Systems & Control Transactions

Original Research Article
Peer Reviewed Conference Proceeding
ESCAPE 36 - European Symposium on Computer Aided Process Engineering
Sheffield, UK. 21-24 June 2026

PSE PRESS

Modeling and experimental validation of a flat-conduit dense-phase receiver for concentrated solar power

Mustapha Hamdan[ab], Malak Hamdan[ab], Bogdan Dorneanu[a], and Harvey Arellano-Garcia[a]*

[a] Department of Process and Plant Technology, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany
[b] Heat2X Ltd., London, United Kingdom
* Corresponding Author: arellano@b-tu.de

ABSTRACT

Thermal management and heat transfer optimization remain central challenges in next-generation concentrated solar power (CSP) systems employing solid particles for thermal energy storage and heat transfer. Conventional particle receiver concepts, such as fluidized beds and falling particle curtains are constrained by limited particle-wall contact, flow instabilities, and restricted operating temperature. This work presents a combined computational and experimental investigation of a gravity-driven dense-phase moving packed bed receiver featuring a flat conduit geometry and sub-millimeter particles. A multiphase modeling framework is developed and validated against pressure-drop measurements and particle velocity data obtained from dedicated experimental setups. The validated model is subsequently used to quantify dense-flow stability and thermal performance under indirect heating conditions. Results demonstrate stable dense-phase operation with particle volume fractions of approximately 0.6, leading to enhanced particle-wall transfer. Alumina particles achieve wall-to-particle heat transfer coefficients of up to 2.7 $kW{\cdot}m^{-2}{\cdot}K^{-1}$, more than twice those obtained with silica sand under comparable conditions. The findings indicate that flat-conduit dense-phase receivers provide a mechanically simple and thermally efficient alternative to conventional particle receiver concepts, supporting high-temperature and more efficient CSP systems.

Keywords: Energy Storage, Concentrated Thermal Solar, Computational Fluid Dynamics, Modelling and Simulations

INTRODUCTION

Concentrated solar power (CSP) technologies play a key role in the transition toward dispatchable renewable electricity and high-temperature industrial heat. In contrast to photovoltaic systems, CSP offers the intrinsic advantage of thermal energy storage, enabling decoupling of energy collection and power generation. While molten salt systems dominate current deployments, their operating temperature is limited by freezing, corrosion, and material compatibility [1].

Solid particles have therefore emerged as a promising alternative heat transfer and storage medium due to their thermal stability and ability to operate at temperatures exceeding 1000 K [2]. In addition, particles can simultaneously serve as heat transfer fluid and storage medium, offering the potential for simplified system layouts and higher energy storage density. These advantages have motivated extensive research into particle-based receiver concepts for next-generation CSP plants.

Several particle-based receiver concepts have been proposed, including fluidized beds, falling particle curtains, and mechanically driven systems [3]. Fluidized beds achieve high heat transfer coefficients but require large gas flow rates, increasing parasitic losses [4]. Falling particle receivers suffer from low residence times and sensitivity to flow instabilities [5]. Mechanically driven receivers can enhance residence time but introduce moving parts that reduce reliability and scalability at high temperatures [6].

Dense-phase, gravity-driven moving packed beds offer an attractive alternative by combining high particle packing density with mechanically simple operation. Heat transfer in such systems is dominated by particle-wall contact rather than gas-solid convection, making them particularly suitable for indirect heating configurations.

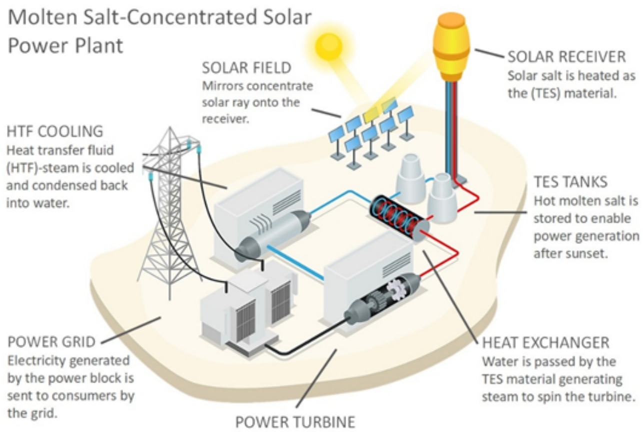


Figure 1. Concentrated solar power (CSP) plant.

