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Solar Receivers**

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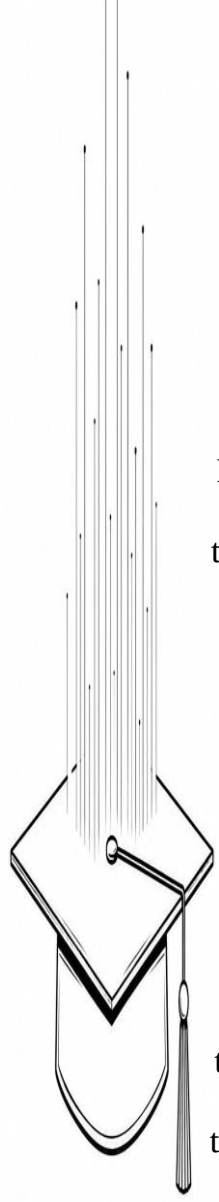
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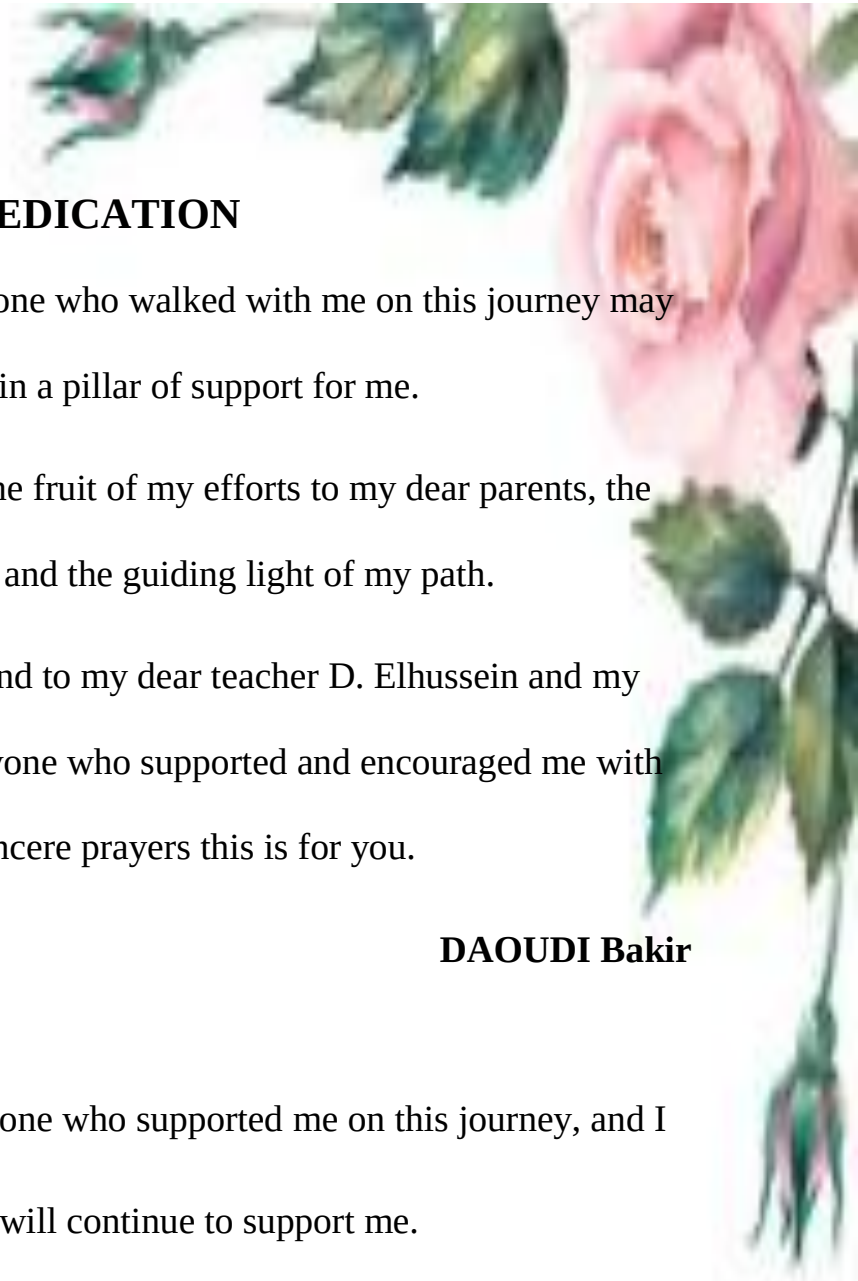
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DEDICATION

I dedicate this success to everyone who walked with me on this journey may
you always remain a pillar of support for me.

With all my love, I dedicate the fruit of my efforts to my dear parents, the
source of my strength and the guiding light of my path.

To my brothers and sisters, and to my dear teacher D. Elhussein and my
relative Nasr Eddine and to everyone who supported and encouraged me with
kind words or sincere prayers this is for you.

DAOUDI Bakir

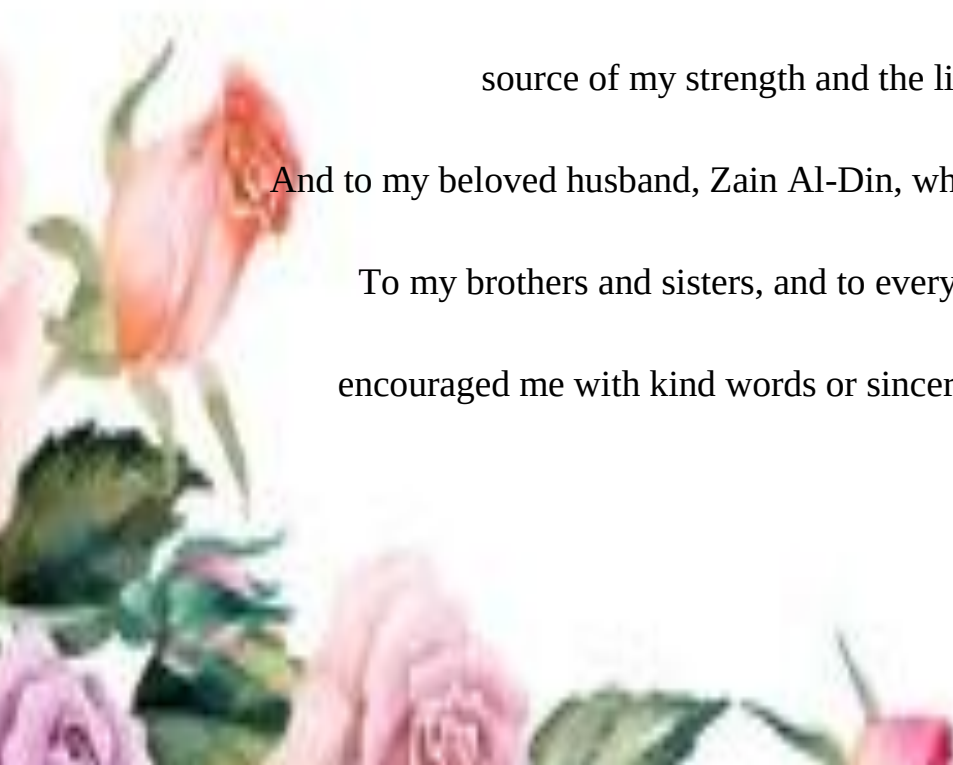
I dedicate this success to everyone who supported me on this journey, and I
pray that God will continue to support me.

With all my love, I dedicate the fruits of my labor to my dear parents, the
source of my strength and the light of my path.

And to my beloved husband, Zain Al-Din, who has always encouraged me.

To my brothers and sisters, and to everyone who supported and
encouraged me with kind words or sincere prayers, this is for you.

REHAIEM Nour elhouda



Summary

The change to temperature concentrated solar power needs good receiver designs. This work shows a model of a free falling particle receiver. The model is made up of 40 parts and it looks at how heat moves through radiation, convection and the movement of falling particles. When we compare this model to data we see that it is very accurate with a small error of only 1.18% for the temperature of the particles. We also did a study to see what factors are most important. We found that how well the particles absorb heat is the most important thing, followed by the amount of heat and the rate at which the particles move.

Our analysis shows that we can get high thermal efficiencies, up to 84.5% when we use a lot of heat. We found some things, like how wind outside can change when the system starts to work from 0.5 to 0.8 megawatts per square meter. We also found that when the particles are around 500 micrometers in size they start to behave. The study also shows that there is a balance to be found where the best performance comes from using particles rather than making them too hot. Finally we made some maps that show how efficient the system can be when we use amounts of particles and this can help us design better systems using computers and optimization techniques with a fixed temperature of 1073.15 Kelvin. Concentrated solar power systems, like these can be very useful and high temperature concentrated solar power systems need designs so we need to keep working on concentrated solar power and high temperature concentrated solar power systems.

KEYWORDS: Free falling Particle Receiver; 1D Modeling; Concentrated Solar Power (CSP); Operability Threshold; Thermal Efficiency.

ملخص

يتطلب التحول إلى الطاقة الشمسية المركزة بدرجة الحرارة تصميمات جيدة لأجهزة الاستقبال. يوضح هذا العمل نموذجًا لجهاز استقبال الجسيمات الساقطة بحرية. يتكون النموذج من 40 جزءًا ويتناول كيفية تحرك الحرارة عبر الإشعاع والحمل الحراري وحركة الجسيمات المتساقطة. عندما نقارن هذا النموذج بالبيانات نرى أنه دقيق للغاية مع خطأ صغير قدره 1.18 % فقط لدرجة حرارة الجسيمات. كما أجرينا دراسة لمعرفة العوامل الأكثر أهمية. لقد وجدنا أن مدى قدرة الجسيمات على امتصاص الحرارة هو الشيء الأكثر أهمية، يليه كمية الحرارة ومعدل تحرك الجسيمات.

يوضح تحليلنا أنه يمكننا الحصول على كفاءة حرارية عالية تصل إلى 84.5% عندما نستخدم الكثير من الحرارة. لقد وجدنا بعض الأشياء، مثل كيف يمكن للرياح الخارجية أن تتغير عندما يبدأ النظام في العمل من 0.5 إلى 0.8 MW/m². لقد وجدنا أيضًا أنه عندما يبلغ حجم الجسيمات حوالي 500 μm فإنها تبدأ في التصرف. وتظهر الدراسة أيضًا أنه يمكن إيجاد توازن حيث يأتي أفضل أداء من استخدام الجسيمات بدلاً من جعلها ساخنة جدًا. وأخيرًا، قمنا بإعداد بعض الخرائط التي توضح مدى كفاءة النظام عندما نستخدم كميات من الجسيمات، وهذا يمكن أن يساعدنا في تصميم أنظمة أفضل باستخدام أجهزة الكمبيوتر وتقنيات التحسين بدرجة حرارة ثابتة تبلغ 1073.15 K. يمكن أن تكون أنظمة الطاقة الشمسية المركزة، مثل هذه، مفيدة للغاية، وتحتاج أنظمة الطاقة الشمسية المركزة ذات درجات الحرارة العالية إلى تصميمات، لذلك نحتاج إلى مواصلة العمل على أنظمة الطاقة الشمسية المركزة وأنظمة الطاقة الشمسية المركزة ذات درجات الحرارة العالية.

كلمات مفتاحية : مستقبلات الجسيمات الساقطة; النمذجة أحادية البعد; الطاقة الشمسية المركزة; عتبة التشغيل; الكفاءة الحرارية.

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List of abbreviations and acronyms

Abbreviation		Unite
1D	One dimension	/
AR	Aperture aspect ratio	/
CFD	Computational Fluid Dynamics	/
DEM	Discrete Element Method	/
EES	Engineering Equation Software	/
FBPSR	Fluidized Bed Particle Solar Receiver	/
FPR	Falling Particle Receiver	/
G3P3	3rd Generation Particle Pilot Plant	/
GAMBIT	Geometry And Mesh Building Intelligent Toolkit	/
LCOE	Levelized Cost of Energy	\$/kWh
MCRT	Mont Carlo Ray Tracing	/
RMSE	Root Mean Square Error	/
sCO_2	Supercritical Carbon Dioxide	/
Latin letters		
c_p	Specific heat capacity	kJ/kg.K
D	diameter	μm
F_{view}	View factor	/
g	Gravity	m/s ²
h	Specific enthalpy	J/kg
H	Height	M
Htc	Heat transfer coefficient	W/m ² .K
HTF	Heat transfer fluid	/
J	Radiosity	MW/m ²
K	Thermal conductivity	W/m.K
$\dot{m}$	Mass flow rate	Kg/s
Nu	Nusselt number	/
q''	Heat flux	MW/m ²
Re	Reynolds number	/
W	Width	/
T	Temperature	K
Th	Thickness	M
V	Velocity	m/s
Y	y coordinate	M
Greek letters		
α	Absorptivity, absorptance	/
ε	Emissivity, emittance	/
η	Efficiency	/

ρ	Density, reflectance	kg/m ³
σ	Stephan-Boltzmann constant	W/m ² .K ⁴
T	Transmittance	/
φ	Volume fraction	/
ϕ	Direction factor	/
ψ	Wind factor	/
Subscripts		
O	no wind scenarios	/
adv	Advection	/
amb	Ambient	/
back	Back side of curtain	/
C	Curtain	/
cv	Convection	/
front	Front side of curtain	/
P	particles	/
rad	Radiation	/
rec	Receiver	/
sol	solar	/
W	Back wall	/

General Introduction

General Introduction

Falling Particle Receivers (FPR) technology represents the cornerstone of third-generation concentrated solar power plants (Gen3 CSP), designed to surpass the thermal limitations of conventional heat transfer media such as molten salts. These systems are capable of operating at temperatures exceeding 800–900°C, enabling their integration with advanced thermodynamic cycles such as the supercritical carbon dioxide (sCO₂) cycle. Moreover, FPR systems allow direct thermal energy storage for up to 16 hours, contributing to a reduction in the Levelized Cost of Energy (LCOE) to approximately \$0.056 per kilowatt-hour. However, the physical processes governing particle receiver behavior are inherently complex, involving strong interactions between radiation heat transfer, particle dynamics, and convective heat losses — interactions that remain challenging to model accurately and efficiently.

The primary objective of this study is to develop and validate a one-dimensional (1D) thermal model capable of predicting the thermal and optical performance of falling particle receivers with sufficient accuracy and minimal computational cost. Specifically, the study aims to: define the operational boundaries of the receiver by mapping the minimum heat flux and particle absorptance required to reach the target outlet temperature of 800°C; investigate the influence of particle diameter on the optical behavior of the curtain. For the latter objective, the study investigates how variations in particle size influence radiation transport within the particle curtain, particularly the transition from a radiation-blocking (optically thick) regime to a more transparent (optically thin) regime. In addition, the model's ability to account for environmental perturbations, such as wind-induced convective losses, is assessed through the integration of correction coefficients derived from high-fidelity CFD simulations.

To achieve these objectives, the study adopts a reduced-order modeling approach based on solving the conservation equations of mass, momentum, and energy along the vertical axis of particle fall. The fall path is discretized into 40 uniform sections, a resolution shown to provide a stable and accurate mathematical solution within a computation time of only a few minutes. The optical properties of the particle curtain, including absorptance, transmittance, and reflectance, are evaluated as functions of particle diameter, volumetric fraction, and curtain thickness. The model is further extended to incorporate setpoint-controlled operation, in which the particle mass flow rate is dynamically adjusted to compensate for fluctuations in incident solar radiation. Validation is carried out by comparison against benchmark Monte Carlo Ray Tracing (MCRT) simulations and high-resolution CFD results.

The developed one-dimensional model demonstrated good predictive capability, with mean relative errors of **1.18%** for particle temperature and **2.97%** for particle velocity, while the back-wall temperature showed a larger deviation of **9.11%** due to simplified heat transfer assumptions. The predicted outlet temperature reached **1046.2 K**, with deviations below **2%** compared to reference models, and the receiver efficiency was predicted as **0.845**.

The parametric analysis showed that receiver performance is strongly governed by thermal and optical interactions. A transition in mass-flow behavior occurred around **150–250 kg/s**, where efficiency approached **0.82–0.83** at high heat flux conditions. The minimum heat flux required for operation ranged from **0.48–0.55 MW/m²** under no-wind conditions and increased to **0.70–0.82 MW/m²** under wind conditions. In addition, a critical particle absorptivity of **0.57–0.58** and a critical particle diameter of approximately **480–500 μm** were identified, beyond which the curtain shifted from an optically thick to an optically thin regime, causing significant efficiency degradation and loss of operability. These findings enabled the definition of an operability boundary separating feasible and non-feasible operating regions.

