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Experimental and Numerical Study of the Thermal Behavior of Clips in Concentrated Solar Tower Receivers

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Abstract. In this study, we investigated the thermal behaviour of a guiding support, referred to as a clip, for a tube resembling those used in solar central receivers. The focus is on the clip's heating process, which occurs when molten salt begins to flow inside the receiver tube. This work involves both experimental measurements and numerical simulations of the clip, which can be considered as a fin attached to the tube. Experimentally, we measured the temperature profile of the clip over time and observed that, despite the characteristic decaying exponential shape of the clip, the heat transfer can be approximated as one-dimensional. Moreover, numerical simulations were performed to gain a better understanding of the clip’s thermal response. By comparing the simulation results to the experimental data, we were able to determine the most suitable boundary condition for the clip end, which is attached to the receiver's supporting structure. Furthermore, the experimental data was compared to an analytical solution for the temperature evolution of a fin that took into account the cooling effect of natural convection and radiation, yielding a maximum error of 8%.

Keywords: Solar Receiver, Thermal Analysis, Clip, Experimental Test

1. Introduction

The external central receiver in solar tower power plants consists of a cylindrical structure composed of several panels of vertical tubes designed to capture incident solar radiation. The non-uniformity in the heat flux causes bending of the tubes, which is typically reduced by means of mechanical attachments, each consisting of a clip and a guide, through which a rod connected to a reradiating wall can freely slide. Because of the deflection restriction, the weld zone between the panel tube and clip experiences considerable thermal stress, which may lead to clip weld leaks in central receivers [1]. Different numerical studies [2,3] have been conducted to determine the tube deflection and stress in central receiver tubes, considering the location of the clips along the tube's length. Their findings demonstrate that displacement increases with the distance between clips, with this deflection being lower than 1 mm when this distance is 2 m or less. Other studies on the receiver’s start-up operation [4,5] concluded that the maximum stresses are located in the connections of the clip with both the tube and the guide.

Apart from being an area of stress concentration, these mechanical attachments increase heat dissipation from the tube to the exterior and can reduce the local temperature of the tube during the receiver start-up, which could result in salt freezing and system failure [6]. In this work, temperature measurements of a clip supporting a tube receiver while molten salt begins to flow through the tube are presented. Besides, a 2D numerical model of the tube and clip ensemble was developed to understand the thermo-mechanical behavior of tube clips. The experimental temperature evolution of the clip suggests that it can be treated as a fin. To check this assumption, the steady-state experimental results were compared to the analytical equation of a fin that considers the cooling effect of natural convection and radiation.

The presented models, which have been validated through experiments, can help to develop more realistic simulations of solar central receivers that use molten salt. These simulations will allow us to reproduce the receiver's thermomechanical behavior, which is required to improve the design. In particular, an optimized clip shape might be proposed, and the number of clips could be reduced in the future, lowering the receiver's cost without compromising its structural integrity.

2. Experimental setup

The experimental campaign was conducted in a molten salt loop, which consists of a 600 l capacity stainless steel tank heated by an electrical furnace, a high temperature pump, coupled with an electric motor equipped with a variable-frequency drive to control the flow rate, an ultrasonic flowmeter, and the test section. The temperature of the molten salt within the tank is regulated to maintain it between 300 ºC and 500 ºC. The tank is connected to a stainless steel 316 L pipe of 4.2 cm outer diameter and 3.56 mm thickness through which the molten salt circulates. The entire loop, except for the 1.5 m test section, is insulated and the pipe is wrapped with electrical heaters to maintain the desired temperature.

