Using Solid Particles as Heat Transfer Fluid-Use in CSP Plants

Cooperative Research and Development Final Report

CRADA Number: CRD-12-00480 (Project 3, Modification 2)

NREL Technical Contact: Zhiwen Ma

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Technical Report
NREL/TP-5700-96587
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Suggested Citation
Ma, Zhiwen. 2025. *Using Solid Particles as Heat Transfer Fluid-Use in CSP Plants: Cooperative Research and Development Final Report, CRADA Number CRD-12-00480 (Project 3, Modification 2).* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-96587. https://www.nrel.gov/docs/fy25osti/96587.pdf.

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Cooperative Research and Development Final Report

Report Date: August 11, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: University of Colorado, Boulder

CRADA Number: CRD-12-00480 (Project 3, Modification 2)

CRADA Title: Using Solid Particles as Heat Transfer Fluid-Use in CSP Plants

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment: No shared resources

Estimated Costs	NREL Shared Resources Government In-Kind
Year 1	$0.00
Year 2	$0.00
Year 3	$0.00
TOTAL	$0.00

Executive Summary of CRADA Work:

NREL assisted the BRIDGE project led by the University of Colorado (CU), Boulder, on developing granular flow and heat transfer simulation tool to serve for an enclosed particle-receiver design. NREL will provide the particle receiver design configuration and operating condition to assist the model setup and may provide certain testing results for model verifications. NREL will attend project reviewing meeting and provide application back-ground including concentrating solar energy technology to collaborate with CU researchers.

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CRADA benefit to DOE, Participant, and US Taxpayer:

- Assisted laboratory in achieving programmatic scope
- Enhanced the laboratory's core competencies
- Used the laboratory's core competencies
    - Enhanced U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.

Summary of Research Results:

Note this report includes only Project 3 (Modification 2) under this CRADA number. Other projects are unrelated and will be published separately.

To achieve the SunShot goal of 6¢/kWh, significant barriers in existing concentrating solar power (CSP) technologies must be overcome. The state-of-the-art in CSP involves the use of salts for thermal energy storage (TES) and as a heat transfer fluid (HTF). NREL has developed a novel CSP system utilizing solid particles for heat storage and transfer exchanger. The critical component in realizing this CSP system was a particle receiver. The BRIDGE project developed modeling tools and guidance in assisting the particle receiver development. In addition, the modeling tool developed had broad usage in chemical and material process designs. NREL tasks focused on providing CSP and particle receiver design configurations to facilitate CU modeling efforts on particle flow and heat transfer. Three main tasks were performed in three phases of the project period of performance as described following.

Task 1. Provide to CU the development background and needs: Project Month One

Task 2. Participate in kickoff meeting and reviewing meeting, Project Month One and ongoing as needed

Participate in kickoff meeting and reviewing meeting, Project Month One and ongoing as needed. This task was successfully completed in support of correctly launching the other 3 main project tasks.

Task 3. Receive report and provide feedback on development needs, according to each DOE reporting period. Project Months 3-36

Provided receiver report and feedback on development needs.

Task 4. May provide testing results for model verification, Ongoing as needed and by Project Month 36

Supported CU particle heat transfer model verification.

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NREL supplied geometric configuration and mild fluidization conditions for CU modeling work to Enhance heat transfer for gas-solid flow within a vertical conduit (references [1-4]). Highlighted results from CU research work and NREL tasks are summarized as below:

When considering multiphase heat transfer in a DEM framework, a wide variety of transport mechanisms arise since each particle is tracked throughout the simulation. For the gas-solid flow in question, these mechanisms include: particle-wall conduction (PW), particle-fluid-wall conduction (PFW), particle-particle conduction (PP), particle-fluid-particle conduction (PFP), fluid-wall convection, and fluid-particle convection. Of these mechanisms, it has been found in previous work with the hexagonal tube array that the PFW mechanism is the dominant mode of heat transfer between gravity driven granular flows and an immersed boundary (the given system) [1]. The physical model implemented to calculate PFW conduction is a minor adaptation of the static fluid lens model developed for PFP conduction by Rong and Horio [2]. The underlying principle of Rong and Horio's model is that each particle is surrounded by an interstitial fluid "lens" that is a fraction of the particle diameter thick. When this lens contacts another body, in this case a wall, conduction occurs through the fluid lens to the particle. A physical illustration of this is given below in Figure 1. *It can therefore be surmised that particles must be extremely close to a wall, within a fluid lens thickness, in order for PFW conduction to occur. Furthermore, conditions which yield high solids concentrations are more likely to have particles near a wall. Ultimately, for systems dominated by PFW conduction, configurations which lead to high solids concentrations (low void fractions) near conducting bodies will result in increased heat transfer.*

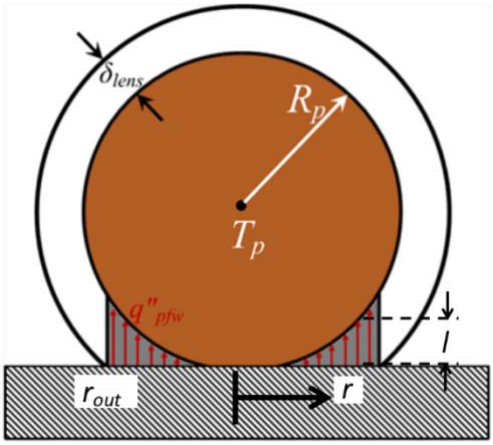

Figure 1. PFW conduction through the interstitial gas between the wall and particle.

Keeping the background information in mind, one would expect the hydrodynamics of a system to strongly impact the heat transfer. In fact, a strong coupling is readily seen when comparing the gas fraction (e.g.) and heat transfer profiles side by side, as seen in Figure 2 for the Baseline Configuration (no baffles). Average heat transfer coefficients were tracked throughout simulations by applying Equation 1 to a given wall every time output data was written for that wall (simulation time strands). The results are shown in Figure 3 below for the Baseline Configuration. From the average heat transfer coefficients, an overall heat transfer coefficient for the Baseline Configuration was found to be $35\left[\frac{W}{m^2K}\right]$, which is well below the Task 1 target of 320 W/m2 K. This was not surprising since the Baseline Configuration contains no means of

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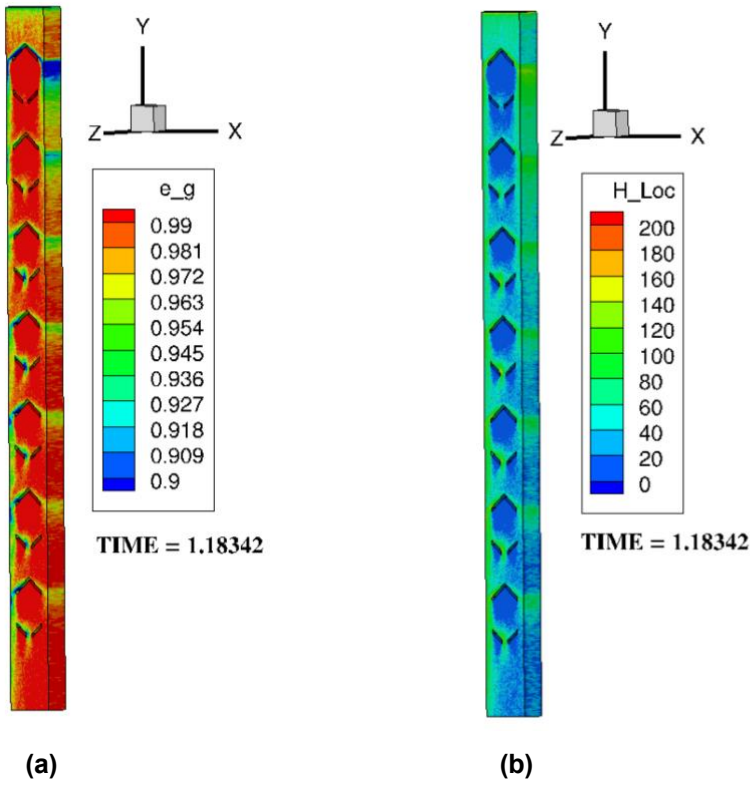
forcing particles into contact with the wall. Furthermore, the Baseline Configuration was not a preliminary design but a standard by which to judge the subsequent designs including baffles and/or fluidization.