Figure 1 illustrates the integration of a particle-based receiver within a CSP system with thermal energy storage (TES). Despite their potential advantages, systematic model-based and experimentally validated studies of dense-phase flat-conduit receiver geometries remain limited.

This work addresses this gap by developing and validating a multiphase modeling framework for a flat-conduit dense-phase particle receiver. The study combines computational fluid dynamics (CFD) modeling with targeted experimental validation to quantify dense-phase flow stability and thermal performance, with particular emphasis on the influence of particle material properties. The results provide insight into the design and operation of mechanically simple, high-performance particle receivers for future CSP applications.

RECEIVER CONCEPT AND OPERATING PRINCIPLE

The investigated receiver consists of a vertical, flat rectangular conduit through which solid particles flow downward under gravity in dense-phase conditions. Heat is supplied indirectly through the receiver wall, representing absorbed solar irradiation transferred to the particles primarily through conduction and contact-based mechanisms. The receiver is intended to operate as part of a particle-based CSP system, where it can be directly coupled to thermal energy storage and high-temperature power conversion units.

As shown schematically in Figure 2, the flat-conduit geometry maximizes particle-wall contact while maintaining a compact and modular design suitable for CSP integration. Unlike fluidized receivers, no external gas flow is required to sustain particle motion. Instead, particles are introduced at the top of the conduit and accelerate under gravity until a balance is reached between gravitational forces, interparticle friction, and wall shear.

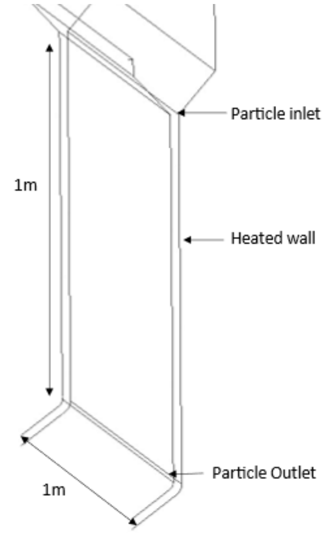


Figure 2. Proposed gravity-driven dense-phase solar receiver with indirect heating configuration.

This balance establishes a stable dense-phase flow regime with high and nearly uniform particle volume fractions across the conduit cross-section.

The flat geometry plays a central role in enhancing heat transfer performance. In dense-phase operation, heat transfer is governed primarily by conductive pathways through the particle network and by repeated particle-wall contact, rather than by convective gas-solid interactions. The planar wall surface increases the effective area available for heat exchange compared to cylindrical or free-falling configurations, while the narrow conduit width limits transverse particle motion and suppresses segregation. As a result, particles experience prolonged and repeated contact with the heated wall over the full receiver height, leading to efficient thermal absorption.

The gravity-driven operating principle further contributes to the robustness and simplicity of the receiver concept. Particle motion is established passively, without mechanical conveyance or fluidization, reducing parasitic energy consumption and mechanical complexity. This passive transport mechanism also decouples hydrodynamic stability from thermal operating conditions, enabling independent adjustment of particle residence time and wall temperature. Such flexibility is particularly advantageous for CSP systems operating under variable solar input, where stable flow behavior is required across a wide range of thermal loads.

MATHEMATICAL FORMULATION

Governing equations

The multiphase flow is modeled using a Eulerian-Eulerian approach [7], in which the gas phase (subscript *g*) and solid particle phase (subscript *s*) are treated as interpenetrating continua. This approach is well suited for dense granular flows, where particle-particle interactions dominate and tracking individual particles becomes computationally prohibitive.