***Figure 1**. a) Photograph of the molten salt test loop. b) Detail of the clip. c) Thermal image of the clip*

Since the objective of this work was to study the thermal behavior of the mechanical attachments of the solar tower plant receiver tubes, a salt loop pipe support system was created utilizing two 1.5 m apart clips that permit the pipe to expand in the axial direction while preventing its movement in the transverse direction, simulating the mechanical support conditions of commercial power plant pipes (see Fig. 1(b)). The temperature distribution of the assembly tube-clip was measured with two infrared cameras (Optris PI640 with O15 telephoto lens), one of which was calibrated to cover the following temperature range: Camera 1 covered 0-250 ºC, whereas Camera 2 covered 150-900 ºC. The cameras have a maximum accuracy of ±2 ºC to ±2% within the specified temperature ranges. According to the manufacturer, the cameras can increase the temperature range from 150-900ºC to as low as 20ºC. However, precision would be punished for deviating from the aforementioned requirements. Consequently, the two-camera setup is recommended. The cameras were set 650 mm from the test section's tube-clip, resulting in 0.27 mm pixels. In addition, a metallic shield was employed to homogenize the background of the cameras' field of vision, preventing potential noise interference from background objects. The tube-clip assembly was painted with Pyromark coating, whose emissivity was estimated at 0.95 after a calibration process of the infrared cameras with emissivity calibration labels.

To determine the effect of the salt temperature on the temperature evolution of the clip during the startup operation of the receiver, a series of experiments were carried out where the temperature of the molten salt was varied. In particular, the HTF temperature was 419ºC, 432ºC, 455ºC, and 470ºC. In these experiments, the temperature of the tube-clip assembly was recorded with the infrared cameras from the moment the molten salt began to fill the cold tube until the steady state was achieved.

3. Numerical modeling

3.1 2D numerical model

To gain a better understanding of the behavior of the tube supports (clips), a simplified 2D numerical model is developed in the commercial software Comsol Multiphysics. The model (see Figure 3) includes (i) the tube, (ii) the clip, and (iii) the cylindrical end of the clip that fixes the tube to the supporting rear structure. The three are subjected to external natural convection and radiation; while the paint emissivity is calibrated as mentioned above, the natural convective coefficient is given a constant value, as explained later in Section 3.2. Moreover, the tube is also subjected to internal forced convection as the hot HTF passes through it at 3 m/s. The cited model is referred to as the 'actual model' in this work.

In order to simplify the geometry for a potential analytical solution, a steady state analysis is carried out to compare the temperature distribution in the 2D simplified model and that in another 2D simplified model that replaces the circular end of the system with a fin extension, allowing the adiabatic tip boundary condition to prevail. The fin extension length is computed by equalizing the convective heat transfer on the circular end and the convective heat transfer in the fin extension [7], considering that the fin thickness is much less than its height:

$$2L_{ext}H(T-T_\infty) = \pi d_{end}H(T-T_\infty) \;\rightarrow\; L_{ext} = \pi d_{end}/2 \quad (1)$$

This simplification is named 'extended model'. Moreover, an additional case where the cylindrical end is omitted and replaced by an adiabatic end without extending the fin is also considered, named the 'cut model'.

The three models are based on the assumption of a straight fin of uniform cross section, in spite of the actual clip in the facility showing a slightly decreasing cross-sectional area near the tube, following a decaying exponential shape. The 2D models were built with 6-node triangular second-order Lagrange elements. A mesh sensitivity analysis was performed in the case of the actual model. The size of the elements was selected as a quarter of the tube thickness, resulting in 5 elements along the tube thickness, 5216 domain elements, and 762 boundary elements.

3.2 Analytical solution in the steady state

As it is shown in the experimental results, the steady state is reached 10 minutes after the salt has started to circulate. In order to easily predict the behavior of the clip once the steady state has been reached, an analytical equation that considers the cooling effect of natural convection and radiation and establishes an adiabatic tip boundary condition was used [8]:

$$\theta(x) = \theta_b cosh(m(1-x))/cosh(m) \quad (2)$$

where $\theta(x) = T(x) - T_\infty$, $\theta_b = T_b - T_\infty$, $m = \sqrt{h\,P/(k\,A_c)}$. The heat transfer coefficient h considers the cooling effect of both natural convection and radiation [9]:

$$h = h_{conv} + \varepsilon\,\sigma(T_b^2 + T_{surr}^2)(T_b + T_{surr}) \quad (3)$$

where h_{conv} is estimated to be 5 W/m^2 K. In this study, the surroundings are assumed to act as a blackbody at the same temperature as the ambient air ($T_{surr} = T_\infty$). Note that the same parameters are considered in the 2D numerical model introduced in section 3.1.

