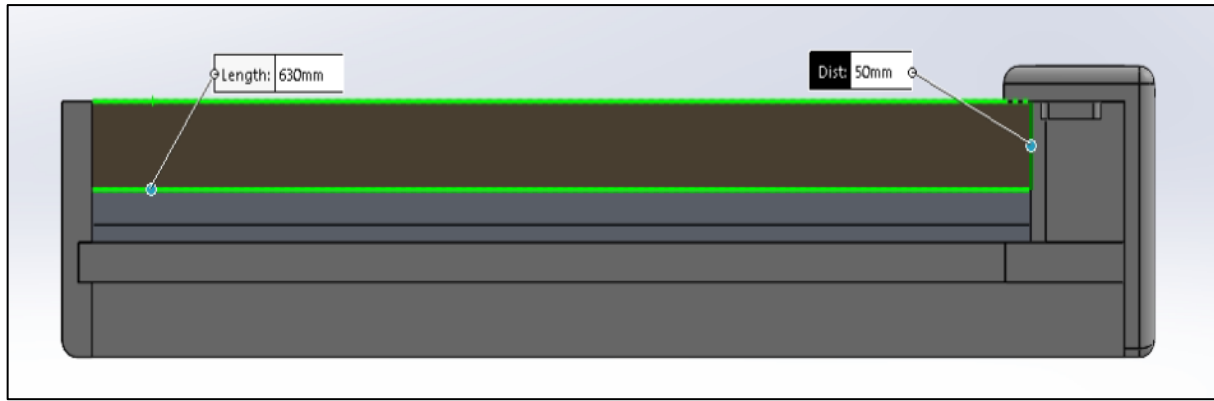


Fig. 2. Cross-section of the assembly showing the selected 50 mm sand layer

2.3 Experimental Validation

The fabricated CFRP prototype was assembled with the heating plate beneath a 50 mm sand layer. The thermal imager was mounted perpendicular to the surface at a fixed distance of 1.00 m to maintain a consistent field of view. Ambient conditions, sand type, heater setting, camera distance, and viewing angle were maintained during testing. The system was heated continuously for 240 min. Thermograms were recorded at 0, 30, 60, 120, 180, and 240 min, and the minimum, centre, and maximum surface temperatures were extracted. Three trials were completed at each interval.

Model validation used the mean centre temperature at 240 min, when the response had approached a stable condition. The relative deviation was calculated using Eq. (1), where T_{exp} is the measured mean centre temperature and T_{sim} is the predicted surface temperature.

$$\text{Percentage Error} = \left| \frac{T_{exp} - T_{sim}}{T_{sim}} \right| \times 100\% \quad (1)$$

A mean surface temperature of 50–55 °C and a model deviation not exceeding 5% were adopted as the primary criteria. Because the thermal imager has a stated accuracy tolerance of approximately ± 2 °C [14], small departures from the nominal upper limit were interpreted together with instrument uncertainty. Spatial maximum temperature was retained as a separate safety and uniformity indicator.

3. Results and Discussion

3.1 Numerical Temperature Prediction

The iterative analysis selected a 50 mm sand layer as the thermal buffer. Under the prescribed 77.4 °C heater boundary, the predicted exposed-surface temperature was 54.90 °C. The temperature field in Figure 3 shows lateral heat spreading across the central region, while the cooler casing boundaries dissipate energy to the surroundings. The result lies within the intended surface range and indicates that the sand layer reduced the heater temperature by approximately 22.5 °C before heat reached the exposed surface.