The local volume fraction of phase *k* is denoted by α_k, its density by ρ_k, and its velocity vector by u_k.

The continuity equation for each phase k is written as:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k u_k)$$

Where *t* denotes time and ∇ • is the divergence operator.

The momentum balance for the solid phase is given by:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s u_s) + \nabla \cdot (\alpha_s \rho_s u_s) = -\alpha_s \nabla p + \nabla \cdot \tau_s + \alpha_s \rho_s g + F_{sg}$$

Here, p is the pressure shared by both phases, τ_s represents the solid-phase stress tensor derived from the kinetic theory of granular flow, g is the gravitational acceleration vector, and F_{sg} denotes the interphase momentum exchange force, modeled using the Syamlal-O'Brien correlation [7].

The energy balance for the solid phase is expressed as:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s h_s) + \nabla \cdot (\alpha_s \rho_s u_s h_s) = \nabla \cdot \left(k_{eff} \nabla T_s\right) + h_{ws} A_{ws} (T_w - T_s)$$

Where h_s is the specific enthalpy of the solid phase, T_s and T_w are the solid and wall temperatures, k_{eff} is the effective thermal conductivity of the packed bed, h_{ws} is the wall-to-particle heat transfer coefficient, and A_{ws} is the specific wall-particle contact area.

Wall-to-particle heat transfer is modeled using the Gunn correlation [8], and the effective thermal conductivity of the packed bed is computed using the Zehner-Bauer-Schlünder formulation [9].

Radiative heat transfer is not included explicitly in the present formulation. This assumption is justified by the moderate temperature range considered and by the objective of isolating conductive and contact-based heat transfer mechanisms in dense-phase operation. While radiation is expected to contribute at higher temperatures, its exclusion allows a clearer assessment of material and hydrodynamic effects and does not affect the comparative analysis between particle materials presented in this study.

The mathematical formulation captures the dominant physical mechanisms governing dense-phase flow and heat transfer in the flat-conduit receiver. By combining granular flow theory with established packed-bed heat transfer correlations, the model provides a physically consistent basis for evaluating receiver performance while remaining computationally tractable for parametric studies.

Table 1: Material properties.

Material	Density (kg·m^{-3})	Specific heat capacity (J·kg^{-1}·K^{-1})
Air	1.225	1006
Alumina	3960	1250
Silica sand	2650	755

All simulations are performed using ANSYS Fluent. Transient simulations are performed to capture dense-phase dynamics. Grid-independence and time-step sensitivity analyses are conducted to ensure numerical stability. Indirect heating is imposed via prescribed wall temperature boundary conditions representative of CSP operation. Table 1 summarizes the thermophysical properties of silica sand and alumina particles used in the simulations. Particles had a size of 500 µm.