4. Results

In this section, the main results obtained from this work are presented. Please note that, in spite of having experimental data for four different cases, only the results of HTF temperatures of 432ºC and 470ºC are shown for simplicity. Yet, the main conclusions drawn from the figures included below also apply to the cases not shown here.

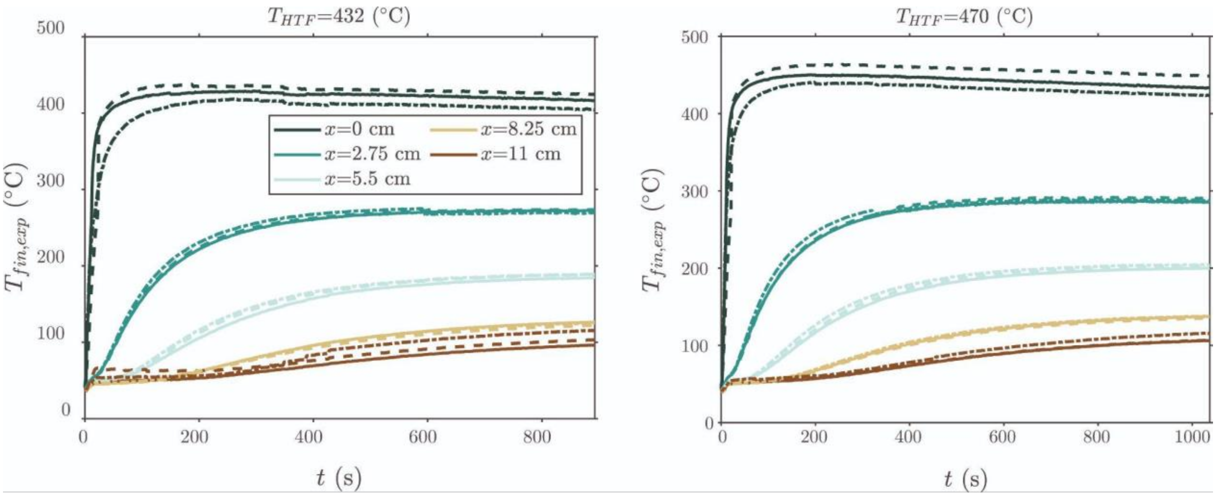

Figure 2. *Fin temperature evolution at various longitudinal positions (legend) and vertical positions: solid line corresponds to the fin middle height; dashed line corresponds to the first quarter (above the middle height) and dashed-dotted line corresponds to the third quarter (below the middle height).*

First, the experimental results are examined by analyzing the temperature evolution over time at three different fin heights (Figure 2) and for two different molten salt temperatures. As can be seen, for the 11 cm long clip, the molten salt temperature influences the temperature at the clip base that touches the tube; however, the variations in clip temperature between the two molten salt temperature cases decrease as one departs from the tube. The variations between the two cases at the clip end are negligible. Furthermore, the temperatures at the vertical positions of a quarter and three quarters of the height of the fin are slightly higher than those at the fin's center line, although they are fairly similar. Hence, a 2D model, or even a 1D model, can be employed as a simplified approach without much error.

