Mathematical Modelling to Assess the Influence of Transients on Refractory-lined Solar Receivers

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1. Aim and Objectives

- To demonstrate an approach to analyse and optimize the thermal performance of a refractory-lined particle receiver in response to solar resource variability.
- To develop a transient model employing the governing mathematical equations for the mass and energy flows through the refractory-lined receiver cavity.
- To calculate the time-dependent temperature fields of receiver cavity walls, particles, and gas from the initial state to another equilibrium.
- To provide new insight on the role of the material and thickness of the refractory lining on the system output when accounting for the allowable heating rate of refractory material to avoid failure due to thermal shock.

2. Introductory Background

- The time-constants of directly irradiated particle receivers are different from those of indirectly irradiated tubular receivers.
- The design temperature of directly irradiated particle receivers is above the melting temperature of mild steel, they must either use more expensive high temperature metals, adding to cost, or a refractory lining.
- Refractory lining is both brittle and has high thermal inertia, making the transient operation more challenging.
- Refractory lining materials have an allowable heating rate limit above which damage can occur.
- Lack of knowledge of the influence of the time-constants of particle receivers on dynamic operation caused by solar resource variability.

Need to address: how to optimize the design of refractory lining for upscaling these emerging receivers to a higher power level under real-time operating conditions.

3. Material and Methods

The transient model employs the governing mathematical equations for mass and energy flows through the receiver cavity, considering the particle and gas phases, thermal losses, and conductive, convective and radiative heat transfer. An energy balance was performed for each phase and for the walls by solving a set of simultaneous equations iteratively for each time step to calculate each of their temperatures.

Energy conservation for receiver cavity walls:

$$\dot{Q}_{sol,ap-w} = \dot{Q}_{thermal} + \dot{Q}_{rad,w-p} + \dot{Q}_{conv,w-a} + \dot{Q}_{cond,w-s} + \dot{Q}_{conv,w-s} + \dot{Q}_{re-rad,w-s}$$

Energy conservation for the particle phase:

$$\Delta H_{p,i} = \dot{Q}_{sol,ap-p} + \dot{Q}_{conv,p-a} + \dot{Q}_{rad,w-p}$$

Energy conservation for air phase:

$$\Delta H_{a,i} = \dot{Q}_{conv,p-a} + \dot{Q}_{rad,w-a}$$

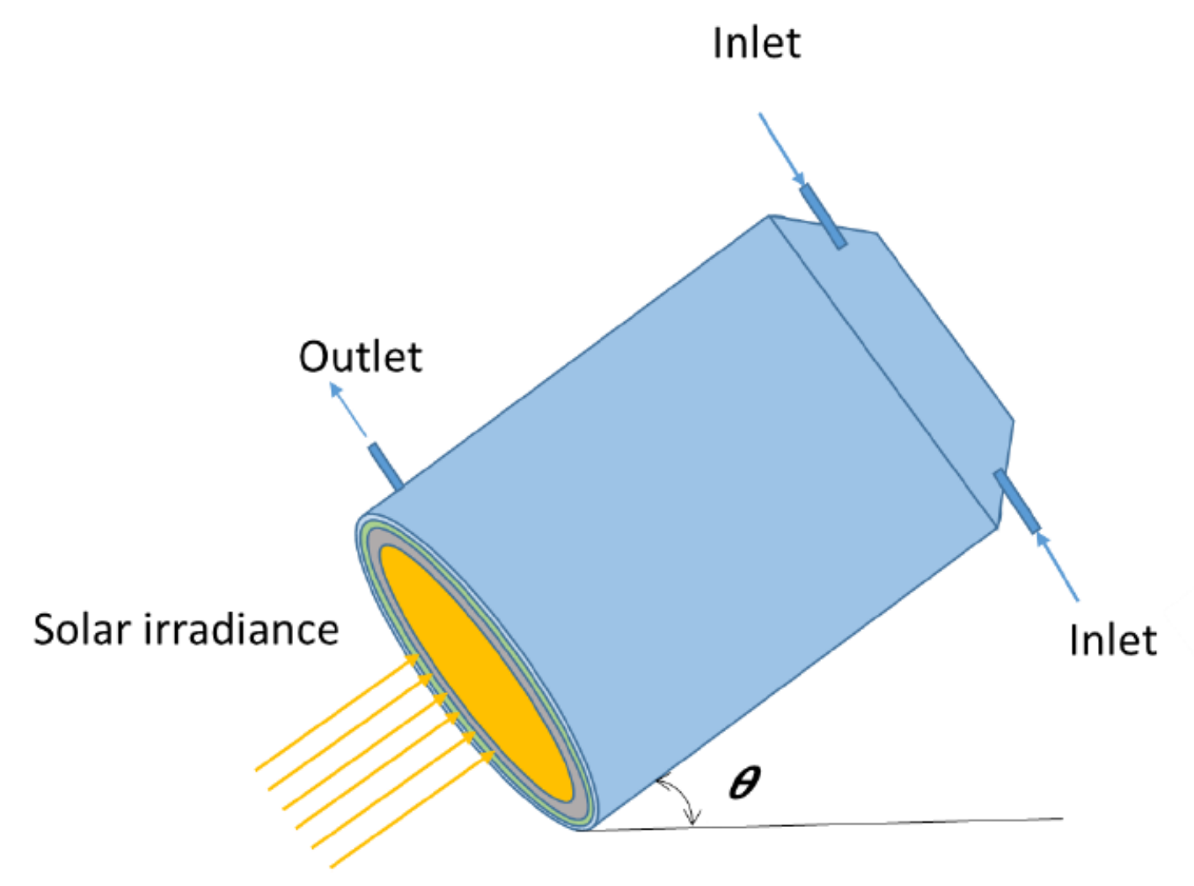

Figure 1. Schematic diagram of the solar cavity receiver, termed the Solar Expanding Vortex Particle Receiver.