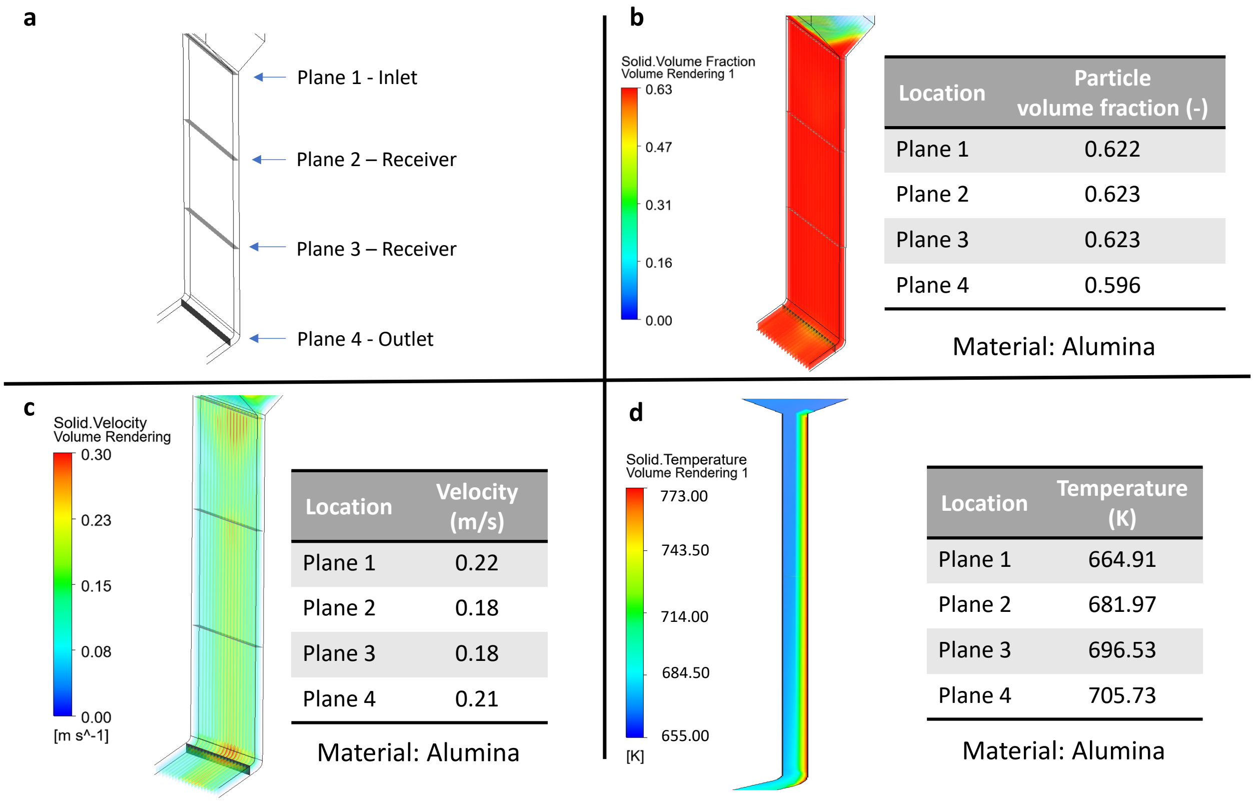
EXPERIMENTAL VALIDATION STRATEGY

The experimental validation strategy is designed to assess the predictive capability of the numerical model under operating conditions representative of gravity-driven dense-phase receiver operation. Rather than attempting full thermal validation at this stage, the focus is placed on validating the hydrodynamic behavior of the particle phase, which is a prerequisite for reliable heat transfer predictions. A transparent flat-conduit receiver prototype is used to obtain particle velocity measurements under controlled operating conditions.

High-speed imaging combined with particle tracking techniques is used to obtain local particle velocities at multiple axial locations along the receiver height. These measurements provide spatially resolved information on particle kinematics, allowing direct comparison with simulated velocity profiles. The experimental setup and measurement planes are shown in Figure 3a.

The validation focuses on particle velocity rather than temperature, as velocity directly governs residence time, particle-wall contact duration, and ultimately heat transfer performance. By ensuring that the model accurately reproduces dense-phase kinematics, confidence is established in its ability to predict thermal behavior when coupled with established heat transfer correlations.

Comparison between experimental and numerical results (Figure 4) shows good agreement, with average relative deviations on the order of 6%. Slight discrepancies are observed near the inlet region, where experimental uncertainties related to particle injection and optical tracking are highest. These deviations do not propagate downstream and do not affect the overall flow regime or residence time distribution.