The present thesis is structured in three main chapters. The first chapter of the dissertation provides a detailed literature review of the FPR technology and existing modelling approaches. The second chapter is dedicated to the mathematical formulation and the numerical implementation of the 1D thermal model. The third chapter is on model validation and parametric analysis, including optical properties, operability limits and wind correction, and discusses the implications of the findings for receiver design. Finally, the work ends with a general summary and perspectives for future research.

CHAPTER 1 . Literature review

1.1. Introduction

This unit reviews previous research and studies on the development of solid particle receiver (SPR), from one-dimensional mathematical models to advanced numerical modeling (CFD), which demonstrated the ability of these systems to operate efficiently at temperatures exceeding 1073.15-1173.15 K. The literature has focused on developing advanced designs, such as centrifugal receivers and fluidized beds, to reduce thermal stresses by up to 73% compared to conventional systems [1].

Previous studies have also examined the impact of environmental factors, especially wind, and the role of particle properties (such as the durability of CARBO) in reducing convection losses. Taken together, this research concludes that optimizing solar field distribution with long-term thermal storage systems can reduce the cost of energy (LCOE) to approximately \$0.056 per kilowatt-hour [2], achieving the desired economic goals of third-generation solar power plants.

1.2. One-dimensional thermal modeling

Direct studies of one-dimensional thermal modelling have shown high accuracy, with a coefficient of determination of 0.996 in windless conditions. A 1D model for free falling particle receivers has been developed and a good agreement with computational fluid dynamics (CFD) simulations is found. Results show that high-absorptivity particles such as CARBO achieve maximum efficiency levels, whereas low-absorptivity particles such as sand cannot operate efficiently at heat fluxes less than 0.5 MW/m² (**Fig. 1-1.**) [3].

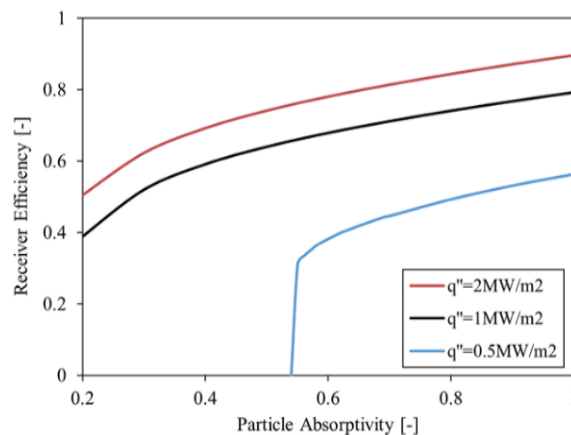


Figure 1-1 : Thermal performance of the heat receiver under different mass flow rate [3].

Moreover, the opaque sand and CARBO barriers were determined to have high absorptance levels, 0.75 and 0.97 respectively. The fast analytical model showed a small error margin of only 0.048 . This indicates that the effectiveness of the particle curtain is highly dependent on the thickness and solids volume fraction of the particle curtain [4]. The results are useful to perform accurate and fast thermal simulations of advanced concentrating solar power systems (**Fig. 1-2**).

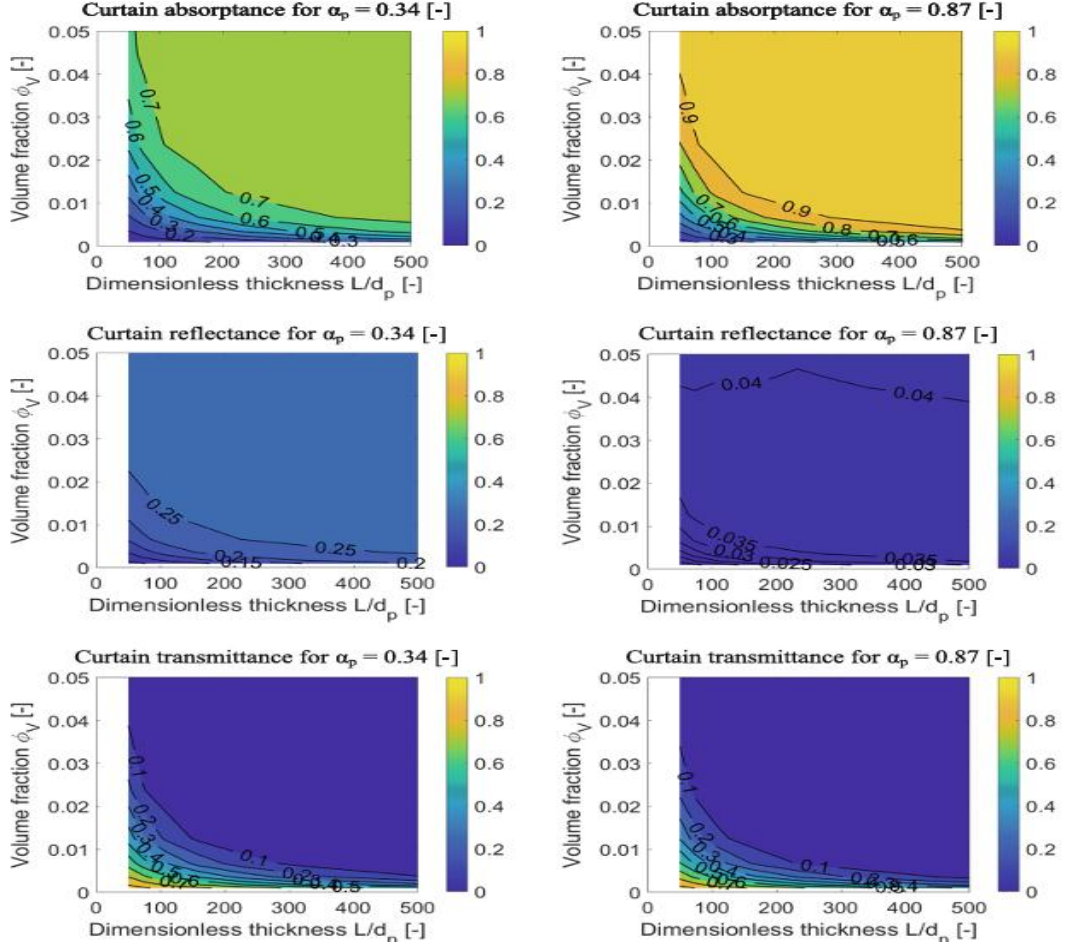


Figure 1-2 : Curtain optical properties (absorptance, reflectance and transmittance) as a function of solids volume fraction and dimensionless thickness for particle absorptivity [4].

Closely related to this, key elements such as the receiver and the primary heat exchanger (PHX) were simulated using 1D models with high physical fidelity in specialised software. The model used the specific properties of CARBO HSP particles, with the heat capacity specified as a temperature dependent variable. The results showed that increasing the mass flow rate enhances the solar absorption and, therefore, the total technical efficiency of the system [5].

Finally, 1D models were coupled with artificial neural networks (ANNs) to simulate the behaviour of particles at ultra-high time resolution. This model has a correlation coefficient of 0.994 with complex physical models. And also allows to predict the outlet temperatures between 1048.15 K to 1073.15 K [6]. The results included an analysis of the dynamic behaviour to control the flow of particles, stable performance under varying weather conditions (**Fig. 1-3**).

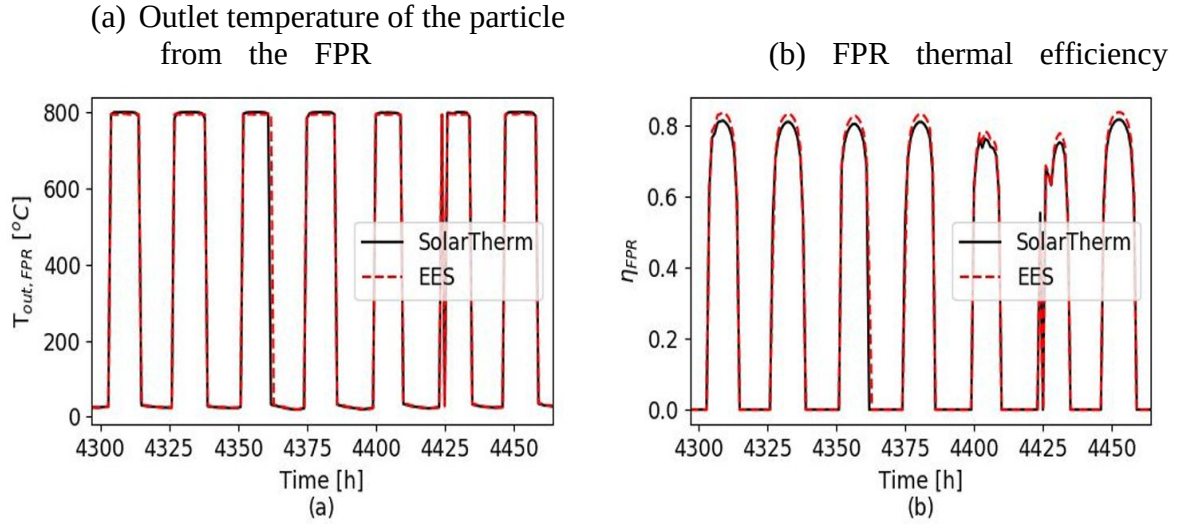


Figure 1-3: The comparison of plant dynamics for selected variables in summer between SolarTherm and EES [6].

1.3. Advanced numerical and CFD modeling

Advanced numerical models i.e. CFD, CFD-DEM and MCRT have been used for the validation of the accuracy of 1D models. Laboratory experiments on a 2.5 MW prototype have shown that particle temperatures above 1173.15 K are achievable, with temperature increases of about 250 K in a single pass. Moreover, the computational fluid dynamics model was validated with experimental data with less than 10% error and proved that receiver efficiency is significantly increased with high mass flow rates and particle curtain opacity [7]. This successful verification is a fundamental pillar for the development of future commercial scale designs (**Fig. 1-4**).

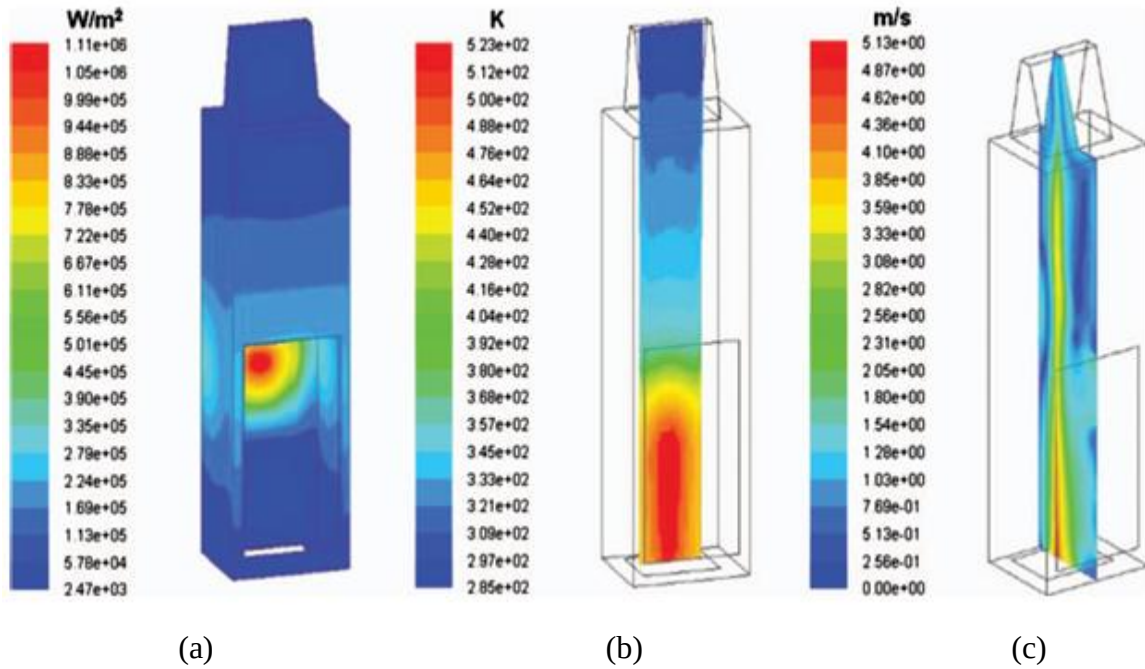
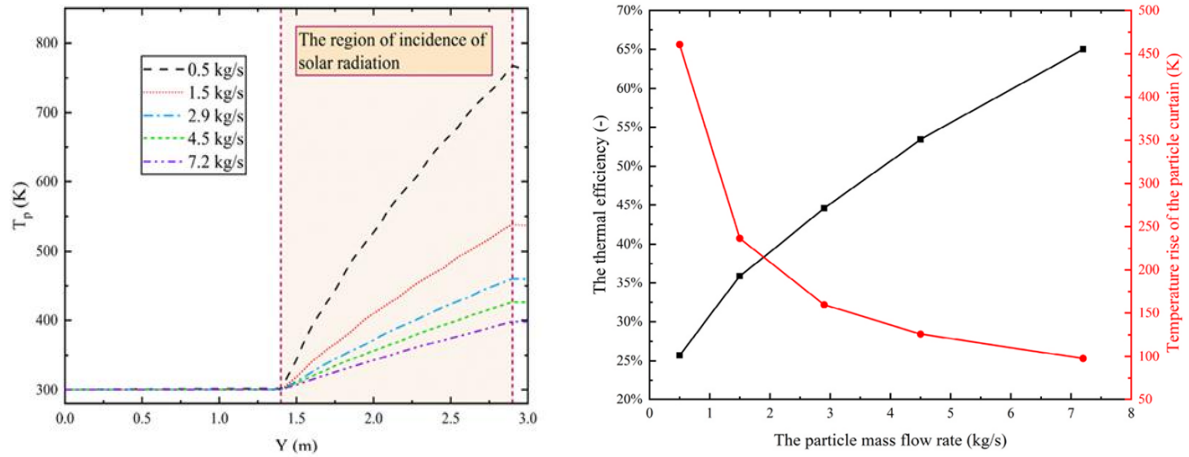


Figure 1-4 : (a) Simulated wall incident radiation, (b) particle tracks colored by temperature, (c) gas flow colored by velocity [7].

Building on these validation models, a model integrating the discrete element method and computational fluid dynamics (CFD-DEM) with a Monte Carlo approach was developed to examine solar particle receiver performance. Notable results indicate that increasing the particle mass flow rate from 0.5 kg/s to 7.2 kg/s enhances thermal efficiency from 25.71% to 60.17% [8]. It was also found that using particles with a diameter of 300 μm produces four times the absorptivity compared to particles with a diameter of 1000 μm . (**Fig. 1-5**).



(a) Temperature distribution curve of the particle curtain along the vertical direction (b) Thermal efficiency and temperature rise

Figure 1-5 : Thermal performance of the heat receiver under different mass flow rates [8].

Monte Carlo Ray Tracing (MCRT) is accurate but slow. Serdar Hicdurmaz et al devised a faster alternative: a reflection model for particle beds in a centrifugal solar particle receiver (CentRec) that eliminates expensive MCRT simulations. The model predicted reflection loss ($\sim 1.6\%$) and absorbed power distribution accurately while cutting computation time from 11 hours to 9 minutes. They measured reflection characteristics across incidence angles from 0° to 85° , **(Fig. 1-6)** [9].

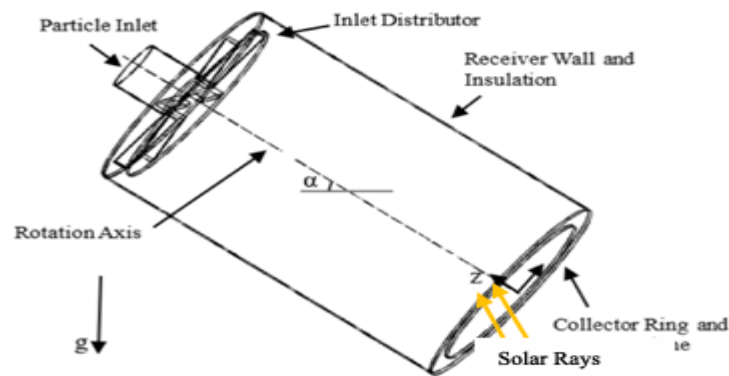


Figure 1-6 : Schematic view of the centrifugal receiver [9].