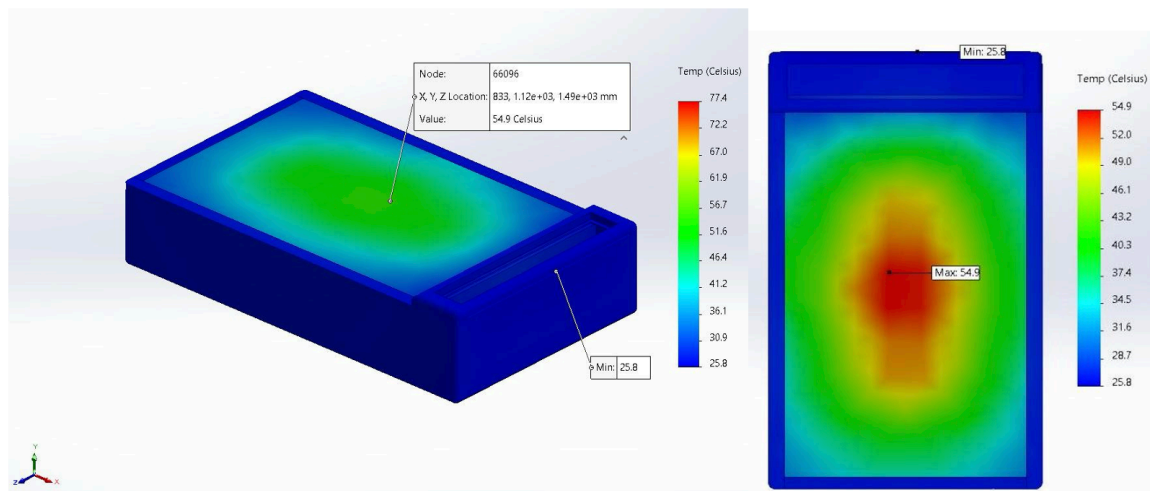


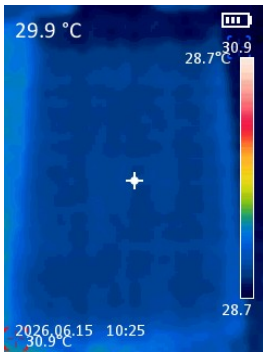
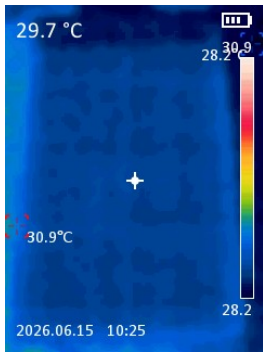
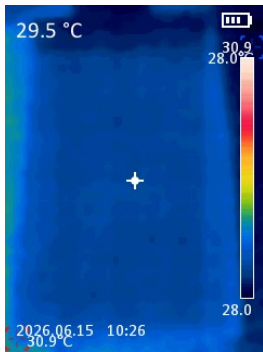
Fig. 3. Predicted steady-state temperature field for the 50 mm sand layer: (a) isometric view of the full assembly and (b) top-down view illustrating lateral heat spreading across the central basking region

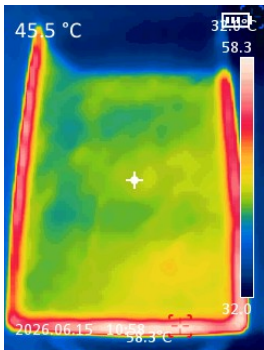
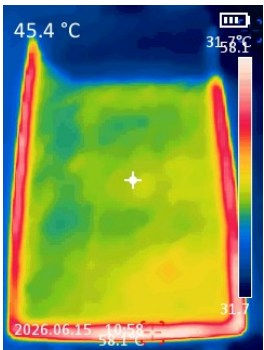
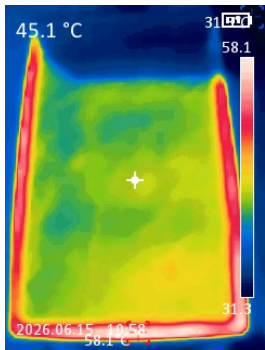
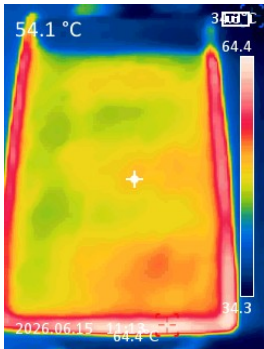
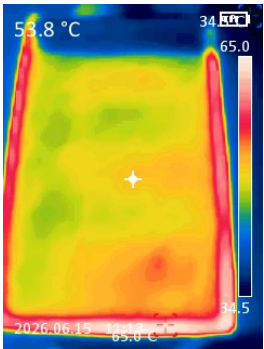
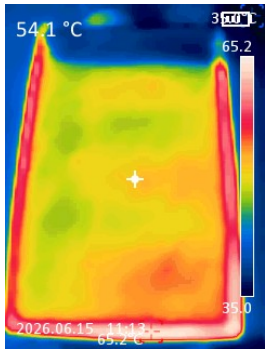
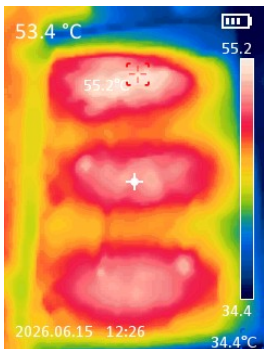
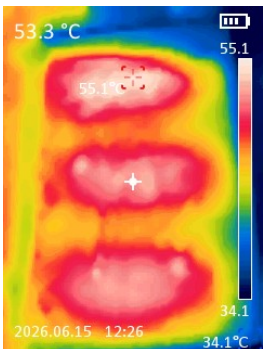
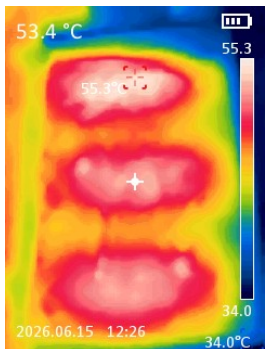
3.2 Transient Experimental Response