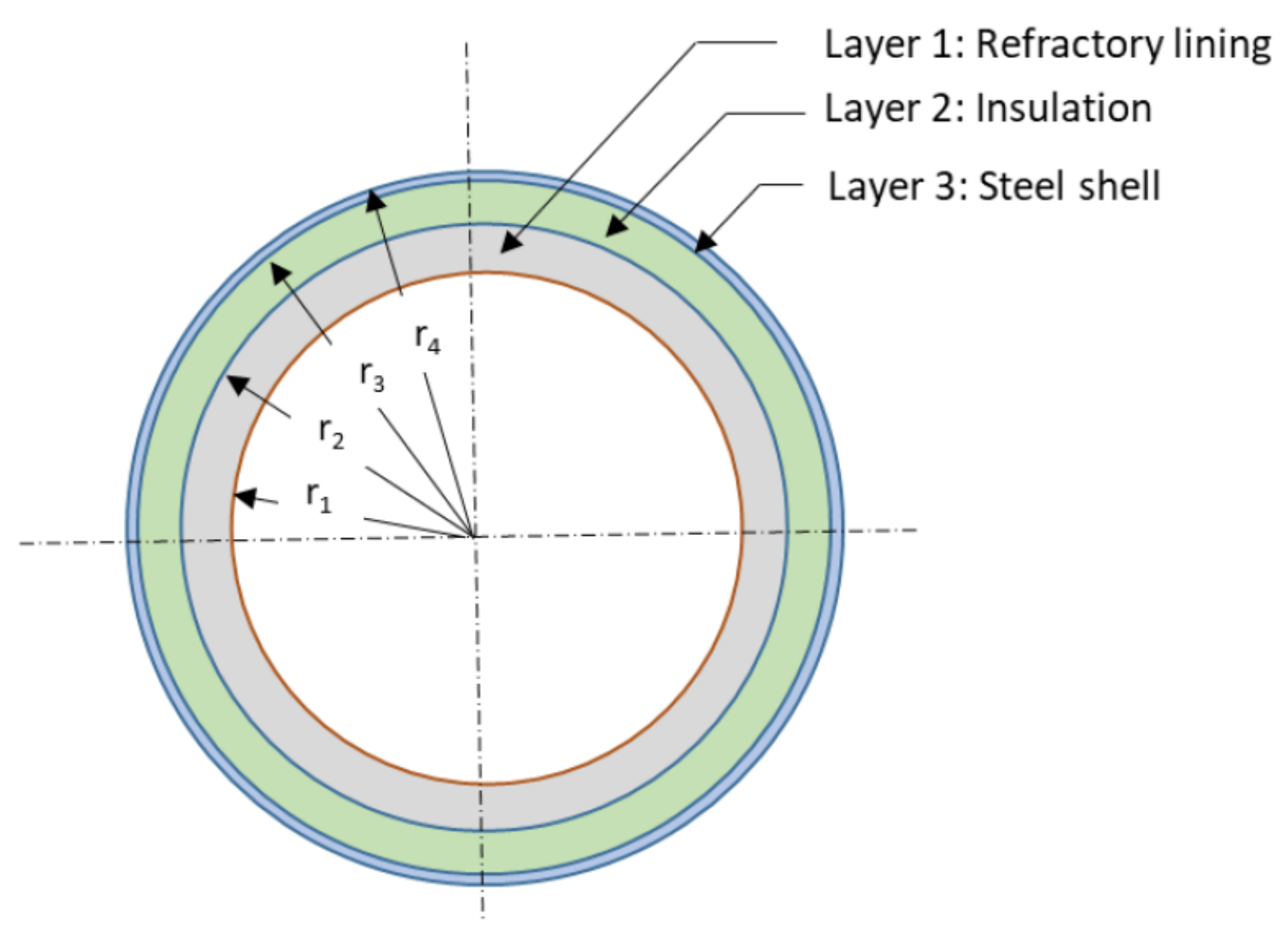

Figure 2. Front view of the multi-layered receiver cavity.