Beyond speed improvements, researchers also looked at efficiency through operating strategies and environmental factors. The free-fall receiver hit 83% efficiency at 400 MW solar input. Three serial recirculation cycles pushed efficiency above 92% by cutting

reflection losses from 10% to 2.2%. Wind speed mattered too: at 15 m/s, efficiency

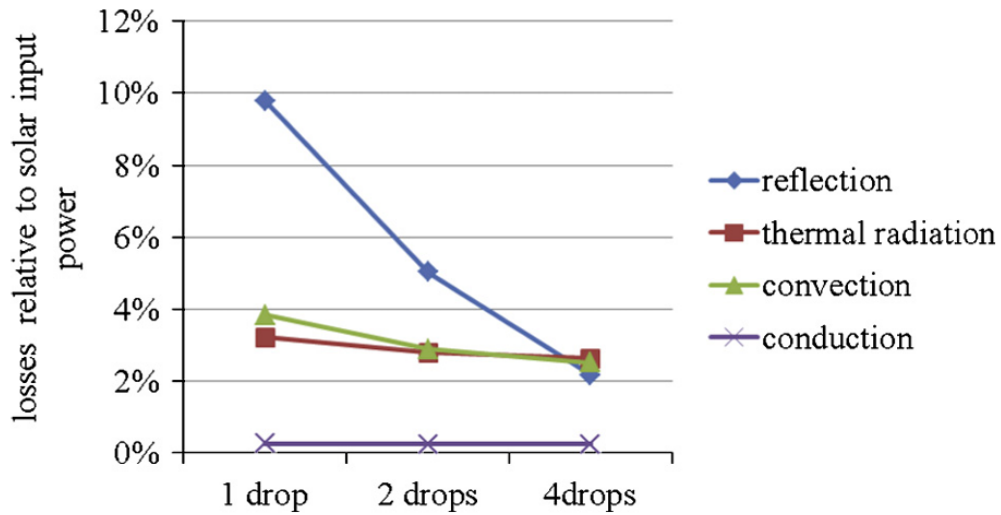


Figure 1-7 : Relative losses at different recirculation strategies [10].

dropped to 84% from 89% **(Fig. 1-7)** [10].

1.4. Heat transfer mechanism and external factor

A study of heat transfer and loss mechanisms found that external winds significantly affect efficiency. In simulations, advection losses reached 25.4%, while all other losses stayed below 10% **(Fig. 1-8)**. South winds improved efficiency at a 1MW receiver a correlation that points to one clear priority: controlling wind-driven heat loss matters far more than anything else **(Fig. 1-9)** [11].

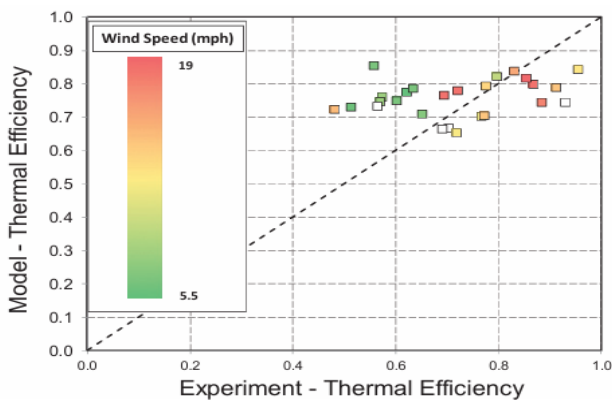


Figure 1-9 : the measured wind speed. [11].

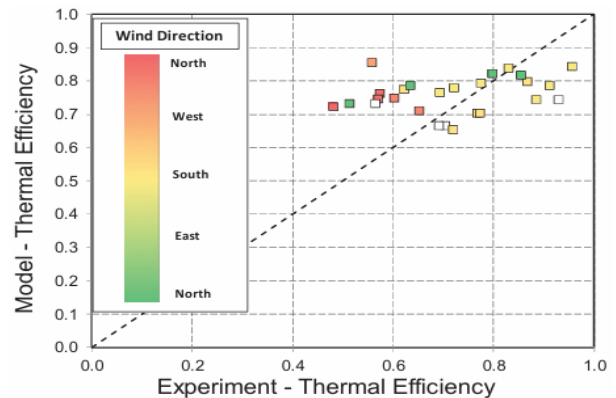


Figure 1-8: the measured wind direction [11].

Furthermore, the effect of wind direction was found to be stronger compared to its speed (up to 15 m/s), resulting in convection losses of 25.4 percent. These losses can be minimized to achieve 90% efficiency if these losses are minimized, noting that particle diameters of 350 μm or more do not significantly change convection losses (**Fig. 1-10**) [12].

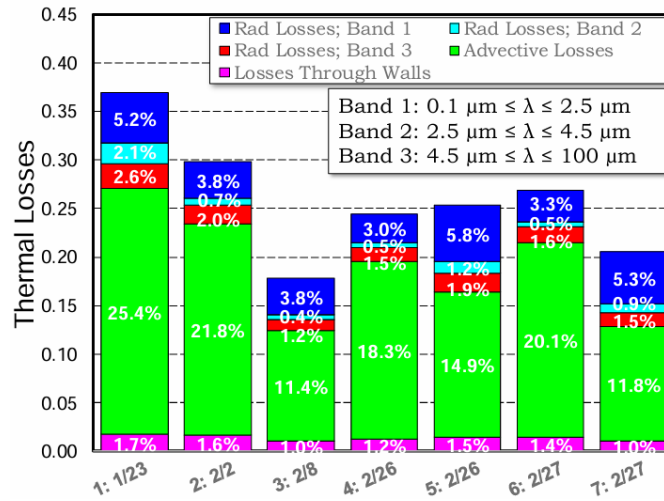


Figure 1-10 : Thermal Loss Distribution Across Various Experimental Conditions [12].

A study Lindsey Yue et al found that quartz caps for falling particle receivers lead to increased radiation losses because temperatures reached 1483.15 K. At 500 K, efficiency decreased from 83% to 75% with full coverage. However, at 873 K, efficiency improved from 71% to 75%, as the cover reduced wind-induced convection losses enough to compensate (**Table 1-1**)

Table 1-1 : Thermal power values of interest. [13]

	No coverage, $T_0 = 500$ K	Half coverage, $T_0 = 500$ K	Full coverage, $T_0 = 500$ K	No coverage, $T_0 = 873$ K	Half coverage, $T_0 = 873$ K	Full coverage, $T_0 = 873$ K
$q_{\text{rad source}}$	117 kW					
$q_{\text{rad hood aperture}}$	111 kW					
$q_{\text{rad receiver aperture}}$	100 kW	93 kW	87 kW	101 kW	95 kW	89 kW
$q_{\text{particles}}$	92 kW	87 kW	83 kW	78 kW	74 kW	80 kW

Comparisons of systems in the process of designing showed that utilizing several stages increases the system's efficiency by reducing convective losses of heat and increasing opacity of curtains more effectively than the free-fall receiver. Thus, the yearly energy efficiency of a five-stage system amounted to 75.3%, outperforming the efficiency of the free-fall receiver (72.0%) (**Fig. 1.11**) [14].

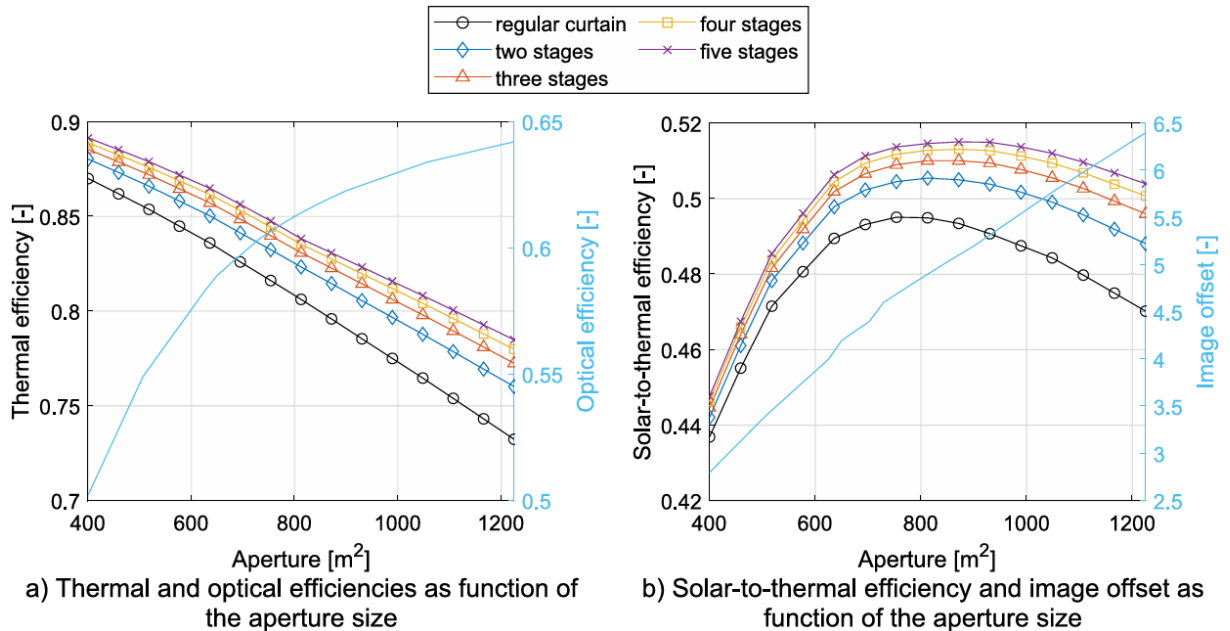


Figure 1-11 : On-design results of the different configurations considered [14].

Finally, it was experimentally established that utilization of intelligent recirculation allows maintaining high receiver efficiency even at low-load conditions (reaching 90% for full loads and 67% at 20% loads). The proposed innovation allows reaching an annual energy efficiency from solar radiation to electricity at approximately 24%, heating particles above 1173.15 K (**Fig. 1-12**) [15].

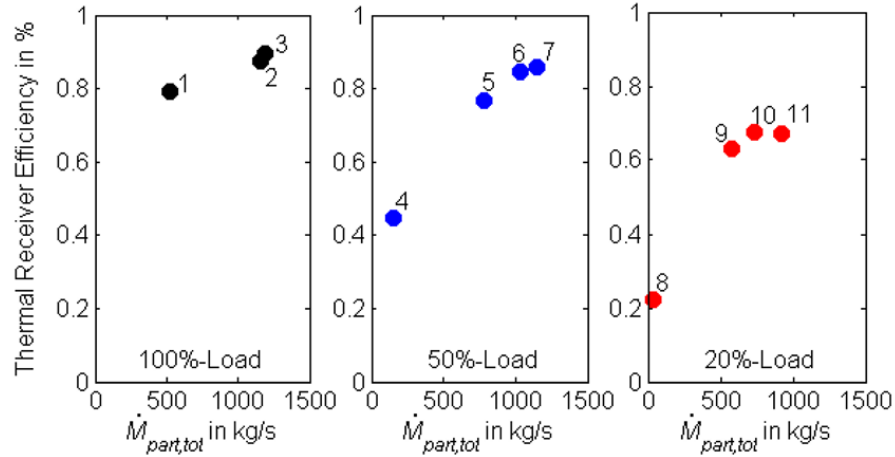


Figure 1-12 : Thermal efficiency of the face-down receiver design for different loads and recirculation patterns [15].

1.5. Advanced receiver technologies and particle properties

The first set of experiments aimed at investigating the energy conversion processes in individual particles inside a counterflow CO₂ solar receiver, whereby a "Z-number" parameter was used to determine the appropriate particles (having $Z > 1$). In the radiation control operating regime, the receiver proved its efficiency with a thermal efficiency above 0.5, with optimal temperatures of particles being 1110 K, and solar intensities at 304 kW/m² [16] (**Fig. 1-12**).

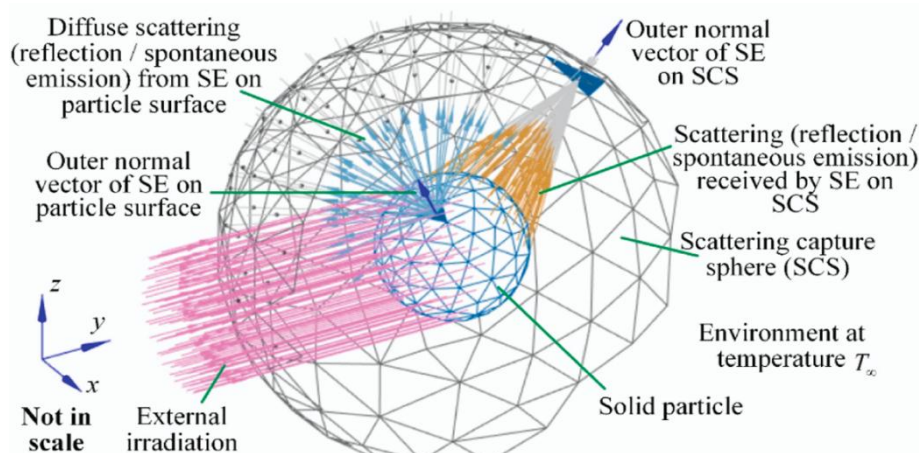


Figure 1-13 : Modeling of radiative/heat transfer of a single particle [16].

In an additional study, computer modeling was conducted to investigate small ceria particles (under 500 μm), which showed that the surface chemical reaction plays a key role in determining the speed of the reduction process. The high thermal demands required for this reaction led to substantial heat losses through radiation, making up 60-75% of the total solar energy input (**Fig. 1-14**) [17].

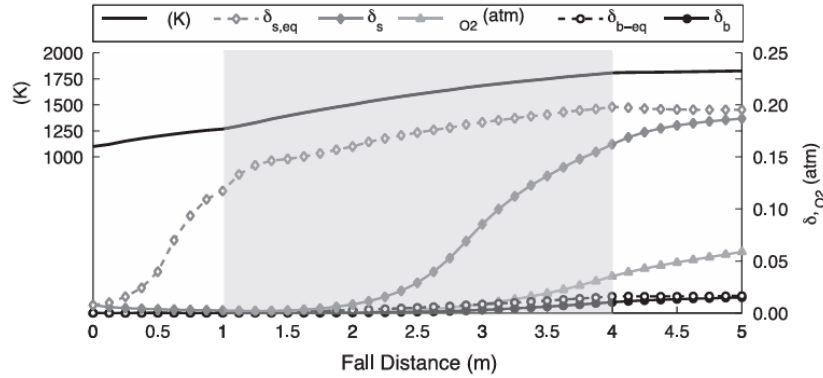


Figure 1-14 : Evolution of curtain temperature T_p , degree of reduction d_s and d_b , and partial pressure P_{O_2} of oxygen along the fall path. [17].

For tackling efficiency concerns, optimized designs were created, which could operate at a theoretical efficiency of 85.1% at experimental temperatures of 1053.15 K. This confirmed that certain design considerations could be used to significantly lower the primary convective loss rate, by more than 10 percentage points. Moreover, it was observed that CARBO particles had outstanding durability, experiencing only 1% decline in their absorptance over 10,000 cycles (**Fig. 1-15**) [18].

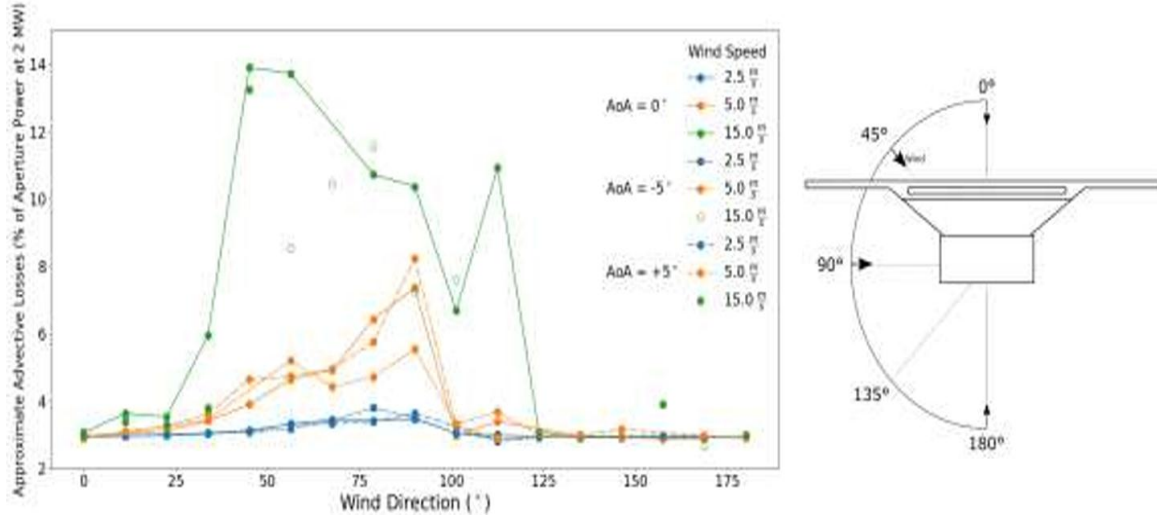


Figure 1-15 : Advection losses for the G3P3 FPR at various wind speeds, wind directions, and angles of attack [18].