During the 240-min continuous heating experiment, thermograms were captured with the UNI-T UTi120S infrared thermal imager at the six specified intervals. The images show a progressive increase in centre temperature together with persistent spatial variation across the 50 mm sand surface. Three independent trials were performed at every interval to assess repeatability, and the extracted measurements are presented in Table 2.

Table 2

Measured surface temperatures during the 240-min heating cycle

Time (min)	Trial 1 Temperature	Trial 2 Temperature	Trial 3 Temperature
0	 Max = 30.9 °C Centre = 29.9 °C Min = 28.7 °C	 Max = 30.9 °C Centre = 29.7 °C Min = 28.2 °C	 Max = 30.9 °C Centre = 29.5 °C Min = 28.0 °C

30	 Max = 58.3 °C Centre = 45.5 °C Min = 32.0 °C	 Max = 58.1 °C Centre = 45.4 °C Min = 31.7 °C	 Max = 58.1 °C Centre = 45.1 °C Min = 31.3 °C
60	 Max = 64.4 °C Centre = 54.1 °C Min = 34.3 °C	 Max = 65.0 °C Centre = 53.8 °C Min = 34.5 °C	 Max = 65.2 °C Centre = 54.1 °C Min = 35.0 °C
120	 Max = 55.2 °C Centre = 53.4 °C Min = 34.4 °C	 Max = 55.1 °C Centre = 53.3 °C Min = 34.1 °C	 Max = 55.3 °C Centre = 53.4 °C Min = 34.0 °C