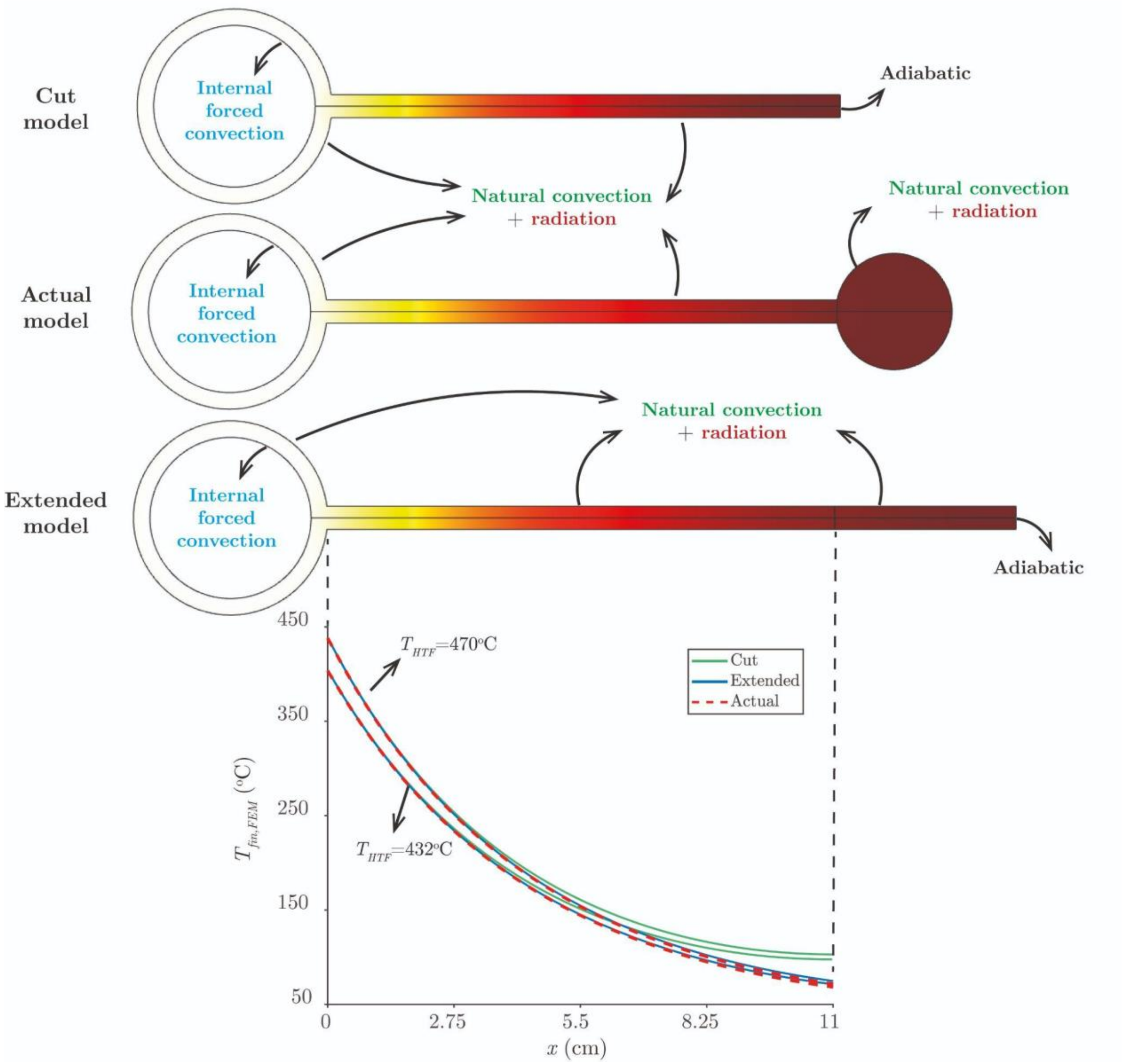

Figure 3. *2D models employed in the FEM simulations and boundary conditions. Comparison of the fin outer wall temperature during steady state for the actual design, the extended one, and the actual design without the cylindrical end (cut model).*

With that in mind, the 2D FEM model results in steady state are compared for the aforementioned cases (T_{HTF} of 432 ºC and 470 ºC). That analysis shows that the actual model and the extended model have very good agreement (Figure 3), with a maximum error of around 4% at the end, with the extended model slightly overestimating the temperature. Conversely, the model without the cylindrical support at the end and the adiabatic tip results in a much larger error (a maximum of 40% overestimation at the tip). Nevertheless, it is the cut model that produces lower temperature differences with respect to the experimental results, as can be seen in Figure 4. The better performance of this model suggests that an adiabatic tip boundary condition could accurately reflect the large mass of the cylinder support at the end of the real design. This mass creates a high thermal inertia that slows the heating of that part of the assembly.