Evaluating these discoveries in the real world, on-sun testing of falling particle receivers revealed that these systems could attain outlet temperatures of close to 1073.15 K. The efficiency level measured in these tests ranged between 60% to 90% at experimental conditions where highly concentrated solar fluxes of around 1000 kW/m² were recorded at a mass flow rate of 11 kg/s (**Fig. 1-16**) [19].

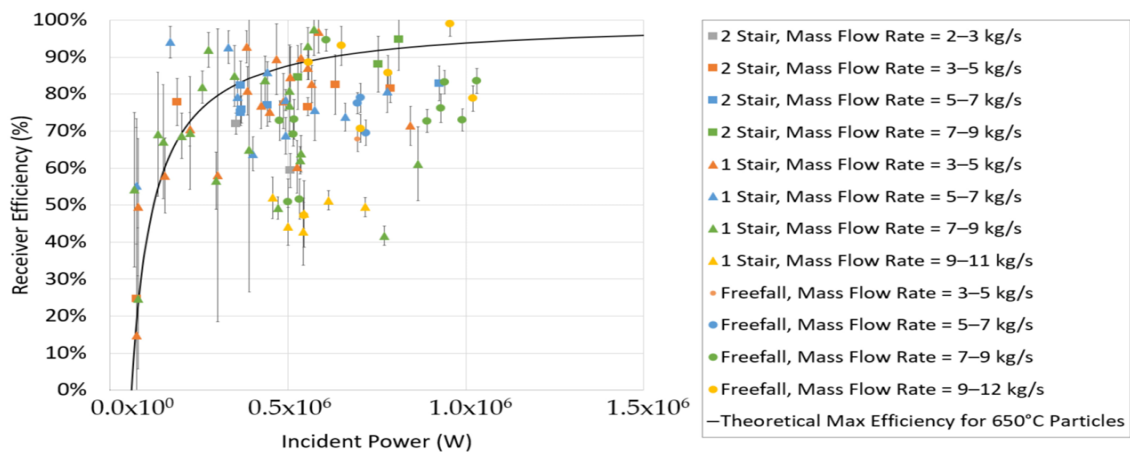


Figure 1-16 : Plot of receiver efficiencies for on-sun StAIR (multistage) tests including free-falling tests and a theoretical maximum efficiency (solid black line) at 923.15 K [19].

Discussing the efficiency of alternate methods like fluidized bed systems, 3D numerical simulation demonstrated that particle temperatures could increase to 1645.34 K in just 10 seconds. Also, guide plates were discovered to improve the average temperature by 3.70% (**Fig. 1.17**). Furthermore, it was found that an increase in radiation intensity could boost temperatures from 1706.26 K to 1872.03 K (**Fig. 1-18**) [20].

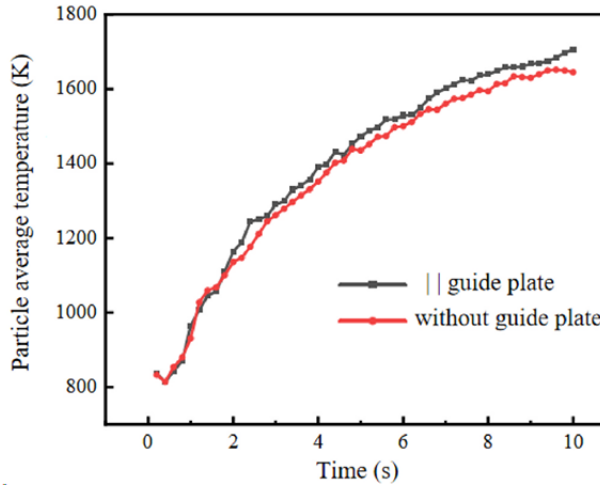


Figure 1-17 :Comparison of the particle average temperature in a heat absorber with the guide plate and without the guide plate [20].

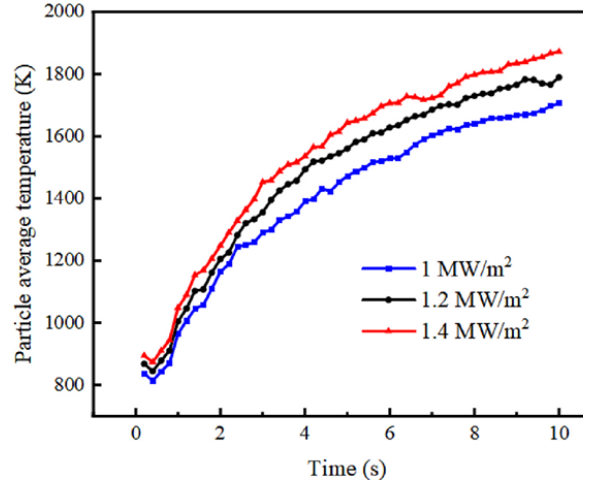


Figure 1-18 : Variation of the average particle temperature with time under different solar radiation intensities [20].

Building further on this approach, a counter-flow fluidized bed receiver design was developed that proved capable of attaining heat transfer coefficients from the bed to wall of more than 1000 W/m²K. It provided for solar intensities greater than 200 kW/m² on the cavity walls while keeping the external wall temperatures below 1223.15 K, forming the basis of systems capable of handling particle exit temperatures beyond 1023.15 K (**Fig. 1-19**) [21].

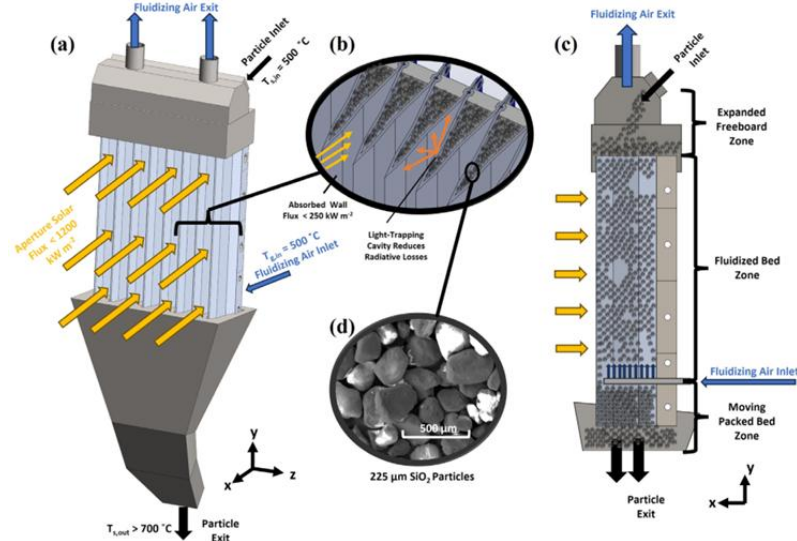


Figure 1-19 : Schematic and photographic section of a fluidized bed particle receiver inside a narrow channel for concentrated solar power applications [21].

In tandem with these advances in thermal efficiency, numerical analysis of the flow dynamics in fluidized bed systems (FBPSR) showed that an increase in gas velocity increases the heat transfer coefficient from 1288 to 1696 $\text{W/m}^2\text{K}$. In particular, it demonstrated that fluidized bed systems could effectively minimize thermal stress by 73% in comparison with conventional molten salt systems (**Fig. 1-20**) [1].

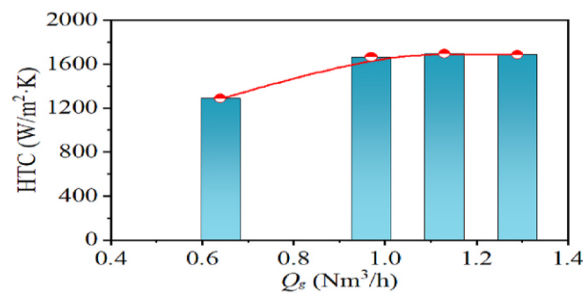


Figure 1-20 : Effects of flow rates on the wall-to-bed HTC [1].

Lastly, experimental results proved that adding particles to the receiver increases the air exit temperature by more than 55% in comparison with air-only systems. The addition of particles resulted in increased heat transfer coefficients, rising from 5–10 $\text{W/m}^2\text{K}$ in air-only systems to 29.5–67.9 $\text{W/m}^2\text{K}$ with particles used (**Fig. 1-21**) [22].

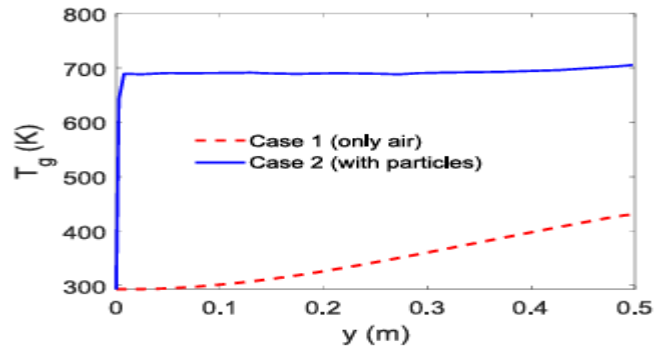


Figure 1-21 : Gas temperature evolution versus height for the nominal case 2 ($U = 0.6$ m/s, $H_b = 0.2$ m) and the case 1 without particles (only air $U = 0.6$ m/s) [22].

1.6. Economic analysis and LCOE optimization

It is shown from the economic analysis that particle receiver systems could be optimized in such a way that they achieve a minimum LCOE of 0.056 \$/kWh. The optimal values for achieving this include a solar multiple of 3, concentration ratio of 2500 and storage duration of 16 hours, together with optimizing the size of solar fields in order to increase energy output and reduce costs (**Table 1-2**) [2].

Table 1-2 : A free-falling particle receiver system's ideal setup parameters to attain the lowest LCOE [2].

Parameter	Value
Solar multiple	3
Storage equivalent hours	16 hours
Tower height	250 m
Concentration ratio	2500

Like-wise, Kevin J. Albrecht et al. proved that a minimum LCOE can be achieved at solar multiples near 2.5 and more than 14 hours of storage for approximately \$0.0592/kWh. It was also proven by them that the costs of the particles above \$1/kg make it impossible to meet the economic objectives. They pointed out that particle loss rates must be controlled strictly due to technical reasons (**Table 1.3**) [5].

Table 1-3 : Anticipated cost allocation in relation to design of experiments objectives [5].

Metric	Target	Baseline
Receiver Cost (\$/kW)	150	95.63
Storage Cost (\$/kWh)	15	17.76
Heat Exchanger Cost (\$/kW)	150	175.00
Power Cycle Cost (\$/kW)	600	600.00
Receiver Efficiency	90%	85.7%
Power Cycle Efficiency	55%	50.2%
Capacity Factor	69%	71%
LCOE (\$/kWh)	0.06	0.0592

Furthermore, results obtained through system modeling show that a multi aperture receiver configuration along with external thermal storage could lead to electricity generation at \$56.03/MWh. The system operates on particles heated up to 1073.15 K to run a super-critical carbon dioxide (sCO₂) cycle which increases annual thermal efficiency to 87.3% for the receiver with a 226m tower **(Fig. 1-22)** [6].

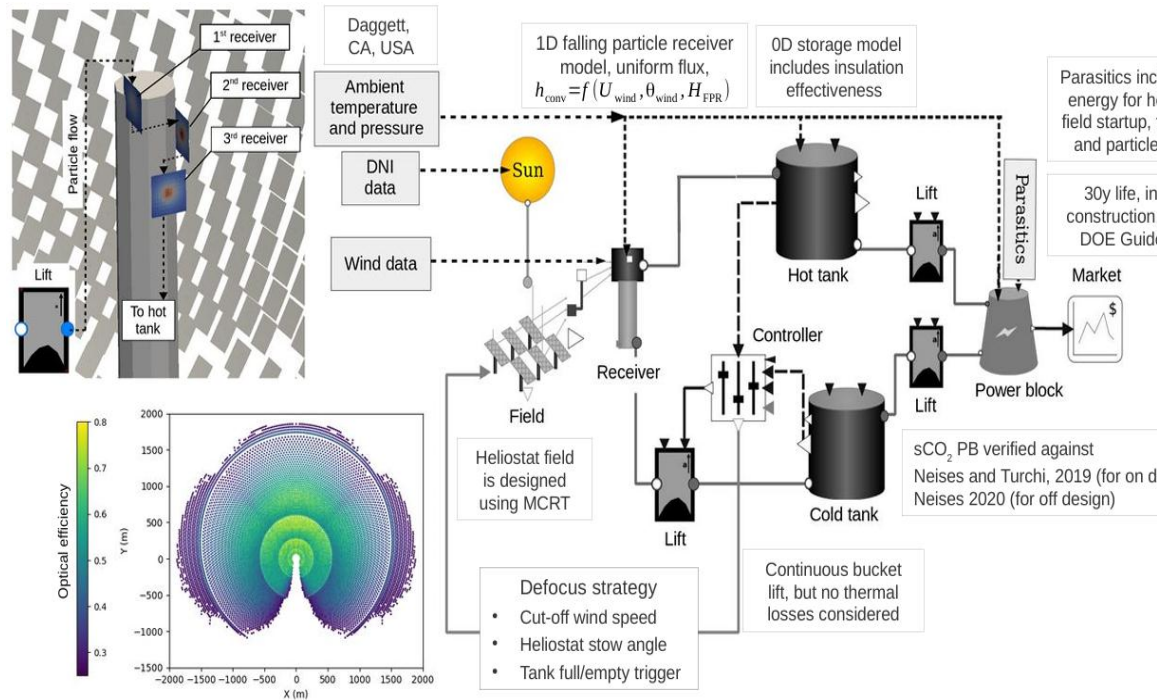


Figure 1-22 : Conceptual overview of the G3P3 particle CSP system model [6].

Within the discussion on innovative designs, Ye Wang et al. highlighted that multi-aperture systems demonstrate a 6% advantage in terms of reducing costs in comparison with the single aperture system. In particular, such a system allows obtaining the lowest costs of less than \$60/MWh, based on optimal parallel system configuration with a tower height of 205.9 m and 12.62 h of storage with the use of particles at different temperatures (**Fig. 1.23**) [23].

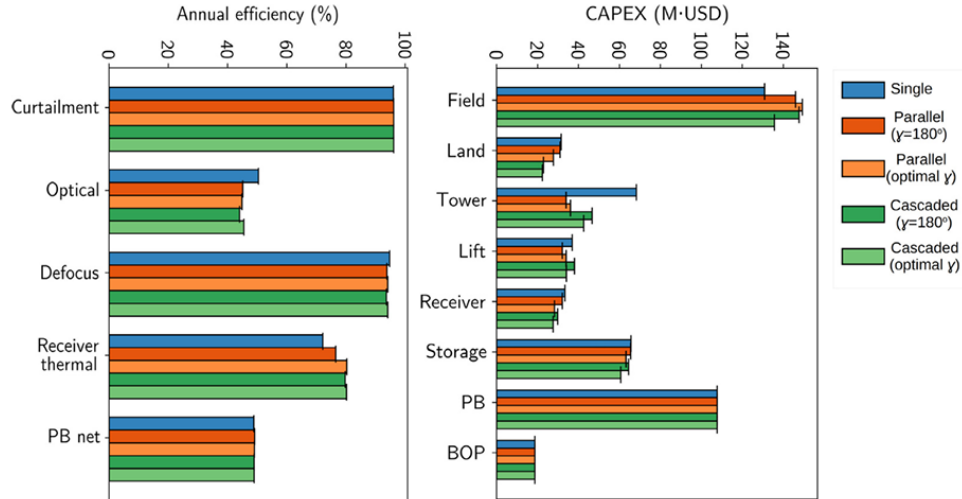


Figure 1-23 : Side-by-side comparison of the annual efficiency performance and cost breakdown, for each aperture arrangement [23].

Concerning power cycle efficiency, researchers noted that the most economical cycle is the supercritical carbon dioxide (sCO₂) cycle. Such a solution is characterized by the highest efficiency (37%), which is about 10% higher in comparison with the conventional steam power cycle. At the same time, to make a power cycle economically competitive, it is necessary to lower costs related to sCO₂ components by 30-50% (**Fig. 1.24**) [24].

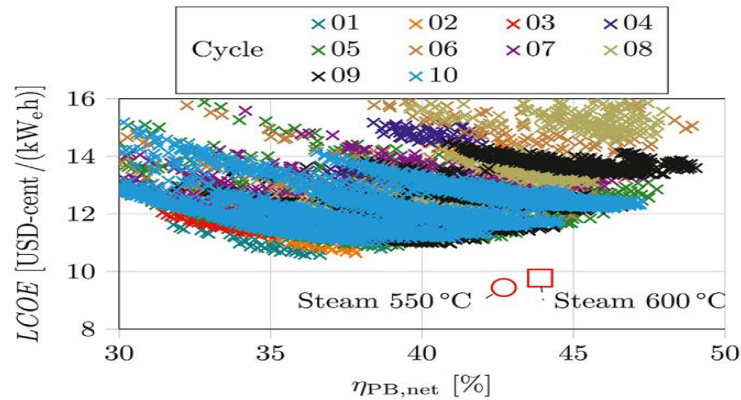


Figure 1-24 : Economic and energetic performance of all simulated variants [24].