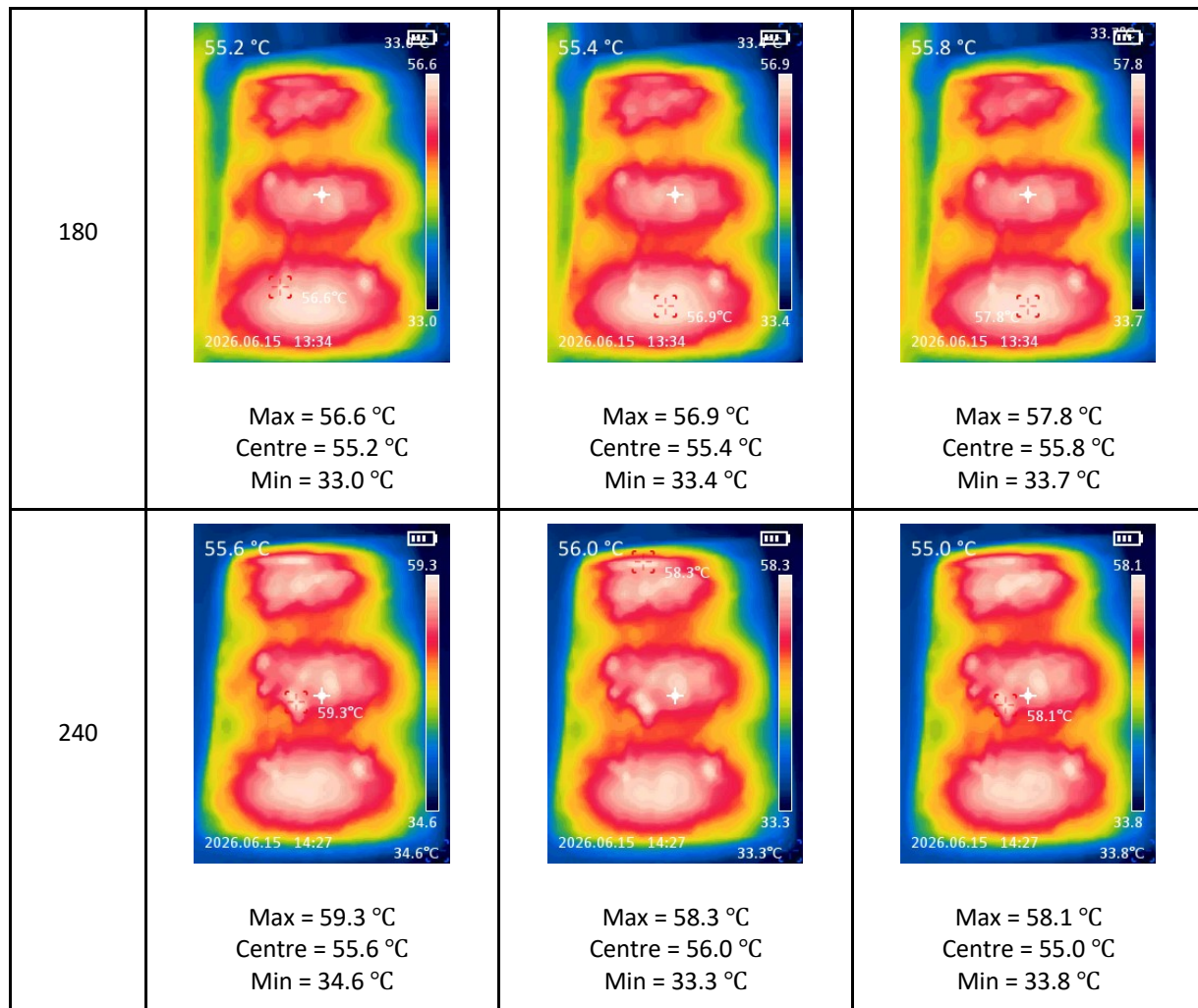


Table 3 presents the temperatures averaged across the three independent trials. The sample standard deviation (SD) is reported for each metric to describe measurement repeatability. The mean centre temperature increased from 29.70 ± 0.20 °C at baseline to 45.33 ± 0.21 °C after 30 min and 54.00 ± 0.17 °C after 60 min. It then varied modestly before reaching 55.47 ± 0.31 °C at 180 min and 55.53 ± 0.50 °C at 240 min. The 0.06 °C difference between the final two means indicates that the central region was close to a quasi-steady condition during the last hour.

Table 3

Mean surface temperatures from three validation trials

Time (min)	Minimum (°C)	Centre (°C)	Maximum (°C)
0	28.30 ± 0.36	29.70 ± 0.20	30.90 ± 0.00
30	31.67 ± 0.35	45.33 ± 0.21	58.17 ± 0.12
60	34.60 ± 0.36	54.00 ± 0.17	64.87 ± 0.42
120	34.17 ± 0.21	53.37 ± 0.06	55.20 ± 0.10
180	33.37 ± 0.25	55.47 ± 0.31	57.10 ± 0.62
240	33.90 ± 0.66	55.53 ± 0.50	58.57 ± 0.64