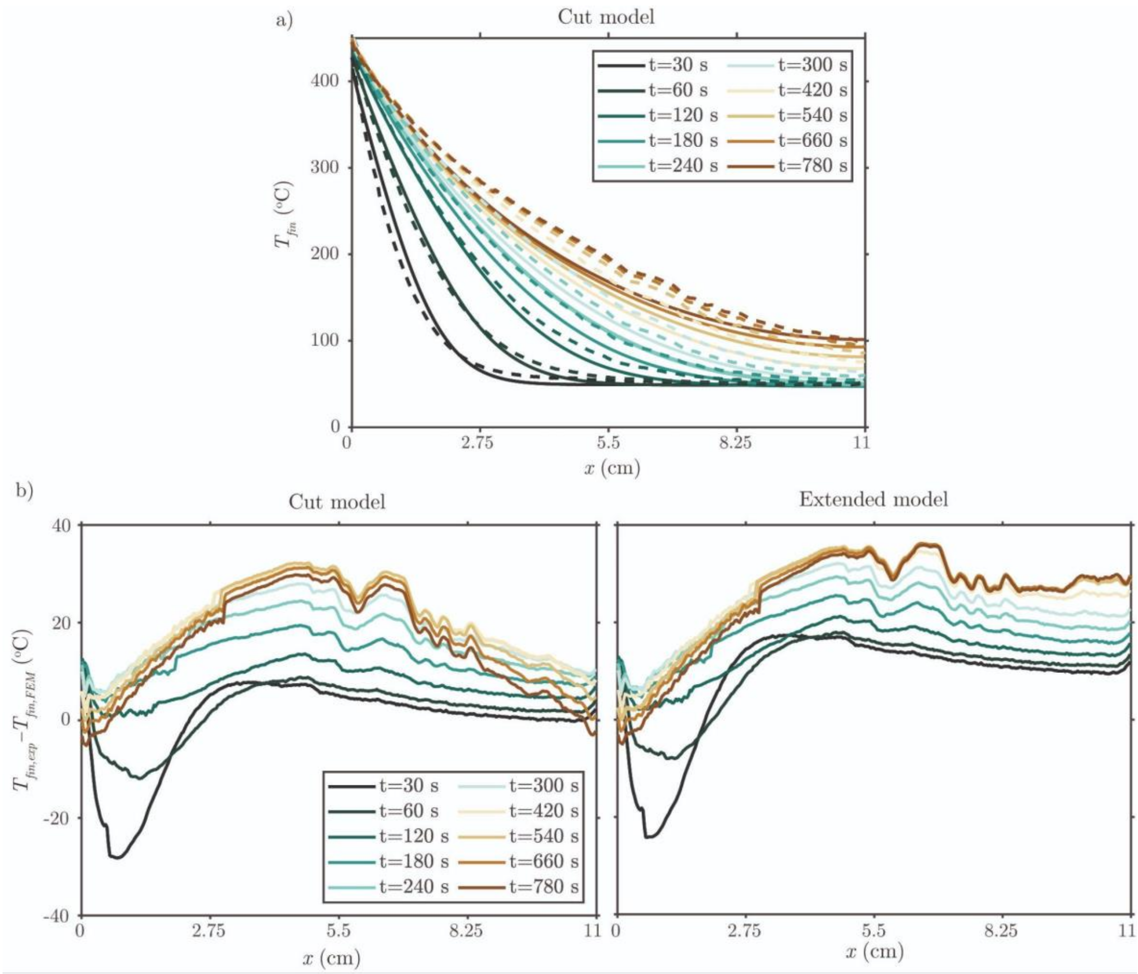

Figure 4. *a) Transient fin temperature comparison between experiments (dashed lines) and the FEM results (solid lines) for the cut model, b) Temperature difference between the experiments and the cut and extended FEM models.*

Figure 5 shows the comparison between the experimental results and the analytical solution in the steady state. It can be noted that the error committed with the analytical model is similar to that obtained with the 2D FEM model that neglects the cylindrical support at the end, which suggests that the discrepancy between the model and experimental results could be caused by uncertainties in the temperature measurements and model parameters, such as the convective heat transfer coefficient or the emissivity of the surface.