Location	Particle volume fraction (-)
Plane 1	0.622
Plane 2	0.623
Plane 3	0.623
Plane 4	0.596

Location	Velocity (m/s)
Plane 1	0.22
Plane 2	0.18
Plane 3	0.18
Plane 4	0.21

Location	Temperature (K)
Plane 1	664.91
Plane 2	681.97
Plane 3	696.53
Plane 4	705.73

Figure 3. Simulated results at *t* = 15s showing: a) Measurement points along the receiver; b) Particle volume fractions; c) Particle velocity in the direction of gravity; and d) Particle temperature profile.

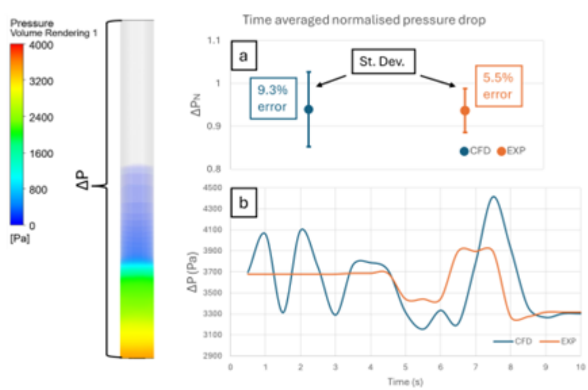


Figure 4. a) Comparison between CFD model (blue) and experimental (orange) results for the normalised bed pressure drop; b) Measurements of the pressure drop comparing experimental and CFD results.

This validation strategy reflects a deliberate modeling hierarchy. Hydrodynamic validation is performed first to confirm correct representation of dense-phase flow behavior. Thermal predictions are then evaluated numerically using well-established correlations for wall-to-particle heat transfer and effective packed-bed conductivity. This approach avoids conflating hydrodynamic modeling errors with uncertainties associated with high-temperature experimentation and radiative heat transfer.

The experimental validation confirms that the numerical framework captures the key dense-phase flow characteristics relevant to flat-conduit receiver operation. The validated model therefore provides a robust basis for assessing thermal performance and for supporting future experimental campaigns at elevated temperatures.

RESULTS AND DISCUSSION

Dense-phase flow characteristics

Simulations of the flat-conduit receiver show stable dense-phase flow with solid volume fractions in the range of 0.62-0.63. As illustrated in Figure 3c, particle velocities remain uniform across the conduit width, with no evidence of channeling or dead zones.

This homogeneous flow structure is a direct consequence of the flat geometry and gravity-driven operation, which promote continuous particle-wall contact and suppress lateral segregation. In contrast to falling particle receivers, where particle dilution and curtain instabilities frequently lead to non-uniform residence times, the dense-phase configuration ensures predictable particle trajectories and well-defined residence times. From a receiver design perspective, this stability is essential for maintaining consistent thermal performance under fluctuating solar input.

Moreover, the absence of localized regions with reduced solid fraction indicates that heat transfer is not limited by intermittent particle contact, which is a common drawback in dilute-phase systems. These results confirm that the proposed flat-conduit configuration provides a robust hydrodynamic basis for indirect particle heating.

Thermal performance and material effects

Temperature fields and absorbed thermal power are summarized in Figure 5. For both particle materials, a clear temperature gradient develops between the heated wall and the particle core, indicating wall-dominated heat transfer under dense-phase conditions. However, alumina particles consistently reach higher temperatures throughout the conduit height compared to silica sand.

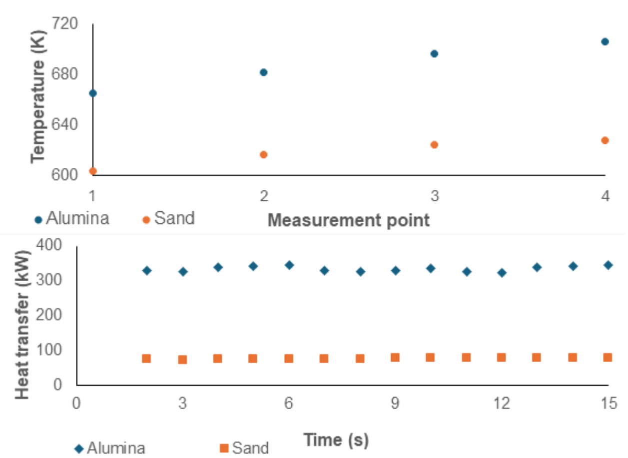


Figure 5. a) Particle temperature measurements at t = 15 s; b) Transient heat transfer rate from the receiver wall, comparing sand an alumina.