The maximum temperature reached 64.87 °C at 60 min before decreasing to 55.20 °C at 120 min, as illustrated in Figure 4. This non-monotonic maximum may reflect preferential heat paths near the casing perimeter and the geometry of the heating plate; it should therefore be interpreted as a spatial observation rather than a uniform surface response. Experimental work on granular media shows

that contact structure and packing strongly influence heat transfer [5]. Sand-specific measurements also identify mineral composition, density, and pore structure as controlling factors [6]. Research on sand-based thermal storage further confirms that granular heat capacity moderates the bulk temperature response [12]. The much lower minimum temperature represents cooler peripheral regions in the thermogram and confirms that centre-temperature agreement alone does not establish complete surface uniformity.

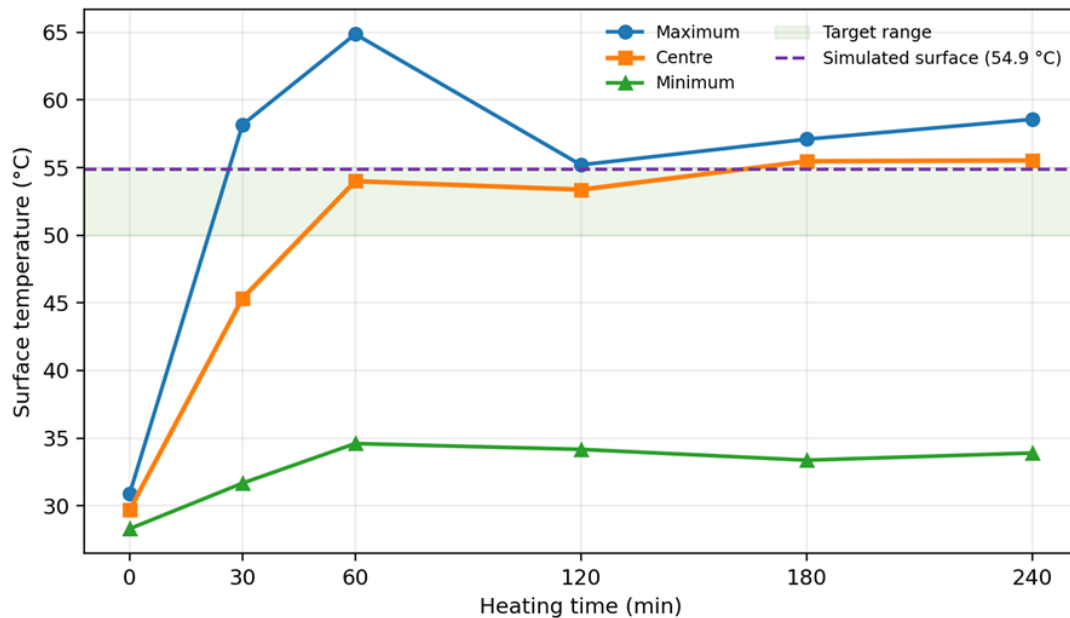


Fig. 4. Transient surface-temperature response and simulated final temperature

3.3 Numerical–Experimental Validation

At 240 min, the measured mean centre temperature was 55.53 °C compared with the numerical prediction of 54.90 °C. The absolute difference was 0.63 °C and the relative deviation was 1.15%, satisfying the predefined $\leq 5\%$ criterion. Table 4 presents the comparison. The experimental centre value was 0.53 °C above the nominal 55 °C upper target, but this difference is smaller than the stated ± 2 °C instrumental tolerance. The result therefore supports the model for preliminary design selection under the reported conditions, rather than proving exact pointwise equivalence across the entire surface.

Table 4

Comparison of predicted and experimental temperature at 240 min

Parameter	Temperature
Simulated surface temperature	54.90 °C
Experimental mean centre temperature	55.53 °C
Absolute temperature difference	0.63 °C
Relative deviation	1.15%

Agreement may partly reflect compensating assumptions. The model ambient temperature was 298.9 K (25.75 °C), whereas the experimental baseline centre temperature averaged 29.70 °C. Perfect component contact, constant convection, dry isotropic sand, and fixed radiative properties also simplify the physical system. Experimental identification studies show that granular conductivity changes with packing and contact structure [5], while sand measurements demonstrate further

sensitivity to density and pore arrangement [6]. Direct tensor measurements confirm that CFRP conduction depends on fibre direction [9], and multiscale modelling shows that fibre architecture and matrix properties affect the effective response [10]. The low final-temperature deviation should therefore not be extrapolated to different substrate moisture levels, packing states, or ambient conditions without additional testing.