Louis F. González-Portillo et al., relying on advanced modeling tools, also concluded that it is possible to attain the LCOE level of 0.056 \$/kWh. This value is lower than the threshold set for Generation III (below \$0.06/kWh). An optimal design includes a tower height of 250 m, thermal storage of 16 hours, and highly absorbent CARBO HSP particles heated to 1073.15 K (**Fig. 1.25**) [25].

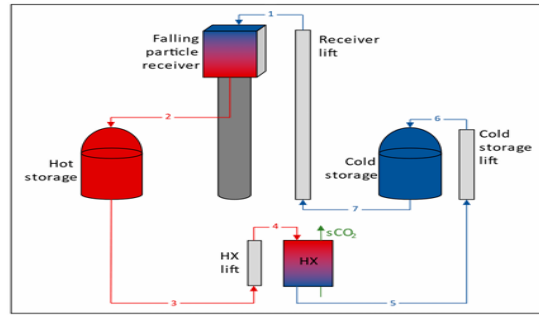


Figure 1-25 : Diagram of particle CSP system coded in EES [25].

Furthermore, the development of optimal models for concentrating solar power peaker plant helped achieve a bid price of only 0.03 \$/kWh. This is through minimizing the size of the system along with lowering the capital cost by 32%. The system uses a tower height of 184 meters and a storage time of 14.68 hours (**Fig. 1.25**) [26].

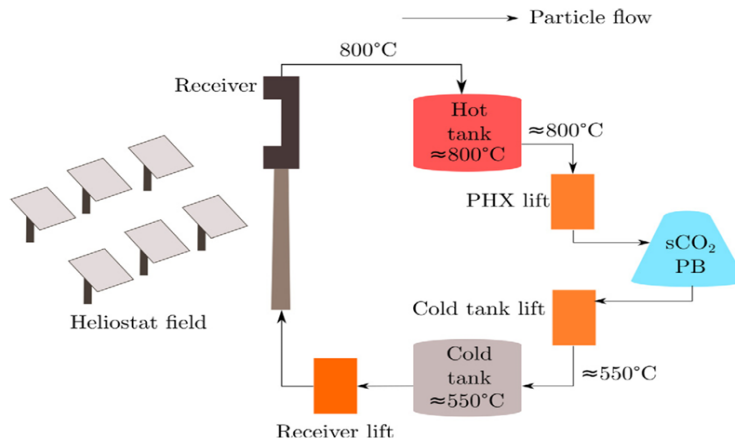


Figure 1-26 : The conceptual system-level model of particle-based CSP plant in SolarTherm [26].

The current research trend involves innovations that seek to minimize the operational cost of electricity and make it simple to operate under very high temperatures above 1073.15 K. They involve studies on particle flow and heat transfer inside the receivers and reactors of solar energy [27].

1.7. Conclusion

Alternatively, studies have shown the importance of environmental factors and material properties on system performance, where researchers have identified external wind as a major challenge resulting in significant convection losses up to 25.4%. Thus, smart recirculation strategies and multi-stage designs have been developed to improve efficiency levels to >90%. The studies show that researchers have been able to reach ambitious economic targets by combining optimised operating parameters such as a 250m tower height and 16-hour storage, and durable, high-absorptivity particles such as CARBO. This implies reducing the levelized cost of energy (LCOE) to approximately \$0.056/kWh, thereby establishing a robust foundation for sustainable, commercial-scale solar power plants .

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CHAPTER 2 . Analysis of 1D Particle receiver model

2.1 Introduction:

Free-falling particle receivers have emerged as a promising technology for next-generation concentrated solar power (CSP) systems due to their ability to operate at high temperatures, enable direct thermal energy storage, and integrate efficiently with advanced power cycles. These advantages make them particularly suitable for high-efficiency and dispatchable solar energy applications.

However, the physical behavior of particle receivers involves complex interactions between radiative heat transfer, particle motion, and convective losses within the cavity. High-fidelity numerical approaches such as CFD and CFD–DEM simulations provide detailed insight into these mechanisms, but their high computational cost limits their use in preliminary design, parametric studies, and system-level optimization.

In this context, reduced-order models, and in particular one-dimensional (1D) formulations, provide an effective alternative by capturing the dominant physical phenomena while significantly reducing computational requirements. When properly calibrated and validated, such models can offer reliable predictions of key performance indicators, including particle temperature evolution, wall temperature, and overall receiver efficiency.

The objective of this chapter is to develop and analyze a 1D optical–thermal model of a free-falling particle receiver. The model integrates recent advances in the characterization of radiative properties of particle curtains and incorporates fitted correlations derived from CFD benchmarking studies. The governing equations for mass, momentum, and energy conservation are formulated and solved using a discretized approach along the falling direction.

Special attention is given to the validation of the model against high-fidelity CFD results, as well as to the identification of the key parameters controlling receiver performance. The outcomes of this chapter provide a solid foundation for subsequent parametric analyses and optimization studies.

2.2. One dimensional model of the particle receiver

The operation of a free-falling particle receiver involves complex interactions between solar radiation, particle motion, and heat transfer processes within the cavity. At the system level, a field of heliostats concentrates solar radiation onto a central receiver, where solid particles are released from the top and fall under gravity, forming a curtain that absorbs the incoming energy. As the particles descend, they are progressively heated through radiative absorption while simultaneously exchanging heat with the surrounding environment and the cavity walls.

To analyze this system efficiently, the physical configuration is simplified into a one-dimensional (1D) model along the falling direction (y), as illustrated in Fig. 2-1. This reduction is based on the assumption that the dominant gradients occur along the vertical direction, while variations in the transverse directions can be neglected in a first approximation. Within this framework, the main physical mechanisms are retained, including solar radiation absorption by the particle curtain, radiative exchange with the back wall, and heat losses to the ambient.

As shown in Fig. 2-1, the real receiver configuration is first translated into a simplified representation where the particle curtain is treated as a continuous medium interacting with an incident radiative flux and a surrounding environment. The governing conservation equations for mass, momentum, and energy are then formulated along the y -coordinate. To solve these equations numerically, the domain is discretized into a finite number of control volumes along the curtain height. In this study, the receiver is divided into 40 sections, while a reduced discretization with 9 sections is illustrated in the figure for clarity. A sensitivity analysis revealed that increasing the number of discretization sections beyond 40 results in negligible changes in the predicted receiver efficiency, with variations below 0.1 percentage points. This confirms that the chosen spatial resolution provides an appropriate balance between computational efficiency and numerical accuracy. Overall, the 1D formulation captures the essential physics of the free-falling particle receiver while significantly reducing computational cost, making it well suited for validation studies, parametric analyses, and subsequent optimization work.

The main objective is to calculate the outlet temperature of the curtain and the thermal efficiency of the receiver. The model follows the same techniques as previous 1D models of particle receivers [1] [2]. The main novelty relies on fitting some specific parameters to adjust

Chapter 2: Analysis of 1D Particle receiver model

the model outputs to agree with results obtained with CFD from Mills et al. [3]. Another significant novelty is the integration of the radiation behavior in particle curtains found in recent investigations [4]

The main equations are described together with the value of the main parameters and the model assumptions. Note that the equations are written in their differential form, but the 1D model solves discrete equations for the different sections. The software Engineering Equation Solver (EES) [5] is used to solve the equations.

The receiver is modeled as a vertically discretized free-falling particle curtain under steady-state conditions. All governing equations are formulated locally along the vertical coordinate y , following the same physical decomposition adopted in recent benchmark studies.

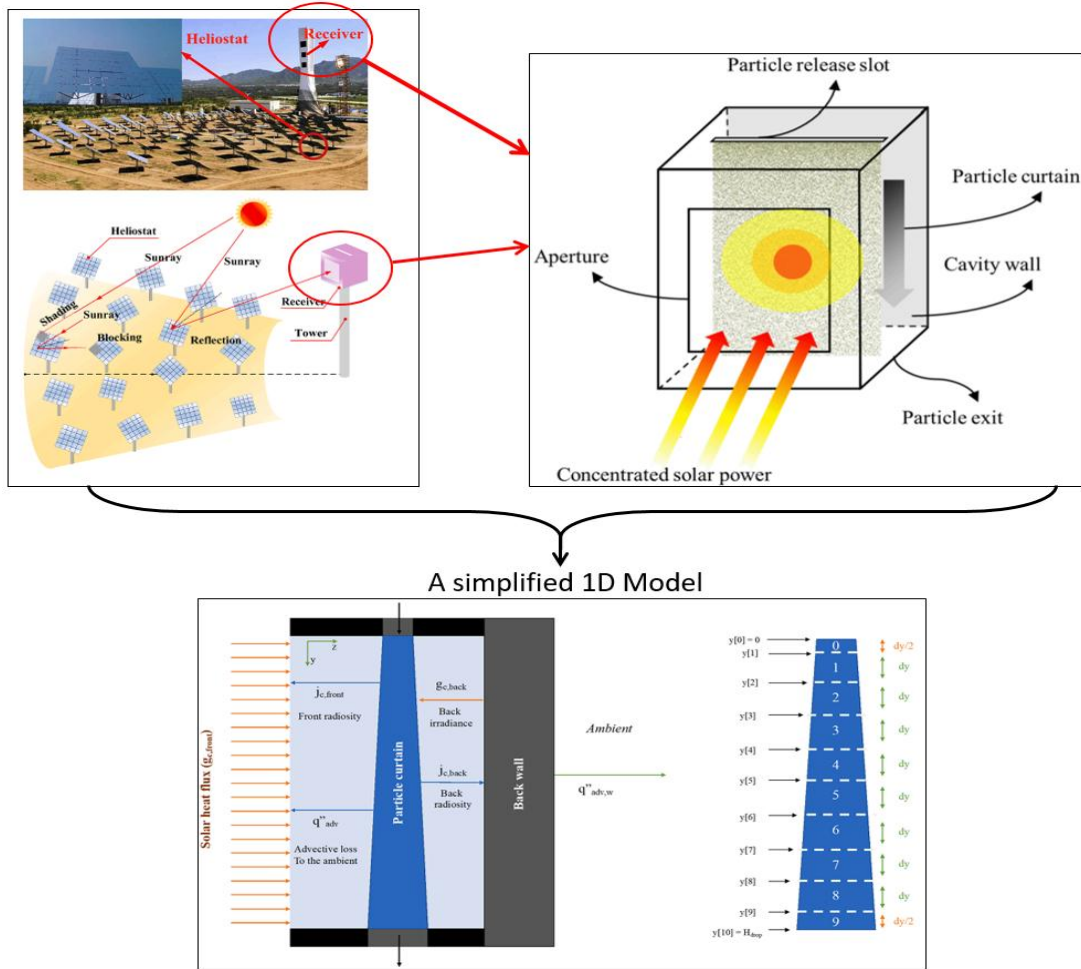


Figure 2-1 : Schematic of the concentrated solar power system and free-falling particle receiver, together with the corresponding simplified 1D model and its spatial discretization (illustrated with 9 sections; 40 sections used in this study) [6].

Chapter 2: Analysis of 1D Particle receiver model

The 1D model's inputs are compiled in **Table 2-1**. While solar radiation, mass flow rate, and aperture area are modified in this study, many of the factors in Table 1 are constants. The beginning conditions for the top of the curtain are the particle inlet temperature and the inlet particle volume fraction.

Table 2-1: Input parameters for the 1D model [6]

Parameter	Value	Reference
Aperture aspect ratio, AR	1	[7]
Back wall emissivity, ϵ_w	0.8	Assumed
Back wall thickness, th_w	0.05 m	Assumed
Back wall conductivity, k_w	$0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	Assumed
Back wall heat transfer coefficient $htc_{cv,w}$	$10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	Assumed
Particle diameter, d_p	$350 \mu\text{m}$	[7]
Particle specific heat capacity, c_p	$1.2 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	[8]
Particle conductivity, k_p	$2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	[8]
Particle density, ρ_p	$3550 \text{ kg}\cdot\text{m}^{-3}$	[8]
Particle absorptivity, α_p	0.9	[4]
Curtain emittance, ϵ_c	0.9	[9]
Ambient temperature, T_{amb}	$20 \text{ }^\circ\text{C}$	Assumed
Solar radiation, q''_{sol}	To be analyzed	—
Mass flow rate, $\dot{m}$	To be analyzed	—
Aperture area, A_{ap}	To be analyzed	—
Particle inlet temperature, $T_p(y=0)$	$615 \text{ }^\circ\text{C}$	[10]
Inletparticle volume fraction, $\phi_p(y=0)$	0.6	[11]

It is possible to get the same level of efficiency from the 1D model as from CFD by using a linear regression model to fit the values of the advection heat transfer coefficient htc_{adv} , the wind factor ψ_{wind} , and the view factor F_{view} . The first step is to change the values of htc_{adv} and F_{view} so that they work when there is no wind. Then, you can adjust the wind factor ψ_{wind} . **Table 2-2** shows the constants that were found for the fit.

Table 2-2 : Coefficients for the 1D model from the CFD fitting [5].

Constant	Value	Constant	Value
A	-12331	F	178.7
B	1.949	G	134.3
C	0.7002	H	27.49
D	0.2370	I	0.9
E	0.0089		

Notes:

- Constants A–C → Nusselt correlation (Eq. 18)
- Constants D–H → wind factor (Eq. 19–20).
- Constant I → view factor F_{view} (Eq. 21).

Table 2-3 sets up a high-power benchmarking environment to test the 1D model's ability to make accurate predictions against high-fidelity CFD simulations. The large aperture and high heat flux work together to simulate solar concentration on a commercial scale. The high mass flow rate keeps the curtain opaque enough to maximise thermal absorption. The simulation isolates the basic ways that heat moves inside the core model by setting the wind speed to zero. This lets us compare the physics of the core model without any outside factors.

Table 2-3 : Simulation conditions for the comparison between 1D and CFD models.[5].

Parameter	Value
Aperture area	144 m ²
Heat flux	1.38 MW·m ⁻²
Mass flow rate	885.5 kg·s ⁻¹
Wind speed	0 m·s ⁻¹
Wind direction	0°

2.3 Governing Equations

Mass Conservation: The particle mass flux along the curtain is defined by the combination of φ_p , th_c , ρ_p , and v_p , its invariance with y denotes a stable regime. Because there is no accumulation, the mass flow rate stays constant throughout the system.

$$-\frac{d(\varphi_p(y)th_c(y)\rho_p v_p(y))}{dy} = 0 \quad (2-1)$$

φ_p : Particle volume fraction.

th_c : Curtain thickness.

ρ_p : Particle densitt.

v_p : Particle velocity.

Momentum Conservation: While acceleration is driven by the gravitational term g , momentum transmission is governed by the velocity v_p . This effect is scaled by the parameters φ_p and th_c , resulting in motion that is solely driven by gravity.

$$-\frac{d(\varphi_p d\varphi_p(y)th_c(y)\rho_p v_p^2(y))}{dy} + \varphi_p(y)th_c(y)\rho_p g = 0 \quad (2-2)$$

g : Gravity.

Energy Conservation of the Particle Curtain: The thermal energy carried by particles is represented by the enthalpy h_p , which changes as a result of radiation exchange between g and j . Convective losses to the surrounding environment are also taken into consideration by the term q_{adv}'' .

$$-\frac{d(\varphi_p d\varphi_p(y)th_c(y)\rho_p v_p(y)h_p(y))}{dy} + g_{c,front}(y) - j_{c,front}(y) + g_{c,back}(y) - j_{c,back}(y) - q_{adv}''(y) = 0 \quad (2-3)$$

h_p : Particle enthalpy.

$g_{c,front}(y)$: Incident Solar Irradiance.

$j_{c,front}(y)$: Front-Side Curtain Radiosity.

$g_{c,back}(y)$: Back-Side Curtain Irradiance.

$j_{c,back}(y)$: Back-Side Curtain Radiosity.

$q''_{adv}(y)$: Advective Heat Loss.

Incident Solar Irradiance: The sun energy received at the front surface is represented by the incident flux q''_{solar} , which warms the particles directly. It is thought to be uniform, giving the curtain a steady temperature input.

$$g_{c,front}(y) = q''_{sol} \quad (2-4)$$

q''_{sol} : Solar heat flux.