This behavior can be attributed to the higher density and thermal conductivity of alumina, which enhance both the effective thermal conductivity of the packed bed and the heat capacity flow rate of the solid phase. As a result, alumina particles are able to absorb and transport more thermal energy for a given residence time.

Quantitatively, alumina particles absorb approximately 334 kW of thermal power at a mass flow rate of 11.7 kg·s^{-1}, whereas silica sand absorbs about 168 kW at 9.5 kg·s^{-1} under identical conditions. These results demonstrate that material selection alone can nearly double thermal performance in dense-phase receivers.

From a system-level perspective, these results suggest that dense-phase receivers offer significant flexibility in performance tuning through material choice, enabling adaptation to different operating temperature ranges or storage requirements without major design modifications.

Wall-to-particle heat transfer coefficients

The resulting wall-to-particle transfer coefficients are shown in Figure 6. Alumina achieves peak values of approximately 2.7 kW·m^{-2}·K^{-1}, while silica sand reaches only 1.2 – 1.4 kW·m^{-2}·K^{-1}.

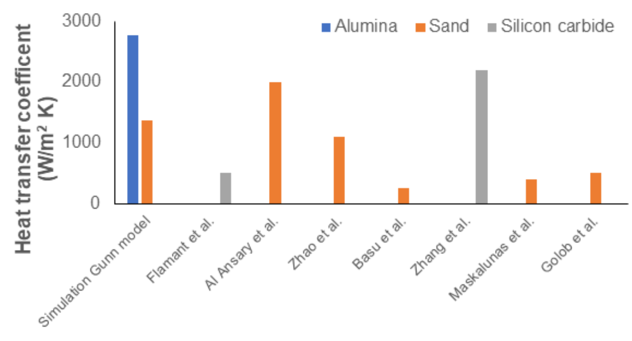


Figure 6. Wall-to-solid heat transfer coefficient from the receiver wall to the gas solid phase, comparing experimental results from literature.

These values compare favorably with experimental data reported in the literature for fluidized and falling particle receivers, while avoiding the need for auxiliary fluidization and its associated parasitic losses. The enhanced heat transfer observed in the dense-phase receiver is primarily driven by sustained particle-wall contact and high packing density, rather than by increased gas-solid convection.

The results also indicate diminishing marginal gains in heat transfer at very high packing densities, where increased particle-particle contact resistance can partially offset improvements in wall contact. This highlights the importance of balancing particle size, material properties, and conduit geometry when designing dense-phase receivers to achieve optimal thermal performance.

The heat transfer coefficients achieved in the present configuration demonstrate that dense-phase flat-conduit receivers can compete with, and in some cases outperform, more complex particle receiver concepts while maintaining mechanical simplicity.

CONCLUSIONS AND OUTLOOK

A flat-conduit dense-phase particle receiver for concentrated solar power applications has been investigated using a combined computational and experimental approach. A multiphase Eulerian-Eulerian model was developed to describe dense-phase hydrodynamics and particle-wall heat transfer and was validated against particle velocity measurements obtained from a transparent receiver prototype. The validation confirms that the model reliably captures gravity-driven dense-phase flow behavior relevant to the proposed receiver concept.

The results show that alumina particles significantly outperform silica sand, achieving wall-to-particle heat transfer coefficients of up to 2.7 $kW \cdot m^{-2} \cdot K^{-1}$ and nearly doubling the absorbed thermal power under comparable operating conditions. These findings underline the critical role of particle material properties in dense-phase receiver performance and demonstrate that substantial efficiency gains can be achieved through material selection alone.