3.4 Implications and Limitations

The study demonstrates a practical numerical-experimental workflow for selecting substrate thickness before manufacture. Convective-radiative finite-element analysis has been successfully applied to multilayer thermal systems [15], supporting the general modelling strategy used here. Moisture-aware modelling of sand shows that water content and grain size can materially change thermal behaviour [16], reinforcing the need to define substrate condition in future validation. Carbon fibres have also been used directly as resistive heating elements in composite processing [17], suggesting a possible future route for integrating heat generation with the structural casing. The present contribution differs by coupling an external electric heater, an orthotropic CFRP casing, and a 50 mm natural sand buffer for reptile husbandry. Under the tested conditions, this arrangement transformed a heater temperature near 77 °C into a stable centre surface near 55 °C.

The principal limitations are the absence of a reported thermal mesh-independence study, explicit solver-convergence information, measured contact resistance, continuous ambient monitoring, and quantified sand moisture. Future work should use embedded thermocouples at material interfaces, measure humidity and substrate water content, evaluate two-dimensional uniformity metrics, and test alternative sand thicknesses. Transient numerical modelling should also reproduce the 60-min maximum-temperature overshoot and support the development of safe control strategies.

4. Conclusions

A SOLIDWORKS thermal model and three-trial infrared-thermography experiment were used to investigate heat transfer through a CFRP heating flatbed containing a sand buffer. With a 77.4 °C heater boundary, orthotropic CFRP properties, a sand conductivity of 0.35 W/(m·K), and convective-radiative heat losses, the model selected a 50 mm sand layer and predicted a surface temperature of 54.90 °C. Experimentally, the mean centre temperature increased from 29.70 to 55.53 °C over 240 min and changed by only 0.06 °C during the final hour. The prediction differed from the final measured centre value by 0.63 °C, corresponding to 1.15%, below the 5% validation limit. However, the final maximum of 58.57 °C and the earlier transient peak of 64.87 °C show that spatial and transient behaviour must be considered together with centre-temperature agreement. Within the tested conditions, the model provides a useful basis for selecting sand thickness. Further work should quantify uncertainty, sand moisture, contact resistance, and mesh sensitivity before broader generalisation.