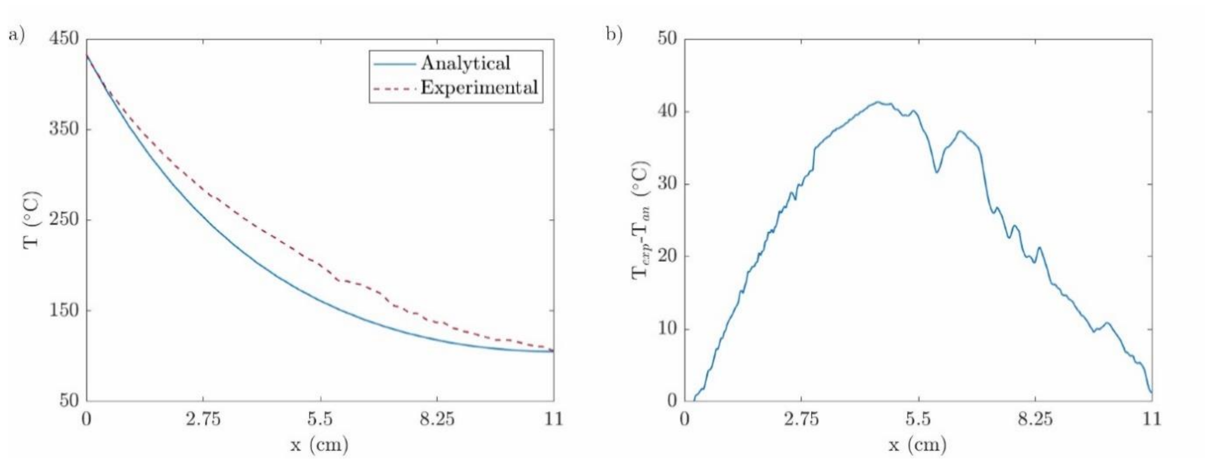

Figure 5. *Comparison between the analytical and experimental temperature profiles along the length of the fin during the steady state.*

5. Conclusions

In this work, the thermal behavior of a typical mechanical attachment (clip) in solar tower receivers was studied. An experimental campaign was conducted in a molten salt loop to simulate the startup operation of a solar receiver. Therefore, the temperature evolution of the clip was measured from the moment the molten salt started to flow through the tube until the steady state was nearly reached. Different experiments were performed varying the molten salt inlet temperature, and it can be concluded that temperature differences of 50 ºC in the HTF barely affect the evolution of the temperature along the clip. Despite the exponential decay shape of the clip, experimental results reveal that the temperature profile remains nearly uniform along the height of the fin, so the problem can be considered two-dimensional.

To get a better understanding of the thermal behavior of a clip, a 2D FEM model was developed. Different boundary conditions at the clip end were studied, i.e., considering the cylindrical end of the clip that fixes the tube to the supporting rear structure, extending the clip length and then imposing an adiabatic tip boundary conduction, or disregarding the cylindrical end of the clip and replacing it by an adiabatic end without modifying the clip length. Comparison with the experimental results suggests that the latter boundary condition gets the best performance, probably due to the large thermal inertia of the cylindrical end that delays the heating of the end of the clip.

The experimental temperature evolution of the clip suggests that it can be treated as a fin. To test this assumption, steady-state experimental findings were compared to an analytical equation for a fin that takes into account the cooling effects of natural convection and radiation. The maximum error between the analytical and experimental results was around 8%, which is considered acceptable regarding the level of uncertainty in the temperature measurements and model parameters.

The validated models presented can aid in creating more realistic simulations of solar central receivers using molten salt, which is essential for enhancing the design of mechanical attachments. Specifically, an optimized clip shape may be suggested, and the number of clips could be reduced in the future, decreasing the receiver's cost while maintaining structural integrity.

Data availability statement

The data used for the study can be made available upon reasonable request.

Underlying and related material

None. We have not deposited any underlying or supplementary material in a public repository.

Author contributions

M. Laporte-Azcué (MLA), M. Fernández-Torrijos (MFT), C. Sobrino (CS), C. Marugán-Cruz (CMC), D. Santana (DS).

Conceptualization and investigation: MLA, MFT, CS, CMC, DS; Methodology, data curation and formal analysis: MLA, MFT; Funding acquisition: CS, DS; writing – original draft preparation: MLA, MFT, CS; writing – review and editing: MLA, MFT, CS, CMC, DS; supervision, CS, CMC, DS; project administration, CS, DS. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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