Front-Side Curtain Radiosity: While ρ_c and τ_c regulate reflection and transmission, the particle temperature T_p controls emission through ϵ_c . The way radiation is dispersed at the front surface is determined by these optical characteristics.

$$j_{c,front}(y) = F_{view} [\epsilon_c \sigma T_p^4(y) + \rho_c(y, \alpha_p) g_{c,front}(y) + \tau_c(y, \alpha_p) g_{c,back}(y)] \quad (2-5)$$

T_p : particle temperature.

ϵ_c : Curtain emittance.

τ_c :Curtain transmittance.

α_p : Particle absorptivity.

Back-Side Curtain Irradiance: Radiation from the wall, which is determined by its temperature T_w , reaches the particular curtain. A radiative coupling is created between the particles and the wall as a result of this interaction.

$$g_{c,back}(y) = j_w(y) \quad (2-6)$$

j_w :Wall radiosity.

Back-Side Curtain Radiosity: T_p determines the emission, and ρ_c and τ_c control the scattering effects at the back. This controls the cavity's energy redistribution.

$$j_{c,back}(y) = \epsilon_c \sigma T_p^4(y) + \rho_c(y, \alpha_p) g_{c,back}(y) + \tau_c(y, \alpha_p) g_{c,front} \quad (2-7)$$

ϵ_c : Curtain emittance.

σ : Stefan – Boltzmann constant.

T_p : Particle temprature.

ρ_c : Curtain reflectance.

α_p : Particle absopitivity.

The optical properties of the particle curtain (ε_c , ρ_c , τ_c), including reflectance and transmittance, are computed using the analytical model proposed by González-Portillo et al. (2021a). A concise description of this model is provided in the annexes to facilitate understanding.

Curtain Thickness Evolution: Particle dispersion during the fall causes the thickness th_c to grow with y . This expansion influences radiative behavior and changes the local concentration ϕ_P .

$$th_c(y) = th_c(0) + 0.0087y \quad (2-8)$$

Advective Heat Loss from the Curtain: Convective heat transfer is driven by the temperature differential between T_{amb} and T_p . The degree of heat loss to the environment is determined by the coefficient htc_{adv} .

$$q_{adv}''(y) = htc_{adv}(T_p(y) - T_{amb}) \quad (2-9)$$

T_{amb} : Ambient temperature.

htc_{adv} : Advection heat transfer coefficient.

Back-Wall Energy Conservation: As T_w changes along y , the conductivity K_w controls heat diffusion inside the wall. The thermal balance is regulated by q_{cv}'' and radiative exchange via g_w and j_w .

$$\frac{d}{dy} \left(K_w \frac{dT_w(y)}{dy} \right) + g_w(y) - j_w(y) - q_{cv}''(y) = 0 \quad (2-10)$$

K_w : Wall thermal conductivity.

g_w : Wall irradiance.

q_{cv}'' : Convective heat flux.

Back-Wall Irradiance: The emission j_c , returning from the particle curtain, determines the incident radiation g_w . This contact causes the wall to heat up and connects it to particle activity.

$$g_w(y) = j_{c,back}(y) \quad (2-11)$$

Chapter 2: Analysis of 1D Particle receiver model

Back-Wall Radiosity: The amount of radiation that comes from the wall depends on its temperature T_w and emissivity ε_w . Some of the incoming radiation g_w is also reflected, which adds to the total radiosity.

$$j_w(y) = \varepsilon_w \sigma T_w^4(y) + (1 - \varepsilon_w) g_w(y) \quad (2-12)$$

ε_w : Wall emissivity.

T_p : Wall temperature.

Back-Wall Convective Loss: Conduction resistance is determined by the wall thickness (th_w) and conductivity (k_w), while convection is determined by $htc_{cv,w}$. They work together to figure out how much heat is lost because of the difference in temperature with T_{amb} .

$$q_{cv}''(y) = \left(\frac{1}{htc_{cv,w}} + \frac{th_w}{k_w} \right)^{-1} (T_w(y) - T_{amb}) \quad (2-13)$$

$htc_{cv,w}$: Wall convective heat transfer coefficient.

th_w : Back wall thickness.

Inlet Particle Velocity: The speed v_p comes from the force of gravity acting on the height H_0 . This shows that potential energy is being turned into kinetic energy without being lost.

$$v_p(y = 0) = \sqrt{2gH_0} \quad (2-14)$$

H_0 : Effective drop height.

Effective Free-Fall Height: The constant term changes the scaling, and the parameter H_c shows the height of the system. This relationship establishes the effective drop height that affects v_p .

$$H_0 = \frac{H_c}{12} + 0.3 \quad (2-15)$$

H_c : System height.

Particle Mass Flow Rate: The mass flow rate $\dot{m}$ is based on the density ρ_p , the velocity v_p , and the concentration of particles φ_p . The flow is fully defined by the geometric parameters th_c and w_c .

$$\dot{m} = \varphi_p(y = 0) \cdot v_p(y = 0) \cdot th_c(y = 0) \cdot w_c \cdot \rho_p \quad (2-16)$$

$\dot{m}$: Mass flow rate.

w_c : Curtain width.

Advective Heat-Transfer Coefficient: The wind factor Ψ_{wind} changes the base coefficient $htc_{adv,0}$. This shows how airflow from outside helps convective heat transfer.

$$\begin{aligned} htc_{adv} &= htc_{adv}(A_{ap}, T_c, T_{amb}, v_{wind}, \theta_{wind}) \\ &= htc_{adv,0}(A_{ap}, T_c, T_{amb})\Psi_{wind}(A_{ap}, v_{wind}, \theta_{wind}) \end{aligned} \quad (2-17)$$

A_{ap} : Aperture area.

T_c : Average curtain temperature.

v_{wind} : Wind velocity.

θ_{wind} : Wind direction.

Ψ_{wind} : Wind factor.

$htc_{adv,0}$: Base Advection heat transfer coefficient.

Nusselt–Reynolds Correlation: The Reynolds number Re tells you what kind of flow it is, and the constants A , B , and C are based on real-world data. The Nusselt number Nu that comes out of this tells you how strong the convection is.

$$Nu = A + B \times Re^C \quad (2-18)$$

Nu : Nusselt number.

Re : Reynolds number.

A , B , and C : Empirical Nusselt correlation constants.

where A through C are constants to be fitted and Re is the Reynolds calculated with the curtain height as the characteristic length, the velocity at the bottom of the curtain and the average temperature between air and curtain.

Wind Speed Correction: The wind speed v_{wind} , controls how strong the external flow is, and A_{ap} adds geometric effects. Both parameters affect how Ψ_{wind} makes heat losses worse.

$$\Psi_{wind} = 1 + (D - E \cdot \sqrt{A_{ap}}) \cdot v_{wind} \cdot \phi_{wind} \quad (2-19)$$

Wind Direction Correction: The angle θ_{wind} tells you which way the wind is blowing, and the parameters F, G, and H shape the response. This function shows how the direction of something affects convective losses.

$$\phi(\theta_{\text{wind}}) = e^{-\left(\frac{|\theta_{\text{wind}} - F| - G}{H}\right)^2} \quad (2-20)$$

Curtain–Cavity View Factor : The factor F_{view} shows how visible surfaces are from each other in three-dimensional space. It controls how much radiation is exchanged in the cavity.

$$F_{\text{view}} = I \quad (2-21)$$

F_{view} : View factor.

I: Fixed view factor value.

2.4 Conclusions

In this chapter, a comprehensive one-dimensional optical–thermal model for a free-falling particle receiver has been developed and analyzed. The model is based on the conservation equations of mass, momentum, and energy, formulated along the vertical direction and discretized into finite sections to ensure numerical stability and accuracy.

The integration of advanced optical modeling, based on the work of González-Portillo et al., allows the representation of radiative interactions within the particle curtain with improved realism. In addition, the calibration of key parameters such as the advective heat transfer coefficient, wind factor, and view factor through CFD-based fitting enhances the predictive capability of the model.

The validation framework, based on benchmark conditions representative of large-scale CSP operation, demonstrates that the 1D model is able to reproduce the main physical trends observed in high-fidelity simulations. Despite its simplified formulation, the model captures the essential coupling between particle dynamics, radiative heat transfer, and thermal losses.

The discretization analysis confirms that the use of 40 sections provides an appropriate balance between computational efficiency and solution accuracy, with negligible impact on predicted efficiency beyond this resolution.

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Overall, the developed model constitutes a reliable and computationally efficient tool for the analysis of particle receiver performance. It is particularly well suited for parametric studies, sensitivity analyses, and system-level investigations where fast evaluation is required.

Further developments can enhance the accuracy and applicability of the model. In particular, the inclusion of multidimensional effects, such as non-uniform solar flux distributions and lateral particle dispersion, would improve the representation of real receiver conditions. Coupling the model with optical simulations (e.g., ray tracing) would allow the use of realistic flux maps instead of uniform irradiation assumptions.

Additionally, refining the treatment of convective heat transfer, especially under varying wind conditions, and incorporating temperature-dependent material properties would improve prediction accuracy. Finally, the model can be extended toward system-level integration and optimization, including coupling with power cycles and the application of advanced optimization or machine learning techniques to accelerate receiver design.

Appendix A. Optical properties

Curtain Reflectance: The optical properties of transmittance and reflectance depend on the y coordinate because the volume fraction and the thickness of the curtain change along the y coordinate. González-Portillo et al. (2021a) came up with the model that was used in this study to figure out transmittance and reflectance. This is a summary of the model to help you understand the whole 1D receiver model better.

The reflectance is computed as the aggregate of probabilities associated with the reflection of a radiation beam, resulting in:

$$\rho_c = \left(P_B \emptyset_S + \frac{4(P_S \emptyset_S)^2}{\emptyset_S} \left(\frac{1}{1-P_B-2P_S} + \frac{P_B+2P_S}{(1-P_B-2P_S)^2} \right) \right) \frac{1-(1-\emptyset_S)^{2N_l}}{1-(1-\emptyset_S)^2} \quad (2-22)$$

P_B : **B**ackward scattering probability.

P_S : side scattering probability.

$\emptyset_S$: Prjected surface fraction.

N_l : Number of particle layers.

l : Virtual cube side length.

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P_B and P_s are the chances that a radiation beam will bounce back and hit a side, respectively. $\emptyset_s$ is the chance that a beam will hit a particle, and N_l is the number of layers in the curtain. We find the probabilities P_B , P_s , and $\emptyset_s$, which are:

Backward Scattering Probability: Probability of backward reflection when radiation hits a particle.

$$P_B = \frac{1-\alpha_p}{2} \quad (2-23)$$

Side Scattering Probability: Probability of side reflection.

$$P_s = \frac{1-\alpha_p}{8} \quad (2-24)$$

Projected Surface Fraction: Projected particle surface fraction per layer.

$$\emptyset_s = \left(\frac{3}{4}\emptyset_p\sqrt{\pi}\right)^{\frac{2}{3}} \quad (2-25)$$

Number of Particle Layers: The number of layers N_l , is equal to the thickness of the curtain th , divided by the side of a virtual cube that holds one particle l :

$$N_l = \frac{th_c}{l} \quad (2-26)$$

Particle Volume Fraction: The side of this virtual cube l is defined by the following equation, which connects this side to the particle volume fraction $\emptyset_p$ and the particle diameter d_p .

$$\emptyset_p = \frac{\frac{4}{3}\pi(d_p/2)^3}{l^3} \quad (2-27)$$

d_p : Particle diameter.

π : The mathematic constant (≈ 3.14)

The transmittance is calculated as the sum of probabilities that a radiation beam has to be transmitted, which is:

$$\tau_c = \tau_0 + \tau_s + \tau_{BF} \quad (2-28)$$

τ_0 : Direct transmittance.

τ_s : Side scattered transmittance.

τ_{BF} : Combined back – forward transmittance.

Where:

$$\tau_0 = (1 - \varphi_s)^{N_l} \quad (2-29)$$

$$\tau_s = N_l (1 - \varphi_s)^{N_l} \frac{4(P_s \varphi_s)^2}{\varphi_s} \left(\frac{1}{1 - P_B - 2P_s} + \frac{P_B + 2P_s}{(1 - P_B - 2P_s)^2} \right) \quad (2-30)$$

$$\tau_{BF} = \left(P_B \varphi_s + 4 \frac{(P_s \varphi_s)^2}{\varphi_s} \left(\frac{1}{1 - P_B - 2P_s} + \frac{P_B + 2P_s}{(1 - P_B - 2P_s)^2} \right) \right)^2 (1 - \varphi_s)^{N_l} \frac{(1 - \varphi_s)^{2N_l - N_l(1 - \varphi_s)^2 + N_l - 1}}{(\varphi_s^2 - 2\varphi_s)^2} \quad (2-31)$$

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CHAPTER 3 . Results and discussion

3.1 Introduction

Free-falling particle receivers represent a promising technology for next-generation concentrated solar power systems due to their ability to operate at very high temperatures, enable direct thermal energy storage, and integrate efficiently with advanced power cycles such as supercritical CO₂ systems. However, the complex interaction between radiative heat transfer, particle dynamics, and thermal losses makes their analysis challenging.

While high-fidelity numerical approaches such as CFD and CFD–DEM simulations provide detailed insight into the underlying physical mechanisms, their significant computational cost limits their applicability in preliminary design, parametric studies, and system-level optimization. In this context, reduced-order models, and in particular one-dimensional formulations, offer an attractive alternative by providing rapid predictions while retaining the dominant physical behavior.

The objective of this chapter is to evaluate the performance of a one-dimensional particle receiver model through validation and parametric analysis. The model is first validated against reference one-dimensional and CFD results to assess its accuracy. Subsequently, a comprehensive parametric study is conducted to investigate the influence of key operating and design parameters, including mass flow rate, heat flux, particle absorptivity, and particle diameter.

Special attention is given to identifying the operability limits of the receiver and understanding the coupling between optical absorption and thermal losses. The results aim to provide both physical insight and practical guidelines for the design and operation of high-temperature particle receivers.

3.2 Results and discussion

This section presents the performance analysis of the developed one-dimensional particle receiver model under various operating and design conditions. The results are first validated against the reference data to assess the accuracy and reliability of the implementation. Subsequently, a parametric study is conducted to investigate the influence of key variables, including incident heat flux, aperture area, wind conditions, particle absorptivity, and particle diameter, on the receiver efficiency and thermal behavior. The

analysis aims to identify the dominant mechanisms governing performance and to provide physical insight into the coupled radiative and convective processes within the particle curtain.

3.2.1 Model validation

The accuracy of the implemented one-dimensional (1D) particle receiver model is assessed by comparison with the reference results reported in the original study for a representative benchmark case [1]. The selected operating conditions correspond to an aperture area of 144 m², an incident heat flux of 1.38 MW/m², a particle mass flow rate of 885.5 kg/s, and no wind. These conditions are consistent with those used for both the 1D and CFD simulations in the reference work.

3.2.1.1 Local profiles validation

Figures 3-1 to 3-4 present the main local variables predicted by the 1D model along the curtain height, including the incident heat flux, particle temperature, particle velocity, and back-wall temperature distributions. The results are compared with extracted CFD data from the reference study, and quantitative error metrics are evaluated in terms of RMSE and mean relative deviation.

Figure 3-1 shows the incident heat flux distribution. The 1D model predicts a nearly uniform flux of approximately 1.35–1.40 MW/m², consistent with the imposed radiative boundary condition. The comparison with CFD data yields an RMSE of 0.118 MW/m² and a mean relative deviation of 7.85%, indicating good agreement despite the simplified assumption of uniform irradiation.

Figure 3-2 presents the particle temperature evolution. The temperature increases monotonically from about 880 K at the inlet to approximately 1040 K at the outlet, closely following the CFD average profile. The agreement is excellent, with an RMSE of 12.04 K and a relative error of only 1.18%, confirming that the 1D model accurately captures the energy balance along the curtain.

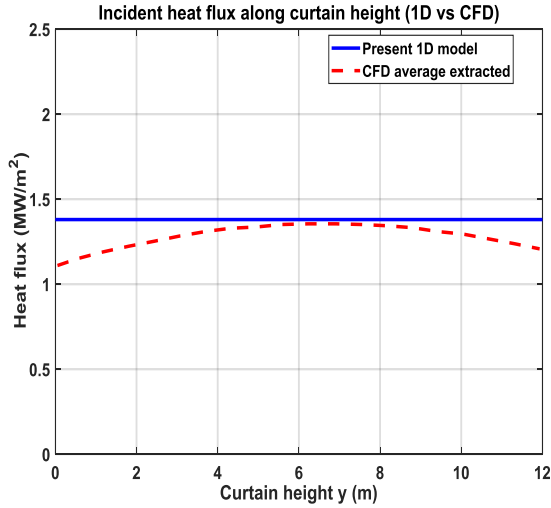


Figure 3-1 : Heat flux distribution for the detailed CFD simulation and the 1D model [1].