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References

- [1] Seman, Sareh Aiman Helmi Abu, Muhammad Hafiz Hassan, Muhammad Fauzinizam Razali, Mohd Syakirin Rusdi, and Joy Mathavan Jebaratnam. "Evaluation of Optimal Flatbed Heating Temperature for *Uromastix aegyptia* in Tropical Captivity." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 135, no. 1 (2025): 139-147. <https://doi.org/10.37934/arfmts.135.1.139147>.
- [2] Garrick, Daniel. "Body surface temperature and length in relation to the thermal biology of lizards." *Bioscience Horizons* 1, no. 2 (2008): 136-142. <https://doi.org/10.1093/biohorizons/hzn014>.
- [3] Zheng, Yuhan, Ruichen Wu, Ziyi Wang, Xunheng Wu, Huawei Feng, and Yi Yang. "Effects of temperature on the thermal biology and locomotor performance of two sympatric extreme desert lizards." *Animals* 15, no. 4 (2025): 572. <https://doi.org/10.3390/ani15040572>.
- [4] Diaz, Jose A., Raúl Izquierdo-Santiago, and Alejandro Llanos-Garrido. "Lizard thermoregulation revisited after two decades of global warming." *Functional Ecology* 36, no. 12 (2022): 3022-3035. <https://doi.org/10.1111/1365-2435.14192>.
- [5] Ciesielski, Mariusz, and Grzegorz Grodzki. "Heat transfer in granular material: experimental measurements and parameters identification of macroscopic heat conduction model." *Applied Sciences* 15, no. 5 (2025): 2596. <https://doi.org/10.3390/app15052596>.
- [6] Haigh, S. K. "Thermal conductivity of sands." *Géotechnique* 62, no. 7 (2012): 617-625. <https://doi.org/10.1680/geot.11.P.043>.
- [7] Nematzadeh, Mahdi, Arash Arjomandi, Maziar Fakoor, Arman Aminian, and Aref Khorshidi-Mianaei. "Pre-and post-heating bar-concrete bond behavior of CFRP-wrapped concrete containing polymeric aggregates and steel fibers: experimental and theoretical study." *Engineering Structures* 321 (2024): 118929. <https://doi.org/10.1016/j.engstruct.2024.118929>.
- [8] Davidson, Matthew, Ryan Graunke, Aidan Green, Hayden Haelsig, Laura Heinemann, Subin Antony Jose, and Pradeep L. Menezes. "Carbon fiber-reinforced polymer matrix composites: Processing, properties, and applications." *Fibers* 14, no. 3 (2026): 29. <https://doi.org/10.3390/fib14030029>.
- [9] Villière, Maxime, Damien Lecointe, Vincent Sobotka, Nicolas Boyard, and Didier Delaunay. "Experimental determination and modeling of thermal conductivity tensor of carbon/epoxy composite." *Composites Part A: Applied Science and Manufacturing* 46 (2013): 60-68. <https://doi.org/10.1016/j.compositesa.2012.10.012>.
- [10] Nasri, Wiem, Zied Driss, Ridha Djebali, Kyu-Yeon Lee, Hyung-Ho Park, Abderazak Bezazi, and Paulo NB Reis. "Thermal study of Carbon-Fiber-Reinforced polymer composites using multiscale modeling." *Materials* 16, no. 22 (2023): 7233. <https://doi.org/10.3390/ma16227233>.
- [11] He, Zeqing, Yingli Shi, Jin Nan, Zhigang Shen, Taihua Zhang, and Zhao Zhao. "An analytic orthotropic heat conduction model for the stretchable network heaters." *Micromachines* 13, no. 7 (2022): 1133. <https://doi.org/10.3390/mi13071133>.
- [12] Radwan, Omar A., and John D. Humphrey. "Uses of sands in solar thermal technologies." *Solar Energy Materials and Solar Cells* 261 (2023): 112533. <https://doi.org/10.1016/j.solmat.2023.112533>.
- [13] Evangelisti, Luca, Claudia Guattari, and Tullio de Rubeis. "Preliminary analysis of the influence of environmental boundary conditions on convective heat transfer coefficients." In *Journal of Physics: Conference Series*, vol. 1868, no. 1, p. 012024. IOP Publishing, 2021. <https://doi.org/10.1088/1742-6596/1868/1/012024>.
- [14] UNI-T. "UTi120S Professional Thermal Imager User Manual and Technical Specifications." Dongguan, China: Uni-Trend Technology (China), 2022.
- [15] Das, Palash, Md Ashraful Islam, Dipayan Mondal, and Md Sharier Nazim. "Analytical and numerical (FEA) solution for steady-state heat transfer in generic FGM cylinder coated with two layers of isotropic material under convective-radiative boundary conditions." *Heliyon* 9, no. 11 (2023). <https://doi.org/10.1016/j.heliyon.2023.e21725>.
- [16] Torres-Rodríguez, Agustín, David Morillón-Gálvez, Daniel Aldama-Avalos, José Diego Morales-Ramírez, and Iván García Kerdan. "Predicting the thermal behaviour of sands considering its moisture content and grain size with applications to geothermal heat pump installations." *Energy and Buildings* 194 (2019): 85-104. <https://doi.org/10.1016/j.enbuild.2019.04.005>.
- [17] Kontaxis, Lykourgos C., Ioannis E. Chontzoglou, and George C. Papanicolaou. "Efficient use of carbon fibers as heating elements for curing of epoxy matrix composites." *Molecules* 26, no. 16 (2021): 5095. <https://doi.org/10.3390/molecules26165095>.