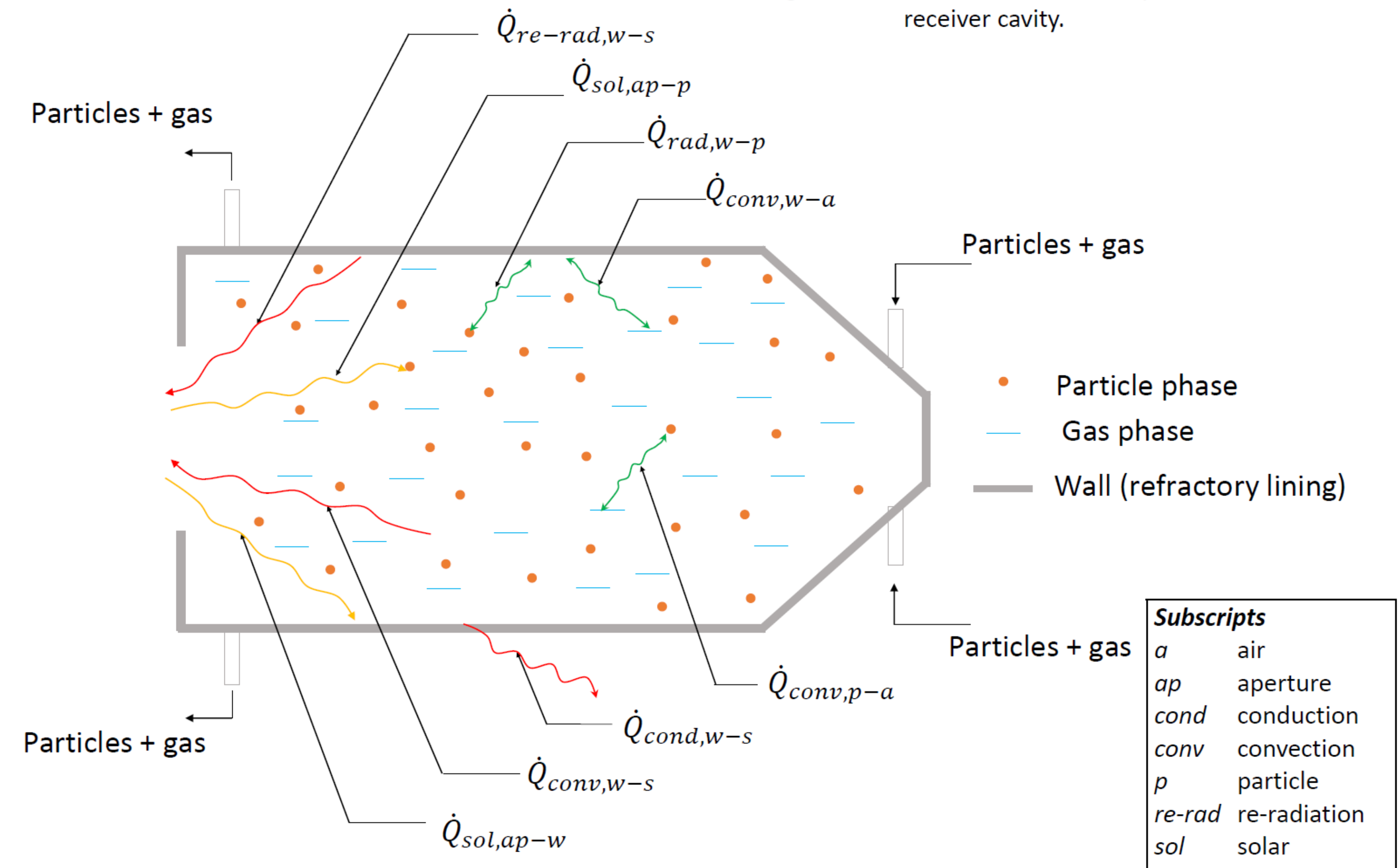

Figure 3. An illustration of all of the heat transfer terms considered in the model

Subscripts	
a	air
ap	aperture
cond	conduction
conv	convection
p	particle
re-rad	re-radiation
sol	solar
s	Surroundings
w	cavity wall