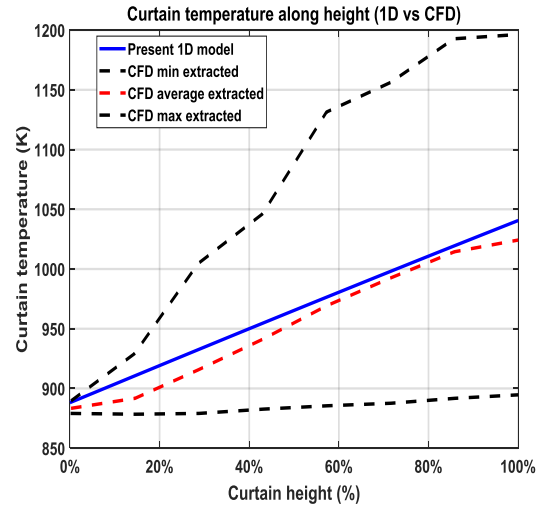


Figure 3-2 : Curtain temperature along the curtain height for CFD and 1D model [1].

Figure 3-3 illustrates the particle velocity profile. The predicted velocity follows the expected free-fall behavior, increasing from approximately 4–5 m/s to 16–17 m/s along the curtain height. The agreement with CFD data is very good, with an RMSE of 0.38 m/s and a relative deviation of 2.97%, demonstrating the reliability of the simplified momentum formulation.

Figure 3-4 shows the back-wall temperature distribution. The wall temperature increases progressively along the curtain height due to radiative exchange with the heated particles, reaching approximately 1020–1030 K at the outlet. The deviation with respect to CFD data is more pronounced, with an RMSE of 99.42 K and a relative error of 9.11%. This discrepancy is attributed to the simplified treatment of radiative and convective heat transfer in the 1D model, particularly the neglect of multidimensional effects and detailed fluid–structure interactions.

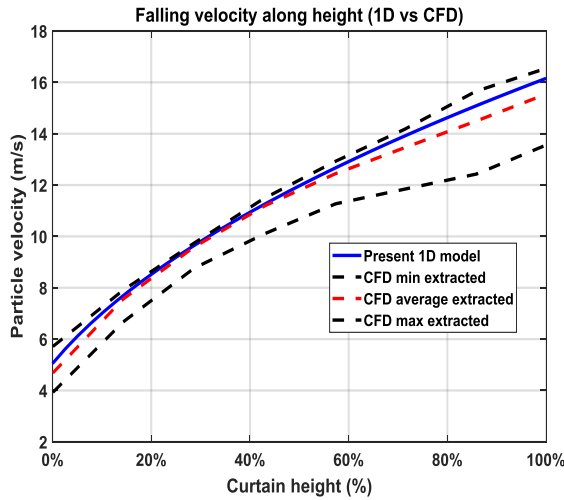


Figure 3-3 : Falling velocity along the curtain height for the CFD and the 1D models [1]

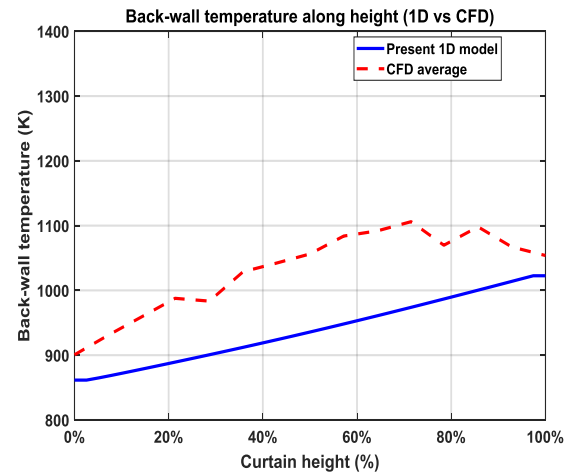


Figure 3-4 : Back wall temperature as a function of curtain height for CFD and 1D model [1].

Overall, the quantitative comparison demonstrates that the 1D model reproduces the dominant physical behavior of the system with good accuracy. The agreement is particularly strong for particle temperature and velocity, while larger deviations are observed for wall temperature due to modeling simplifications. These results confirm that the model provides a reliable and computationally efficient tool for the analysis and preliminary design of particle receivers.

Table 3-1 : Quantitative validation of the 1D model against CFD data (Figs. 3-1,3-4)

Variable	RMSE	Mean relative error (%)	Agreement level
Incident heat flux	0.118 MW/m ²	7.85	Good
Particle temperature	12.04 K	1.18	Excellent
Particle velocity	0.38 m/s	2.97	Very good
Back-wall temperature	99.42 K	9.11	Acceptable

The results summarized in Table 3.1 confirm that the 1D model provides accurate predictions for the main flow and thermal variables, with particularly strong agreement for particle temperature and velocity, while the slightly higher deviation in wall temperature reflects the simplified treatment of heat transfer at the wall. All deviations remain below 10%, which is considered acceptable for reduced-order modeling of high-temperature particle receivers.

3.2.1.2 Global performance validation

To further assess the accuracy of the model, the main global performance indicators are compared with both the 1D and CFD results reported in the reference study. Table 3.2 summarizes the outlet particle temperature, receiver efficiency, and maximum back-wall temperature.

The predicted outlet temperature (1040.6 K) shows a deviation of +1.32% relative to the reference 1D value (1027 K) and remains in very close agreement with the CFD result (1043 K), with a deviation of only -0.23%. Similarly, the receiver efficiency is predicted as 0.8151, corresponding to a deviation of -1.20% compared to the 1D reference (0.825) and -1.68% relative to the CFD result (0.829).

The maximum back-wall temperature is slightly underestimated compared to the 1D model (-0.72%), indicating good agreement in terms of global thermal behavior. However, a larger deviation is observed when compared to the CFD result (-22.35%), where significantly higher peak temperatures are predicted.

This discrepancy is expected and can be attributed to the inherently different modeling approaches. The CFD simulation captures multidimensional effects, including localized radiative flux concentration, non-uniform particle distribution, and complex flow structures, which lead to higher local peak temperatures. In contrast, the present 1D model relies on averaged properties and neglects lateral gradients, resulting in smoother temperature profiles.

Overall, the results demonstrate that the present implementation reproduces the reference 1D model with high accuracy and provides reliable predictions of the global performance metrics of the receiver.

Table 3-2 : Validation against 1D and CFD reference results [1].

Metric	1D	CFD	Present model	Δ vs 1D (%)	Δ vs CFD (%)
Outlet temperature (K)	1027	1043	1046.2	+1.8689	+0.30622
Receiver efficiency	0.825	0.829	0.8451	2.4358	1.9416
Maximum back-wall temperature (K)	1030	1317	1027.7	-0.22292	-21.966

The validation confirms that the simplified assumptions of the 1D model, including the free-fall velocity formulation and the use of averaged thermophysical properties, are sufficient to capture the dominant physical mechanisms governing receiver performance. Despite neglecting multidimensional effects such as lateral heat transfer, particle dispersion, and turbulence, the model provides accurate predictions of both global performance indicators and temperature levels along the receiver height. The observed discrepancies remain within acceptable engineering accuracy and are primarily attributed to numerical discretization, property evaluation methods, and convergence criteria. Therefore, the validated model can be confidently used for parametric studies and optimization analyses, particularly in the context of system-level design and performance assessment.

3.2.2 Parametric analysis of receiver performance

The performance of the particle receiver was investigated through a comprehensive parametric analysis, considering the influence of mass flow rate, incident heat flux, particle absorptivity, and particle diameter. The results are presented in Figs. 3-5,3-8.

3.2.2.1 Influence of Mass Flow Rate

Figure 3-5 illustrates the variation of outlet temperature and receiver efficiency as a function of particle mass flow rate for representative operating conditions.

At low mass flow rates ($\dot{m} < \sim 100$ kg/s), the outlet temperature increases sharply and reaches a maximum of approximately 1573.15–1623.15 °C, indicating strong overheating due to limited thermal capacity. In this regime, the receiver efficiency remains low ($\eta < 0.3$) because a significant portion of the absorbed energy is lost through radiation and convection at elevated temperatures.

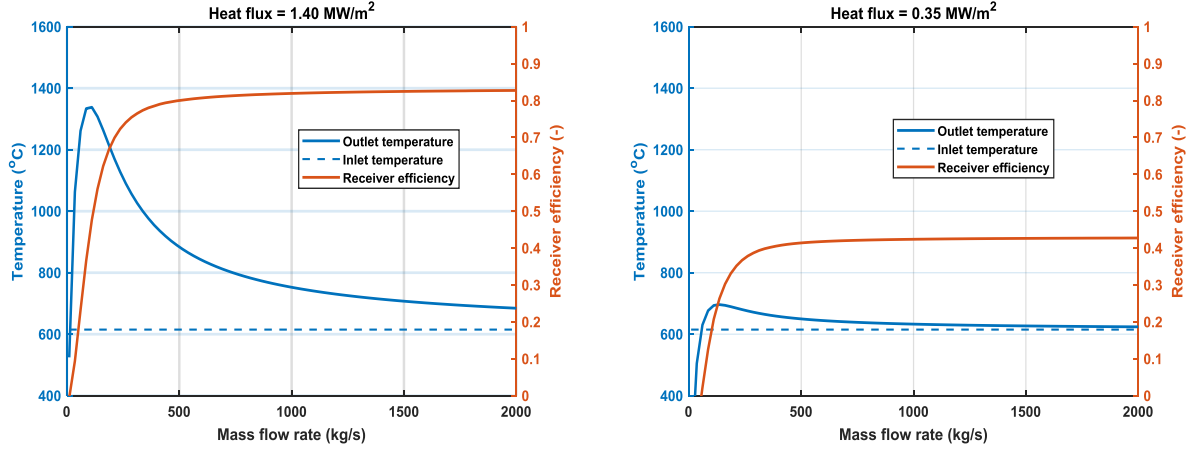


Figure 3-5 : Inlet temperature, outlet temperature and receiver efficiency as a function of mass flow rate for two different heat fluxes. Aperture area =144 m² and no wind conditions.

As the mass flow rate increases, the outlet temperature decreases and approaches the imposed operating level, while efficiency increases rapidly. A transition (knee point) is observed around:

- $\dot{m} \approx 150\text{--}250$ kg/s

Beyond this range, the efficiency stabilizes and reaches asymptotic values of:

- $\eta \approx 0.82\text{--}0.83$ for high heat flux conditions.
- $\eta \approx 0.42\text{--}0.45$ for low heat flux conditions.

This behavior reflects the balance between energy absorption and heat losses and is consistent with classical thermal receiver theory, where increasing mass flow enhances heat extraction and reduces surface temperature, thereby limiting radiative losses. Similar trends have been reported in the literature for particle-based solar receivers, confirming the validity of the present model.

3.2.2.2 Influence of Heat Flux, Aperture Area, and Wind Speed

Figure 3-6 presents the receiver efficiency as a function of incident heat flux for different aperture areas and wind conditions.

A distinct operability threshold is observed for all configurations. Below a critical heat flux, the receiver is unable to reach the imposed outlet temperature (1073 K), resulting in zero efficiency. The threshold values are approximately:

- $q'' \approx 0.48\text{--}0.55 \text{ MW/m}^2$ (no wind)
- $q'' \approx 0.70\text{--}0.82 \text{ MW/m}^2$ ($v = 10 \text{ m/s}$)

The presence of wind significantly shifts the threshold toward higher flux values, with an increase of approximately: $\Delta q'' \approx +0.25\text{--}0.30 \text{ MW/m}^2$

This shift is attributed to enhanced convective heat losses at higher wind speeds.

Above the threshold, the efficiency increases rapidly and then gradually approach an asymptotic regime. At high heat flux ($q'' \approx 2 \text{ MW/m}^2$), the efficiency reaches:

- $\eta \approx 0.88\text{--}0.90$ for $A_{ap} = 25 \text{ m}^2$, $v = 0 \text{ m/s}$
- $\eta \approx 0.84\text{--}0.87$ for larger apertures

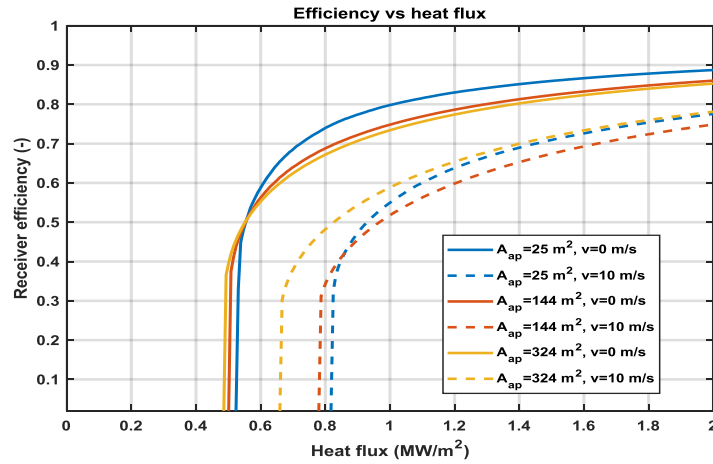


Figure 3-6 : . Receiver efficiency calculated with 1D model as a function of thermal heat flux for different aperture areas and wind velocities (wind direction = 315°).

The influence of aperture area is moderate, with larger apertures exhibiting slightly lower efficiencies due to increased radiative and convective losses. The overall trends, including the existence of a minimum flux threshold and the sensitivity to wind conditions, are in strong agreement with previously reported results for high-temperature solar receivers.

3.2.2.3 Influence of Particle Absorptivity (Fig. 3-7)

Figure 3-7 shows the variation of receiver efficiency as a function of particle absorptivity for different heat flux levels.

At high heat flux (2 MW/m²), the receiver operates over the entire absorptivity range. The efficiency increases monotonically from: $\eta \approx 0.58$ at $\alpha = 0.2$ to $\eta \approx 0.90\text{--}0.91$ at $\alpha = 1.0$

At intermediate heat flux (1 MW/m²), a similar trend is observed, with efficiency increasing from:

- $\eta \approx 0.46$ to $\eta \approx 0.82$

At low heat flux (0.5 MW/m²), a pronounced threshold behavior appears. The receiver becomes operational only above a critical absorptivity:

- $\alpha_{\text{threshold}} \approx 0.57\text{--}0.58$

Below this value, the efficiency is zero, indicating that the absorbed energy is insufficient to overcome thermal losses. Above the threshold, efficiency increases sharply to approximately:

- $\eta \approx 0.33\text{--}0.35$,

and then gradually rises to: $\eta \approx 0.58$ at $\alpha = 1.0$

This non-linear behavior highlights the critical role of optical absorption under low-flux conditions. Such threshold phenomena have been widely reported in the literature and are characteristic of systems operating near the balance between absorbed energy and thermal losses.

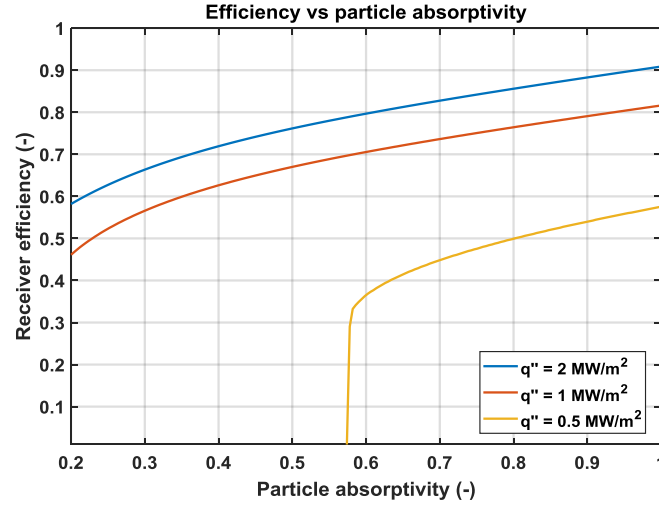


Figure 3-7 : Receiver efficiency calculated with 1D model as a function of particle absorptivity for different heat fluxes. Aperture area = 144 m².

3.2.2.4 Influence of Particle Diameter

Figure 3-8 presents the variation of receiver efficiency and average transmittance as a function of particle diameter. At high heat flux (2 MW/m²), the efficiency remains nearly constant:

- $\eta \approx 0.87\text{--}0.89$

while transmittance remains negligible ($\tau \approx 0$), indicating an optically thick regime. At intermediate heat flux (1 MW/m²), efficiency decreases slightly with increasing diameter:

- $\eta \approx 0.79 \rightarrow 0.78$,

while transmittance remains low ($\tau < 0.05$).

At low heat flux (0.5 MW/m²), a critical diameter is observed: $d_{\text{crit}} \approx 480\text{--}500 \text{ }\mu\text{m}$.

Below this value, efficiency decreases gradually from: $\eta \approx 0.61$ to $\eta \approx 0.36$.