Beyond quantitative performance metrics, the study highlights the advantages of flat-conduit dense-phase receivers in terms of flow stability, predictability of residence time, and mechanical simplicity. These characteristics make the concept particularly attractive for integration with particle-based thermal energy storage systems and high-temperature CSP architectures.

The present work is subject to certain limitations that define its scope. Thermal predictions are based on conductive and contact-dominated heat transfer mechanisms under indirect heating conditions, and radiative heat transfer effects are not considered explicitly. While this assumption is appropriate for the objectives of the current study and enables a clear assessment of material and hydrodynamic effects, it also motivates further investigation at higher temperatures and under direct solar irradiation

Future work will therefore focus on extending the experimental validation to elevated temperature operation, incorporating radiative heat transfer into the numerical framework, and assessing long-term material behavior under cyclic thermal loading. In addition, scale-up studies and modular receiver integration will be investigated to evaluate system-level performance and economic feasibility. Coupling the validated model with optimization and control methodologies will further support the design of robust dense-phase receivers capable of operating under transient solar conditions.

AUTHOR IDENTIFIERS

Hamdan Malak: 0000-0001-8104-4539
Dorneanu B: 0000-0003-3553-6625
Arellano-Garcia H: 0000-0002-8297-0232

REFERENCES

1. Zhang HL, Baeyens J, Degrève J, Cacères G. Concentrated solar power plants: review and design methodology. Renewable and Sustainable Energy Reviews 22:466-481 (2013). https://doi.org/10.1016/j.rser.2013.01.032
2. Fernández AG, Ushak S, Galleguillos H, Pérez FJ. Thermal characterisation of an innovative quaternary molten nitrate mixture for energy storage in CSP plants. Solar Energy Materials and Solar Cells 132:172-177 (2015). https://doi.org/10.1016/j.solmat.2014.08.020
3. Al-Ansary H, El-Leathy A, Al-Suhaibani Z, Jeter S, Sadowski D, Alrished A, Golob M. Experimental study of a sand–air heat exchanger for use with a high-temperature solar gas turbine system. Journal of Solar Energy Engineering 134: (2012). https://doi.org/10.1115/1.4007585
4. Salatino P, Ammendola P, Bareschino P, Chirone R, Solimene R. Improving the thermal performance of fluidized beds for concentrated solar power and thermal energy storage. Powder Technology 290:97-101 (2016). https://doi.org/10.1016/j.powtec.2015.07.036
5. Imran Khan M, Asfand F, Al-Ghamdi SG. Progress in technology advancements for next generation concentrated solar power using solid particle receivers. Sustainable Energy Technologies and Assessments 54:102813 (2022). https://doi.org/10.1016/j.seta.2022.102813
6. Ho CK, Iverson BD. Review of high-temperature central receiver designs for concentrating solar power. Renewable and Sustainable Energy Reviews 29:835-846 (2014). https://doi.org/10.1016/j.rser.2013.08.099
7. Syamlal M, O'Brien TJ. Computer Simulation of Bubbles in a Fluidized Bed. *AIChE Symp Series* 82:22-31 (1989).
8. Gunn DJ. Transfer of heat or mass to particles in fixed and fluidised beds. International Journal of Heat and Mass Transfer 21:467-476 (1978). https://doi.org/10.1016/0017-9310(78)90080-7
9. Tsotsas E, Martin H. Thermal conductivity of packed beds: a review. Chemical Engineering and Processing: Process Intensification 22:19-37 (1987). https://doi.org/10.1016/0255-2701(87)80025-9

© 2026 by the authors. Licensed to PSEcommunity.org and PSE Press. This is an open access article under the creative commons CC-BY-SA licensing terms. Credit must be given to creator and adaptations must be shared under the same terms. See https://creativecommons.org/licenses/by-sa/4.0/