4. Results

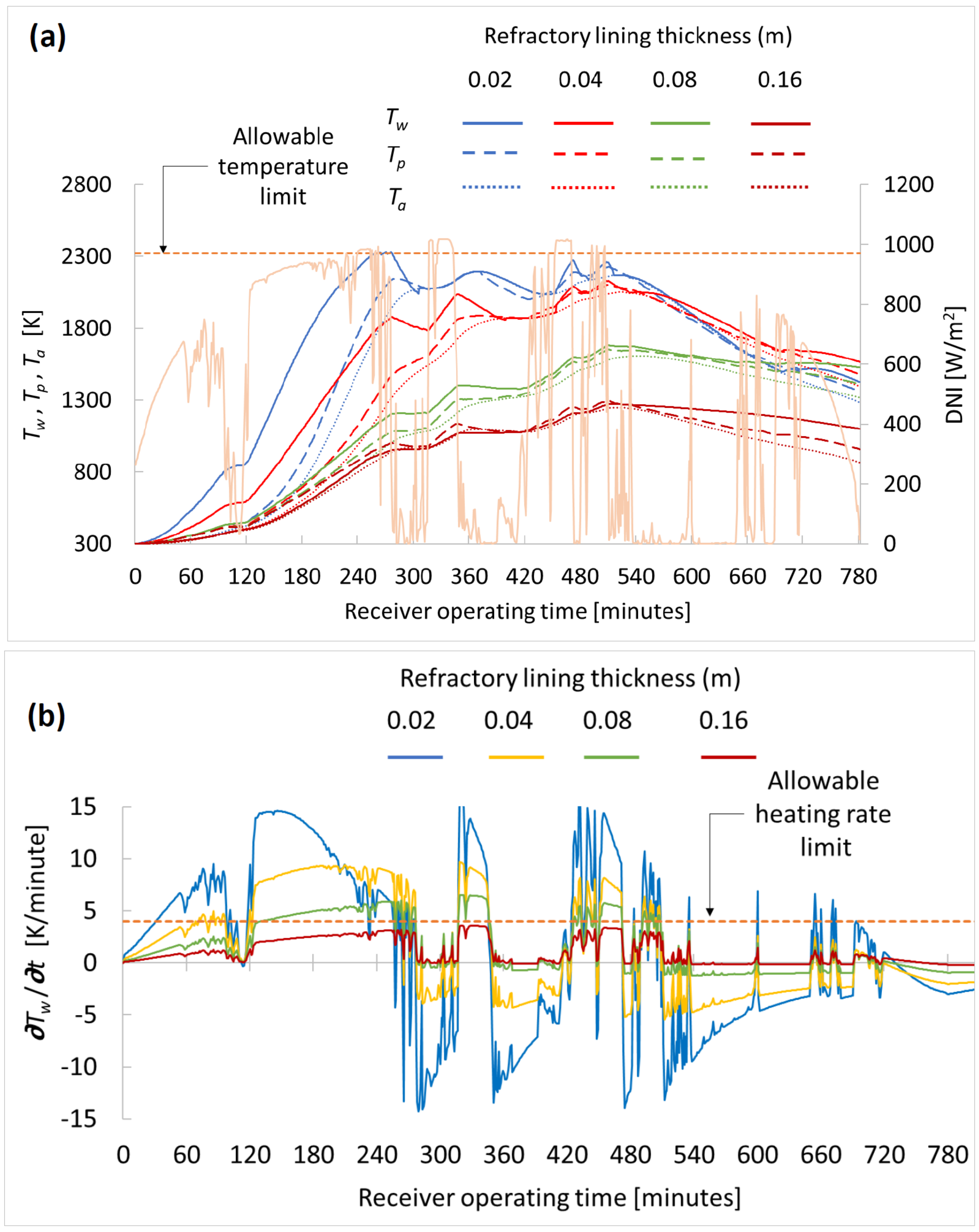

Figure 4. Influence of refractory lining thickness on (a) the transient temperature distributions of the receiver wall (T_w), the particle phase (T_p), and the air phase (T_a) and (b) the cavity heating rate ($\partial T_w/\partial t$) for a variable solar input on a cloudy summer day in Alice Springs, Australia (cavity inner diameter = 12m, aperture to cavity diameter ratio = 0.55, aperture to cavity diameter ratio = 1.6.

Key findings:

- the rate of increase in temperatures increases with a reduction in the lining thickness.
- increasing the refractory thickness decreases the output temperature of the particles, which is undesirable.
- control strategy would be needed to maintain a constant output temperature, such as by varying the mass flow rate.
- the refractory greatly damps the fluctuations in particle temperature and result in a relative stable and robust receiver operation despite the large fluctuations in the solar input.

4. Summary

- Transient modelling of refractory-lined particle receivers is important for their practical implementation.
- The thickness of the refractory must be optimised for a range of competing influences.
- The thickness of the refractory has a strong influence on the thermal inertia of the receiver, on its maximum internal temperature and on the maximum heating rate.
- The results highlight the role of refractory in damping the solar fluctuations and show that careful choice of this parameter can be strongly beneficial to receiver operation and its practical implementation.

	⬇	⬇	⬆	⬇	⬇
Refractory thickness (mm)	Heating time (hours)	Maximum cavity heating rate (°C/minutes)	Maximum particle temperature (°C)	Maximum outer steel shell temperature (°C)	ΔT when DNI drops to zero (°C)
20	4.2	12.1	2422	362	Less than 120
40	5.8	6.2	2277	277	Less than 80
80	7.5	3.9	2017	192	Less than 25
160	8.3	3.1	1467	130	Less than 20

⬇ Lower value is desirable ⬆ Higher value is desirable

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Zoom Link: https://adelaide.zoom.us/j/89970934255?pwd=SWFqWVl4RENYb0RidnNNbm5heGRMQT09