At the critical diameter, a sharp drop to zero efficiency occurs, corresponding to loss of operability. This transition is accompanied by a rapid increase in transmittance: $\tau \approx 0.45\text{--}0.48$.

This behavior indicates a transition from an optically thick to an optically thin regime, where a significant fraction of the incident radiation escapes without being absorbed. Similar

trends have been reported in previous studies on particle receivers, confirming that particle size plays a crucial role in controlling optical thickness and overall efficiency.

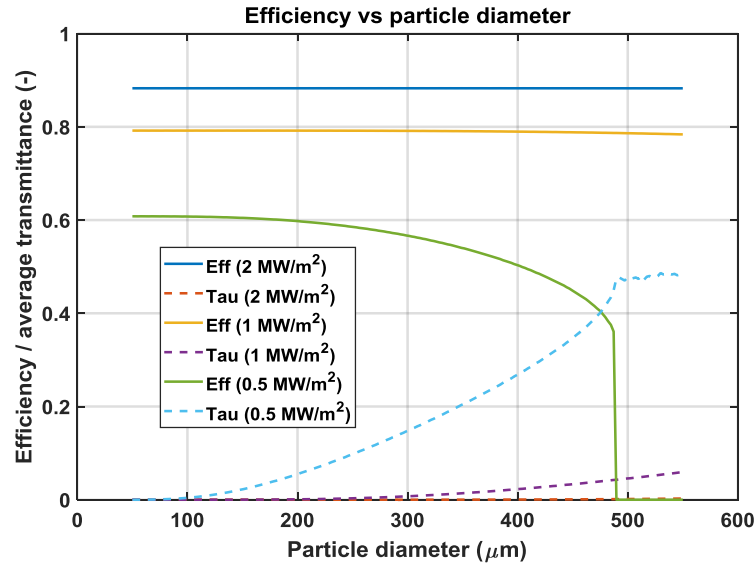


Figure 3-8 : Receiver efficiency calculated with 1D model as a function of particle diameter for different heat fluxes. Aperture area = 144 m²

While Fig. 3-8 analyzes the influence of particle diameter under specific operating conditions, a more comprehensive understanding of receiver performance requires examining the combined effects of incident heat flux and particle absorptivity. This is achieved in Figs. 3-10 and 3-11, where the receiver behavior is mapped under setpoint-controlled operation in a two-dimensional parameter space.

3.2.2.5 Combined Influence of Heat Flux and Particle Absorptivity under Setpoint-Controlled Operation

Figures 3-10 and 3-11 present the receiver behavior under a constant outlet temperature of 1073.15 K, where the particle mass flow rate is dynamically adjusted to satisfy the thermal setpoint. Figure 3-10 shows the resulting efficiency map, while Fig. 3-11 provides the corresponding mass flow rate required to maintain this condition.

A well-defined operability boundary is observed in both figures, located in the low heat flux–low absorptivity region. Below this boundary, the absorbed solar energy is insufficient to reach the imposed temperature, and no feasible mass flow rate exists. The boundary occurs around $q'' \approx 0.5\text{--}0.6$ MW/m² for absorptivity values near $\alpha \approx 0.55\text{--}0.60$, which is consistent with the threshold identified in the one-dimensional analysis.

Above the operability limit, the efficiency increases with both heat flux and absorptivity. At low heat flux, efficiency is highly sensitive to absorptivity, rising from nearly zero to about 0.5–0.6 as α approaches unity at $q'' \approx 0.5 \text{ MW/m}^2$. At higher heat flux levels (above 1.5 MW/m^2), the receiver operates efficiently over the entire absorptivity range, with efficiencies exceeding 0.8 and approaching 0.9 for high absorptivity values. In this regime, the influence of absorptivity becomes less pronounced, as the available solar input dominates thermal losses.

Figure 3-11 reveals the corresponding operational requirement. The mass flow rate increases strongly with heat flux, from approximately 100–200 kg/s near the operability boundary to more than 1000 kg/s at 2 MW/m^2 . At a given heat flux, higher absorptivity allows for higher mass flow rates, as improved absorption enhances the energy transferred to the particles.

The comparison between Figs. 3-10 and 3-11 highlights a key trade-off: regions of high efficiency are associated with high mass flow rates, indicating that optimal performance is achieved by processing a larger particle flow rather than overheating a smaller one. Together, these figures define the feasible and efficient operating domain of the receiver and provide a practical design map linking performance and operational requirements.

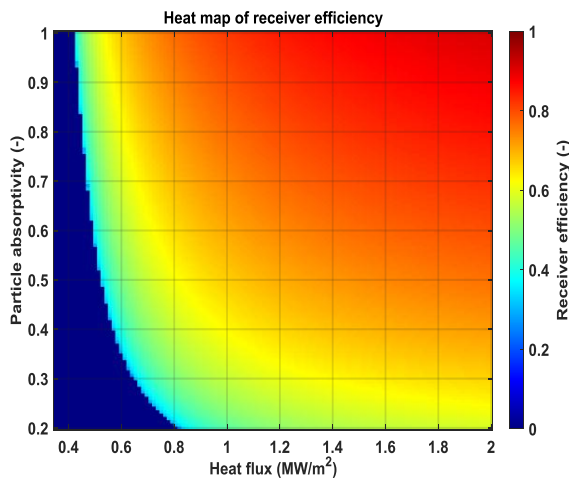


Figure 3-9 : Receiver efficiency map versus heat flux and particle absorptivity at constant outlet temperature (1073.15 K).

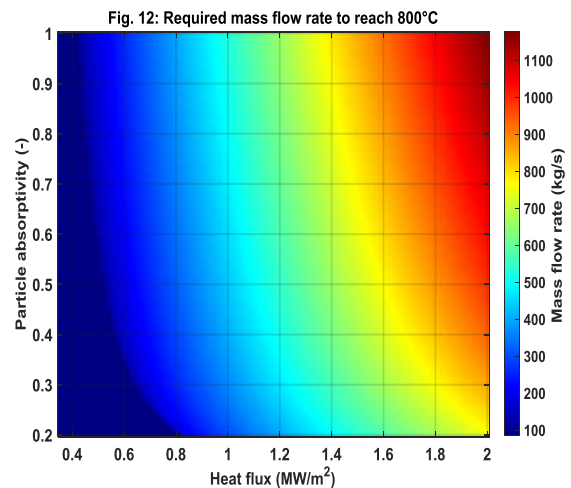


Figure 3-10 : Mass flow rate required to reach 1073.15 K versus heat flux and particle absorptivity.

3.2.2.6 Operability Boundary and Feasible Operating Domain

The operability limits of the receiver are further clarified in Figs. 3-12 and 3-13, where the operability boundary is superimposed on the efficiency and mass flow maps derived from Figs. 3-12 and 3-13. This boundary represents the minimum particle absorptivity required to achieve the imposed outlet temperature of 800 °C for a given incident heat flux, and therefore defines the feasible operating domain of the receiver.

A clear separation between non-operable and operable regions is observed. Below the boundary, corresponding to low heat flux and low absorptivity, the absorbed solar energy is insufficient to satisfy the thermal setpoint, and no feasible solution exists. Above the boundary, the receiver operates successfully, with the particle mass flow rate adapting to maintain the prescribed outlet temperature.

The boundary exhibits a strongly nonlinear behavior. At low heat flux levels, particularly around $q'' \approx 0.5 \text{ MW/m}^2$, relatively high absorptivity values ($\alpha \approx 0.55\text{--}0.60$) are required to sustain operation. As the heat flux increases, the minimum required absorptivity decreases rapidly, reaching values close to $\alpha \approx 0.2\text{--}0.25$ for heat fluxes above 1.5 MW/m^2 . This trend reflects the progressive dominance of the available solar input over radiative and convective losses as the heat flux increases.

The consistency between Figs. 3-12 and 3-13 confirms the robustness of the boundary definition. The same curve separates feasible and infeasible regions in both the efficiency and mass flow representations, demonstrating that the operability limit is an intrinsic property of the receiver energy balance, independent of the chosen performance metric.

From a design perspective, the operability boundary provides a powerful tool for selecting appropriate material and operating conditions. It directly links the required particle optical properties to the available solar flux, and shows that improving particle absorptivity significantly enlarges the feasible operating domain, particularly under low-flux conditions. Conversely, at high heat flux, the system becomes less sensitive to absorptivity, and efficient operation can be achieved even with moderate optical performance.

Overall, Figs. 3-12 and 3-13 synthesize the combined effects of optical absorption, solar input, and thermal constraints into a single design-oriented representation, enabling a clear identification of both the feasible operating region and the optimal performance zone of the receiver.

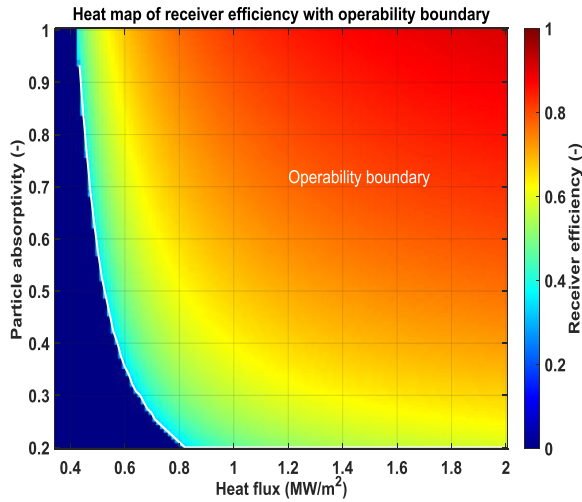


Figure 3-11 : Receiver efficiency map with operability limit (1073.15 K).

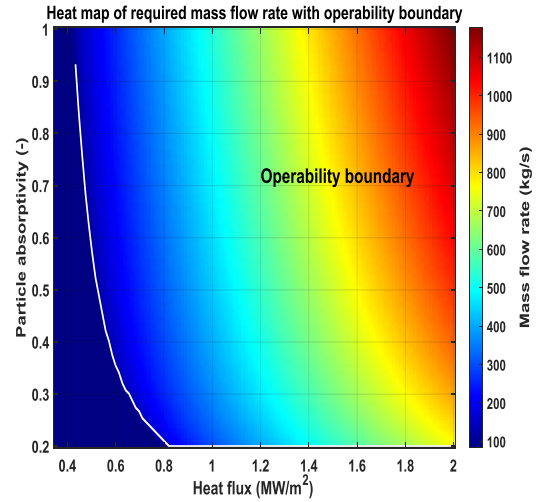


Figure 3-12 : Mass flow map with operability limit (1073.15 K).

3.3 Conclusions

This chapter presented the validation and parametric analysis of a one-dimensional model for a free-falling particle solar receiver. The model demonstrated very good agreement with reference one-dimensional and CFD results, with deviations generally within a few percent for key performance indicators such as outlet temperature and receiver efficiency. This confirms that the simplified formulation captures the dominant physical mechanisms governing receiver behavior while maintaining a significantly lower computational cost.

The parametric study revealed that receiver performance is governed by a strong coupling between thermal and optical effects. The incident heat flux was identified as the primary parameter controlling the operability threshold, with minimum flux levels required to overcome radiative and convective losses. Particle absorptivity plays a critical role in determining the efficiency, particularly near the operability limit, where insufficient absorption leads to complete loss of functionality. Particle diameter was shown to control the

optical thickness of the curtain, with a transition from optically thick to optically thin regimes leading to sharp efficiency degradation.

The analysis under setpoint-controlled operation further highlighted the existence of a well-defined operability boundary, separating feasible and infeasible operating conditions in the heat flux–absorptivity space. This boundary was shown to be independent of the chosen performance metric and represents an intrinsic property of the receiver energy balance. In addition, a clear trade-off was identified between efficiency and mass flow rate, indicating that high-performance operation requires processing larger particle flows rather than increasing particle temperature.

Overall, the results demonstrate that the developed 1D model is a reliable and efficient tool for performance evaluation and preliminary design of particle receivers. The generated parametric maps and operability boundaries provide valuable guidance for selecting suitable operating conditions and material properties, and constitute a solid basis for future optimization and integration studies.

Despite the good agreement with reference results, several extensions can further improve the model and expand its applicability. First, the incorporation of multidimensional effects, such as lateral radiative exchange, particle dispersion, and non-uniform flux distributions, would allow a more accurate representation of real receiver conditions. In particular, coupling the present model with ray-tracing simulations would enable the use of realistic flux maps instead of uniform heat flux assumptions.

Second, the integration of advanced heat transfer mechanisms, including detailed convective correlations and turbulence effects, would improve the prediction of thermal losses, especially under wind conditions. The inclusion of temperature-dependent thermophysical properties and particle size distributions would also enhance model fidelity.

Third, the model can be extended toward system-level integration, including coupling with power cycles (e.g., sCO₂ Brayton cycles) and thermal energy storage systems. This would allow direct evaluation of global performance indicators such as overall efficiency and levelized cost of energy.

Finally, the low computational cost of the present model makes it particularly suitable for optimization and artificial intelligence applications, such as surrogate modeling, machine

learning-assisted design, and multi-objective optimization of receiver geometry and operating conditions. These approaches represent a promising direction for accelerating the design and deployment of high-temperature particle receiver technologies.

References

- [1] González-Portillo, L.F., et al., Benchmark and analysis of a particle receiver 1D model, Solar Energy, 255 (2023) 301–313. <https://doi.org/10.1016/j.solener.2023.03.04>

General Conclusion

General conclusion

falling solid particle receivers (SPR) are an important technology for next-generation concentrating solar power (CSP) systems. They can work at high temperatures over 1073 K and they can store thermal energy directly. They can also work with power cycles like supercritical CO₂. However these systems are complex. Involve a lot of interactions between heat transfer and particle motion. This makes it hard to do fidelity Computational Fluid Dynamics (CFD) simulations without using a lot of computer power. This research wants to develop and analyze a one- 1D) optical–thermal model** that is fast and reliable. It can be used for design and parametric studies.

The study simplifies the receiver's configuration into a 1D model along the vertical falling direction (y). It assumes that the important changes happen vertically. The researchers solved equations for mass, momentum and energy numerically. They divided the domain into 40 sections using Engineering Equation Solver (EES. This balance between accuracy and speed is optimal. The model uses advances in characterizing the optical properties of the particle curtain, like reflectance and transmittance. It also uses correlations derived from CFD benchmarks to adjust the advective heat transfer coefficient and wind factors. The model takes into account the evolution of curtain thickness during the fall and radiative exchange between the curtain, back wall and aperture.

The researchers checked the models accuracy against reference CFD data under operating conditions. The conditions were a heat flux of 1.38 MW/m² and an aperture area of 144 m². The results showed that the model is very accurate. The mean relative error was only 1.18% for particle temperature. 2.97% For falling velocity. The model predicted a thermal efficiency of 84.5% which is very close to complex simulation results. This confirms that the 1D model can capture the physical mechanisms despite its simplifications.

The analysis found a "operability threshold". Under no-wind conditions the receiver needs a heat flux of 0.5 MW/m² to reach the target temperature. If there are winds of 10 m/s the threshold increases to 0.8 MW/m². This is because of increased losses. Particle diameter is an important factor. A critical diameter of 480–500 µm marks the transition from an thick to an optically thin regime. This results in an efficiency drop. Particle absorptivity is also very important. It is the driver of efficiency. Efficiency rises from 0.58 to 0.91 as absorptivity increases from 0.2 to 1.0 under high-flux conditions. Falling solid particle receivers (SPR) are really important, for generation **concentrating solar power (CSP) systems.

General conclusion

This study shows that using one- modeling, which is supported by accurate correlations is a good way to make high-temperature concentrated solar power technologies available faster. This method is also cost efficient. The use of temperature concentrated solar power technologies can help reduce the cost of energy and contribute to global sustainability. Temperature concentrated solar power technologies are important for reducing the Levelized Cost of Energy and achieving global sustainability goal. The study confirms that relying on one- modeling is an effective pathway, for high-temperature concentrated solar power technologi.

General conclusion

Approval for Final Printing of a Master's Dissertation

	Name and Surname	Signature
Examiner 1	Maiz Hadj Ahmed Hamza	
Examiner 2	Harrouz Omar	
Supervisor	Arrif Toufik	

I, the undersigned, Mr: **Pr. Daoudi Bahmed**

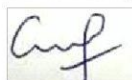
President of the jury for the student(s): **Daoudi Bakir** and **Rehaïem Nour Elhouda**

Field: Physics; **Specialization:** Energy physics and renewable energies

Thesis Title: **One-Dimensional Thermal Modeling of Falling-Particle Solar Receiver**

Hereby authorize the above-mentioned student(s) to print and submit their final manuscript to the department.

President of the jury



Ghardaia : 08/07/2026

Head of the department

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