The introduction of baffles was initially expected to dramatically increase heat transfer. However, it became apparent that only specific combinations of inlet conditions and baffle configurations would lead to overall heat transfer coefficients on the order of magnitude as the target value. The first baffled system considered, Baffle Configuration 1, consisted of alternating converging and diverging baffles. It had initially been hypothesized that this type of baffle staging would promote particle wall contacts and improve mixing. However, as the hydrodynamics and heat transfer data (Figures 2-4) show below, only modest gains were observed over the Baseline Configuration. An overall system heat transfer coefficient of 78$\left[\frac{W}{m^2K}\right]$ was determined for Baffle Configuration 1.



(a) (b)

Figure 2. Baffle Configuration 1: (a) Gas fraction (e_g) and (b) local heat transfer coefficients (H_Loc).

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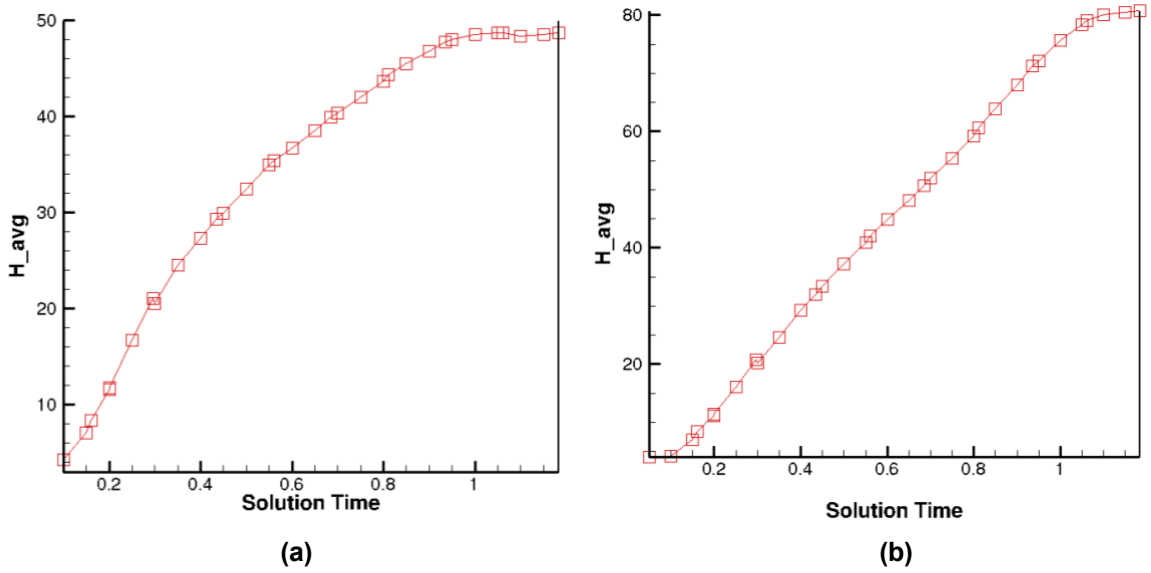

Figure 3. Baffle Configuration 1: (a) The average heat transfer coefficient for the East XY plane wall during the simulation. (b) The average heat transfer coefficient for the West XY plane wall during the simulation.

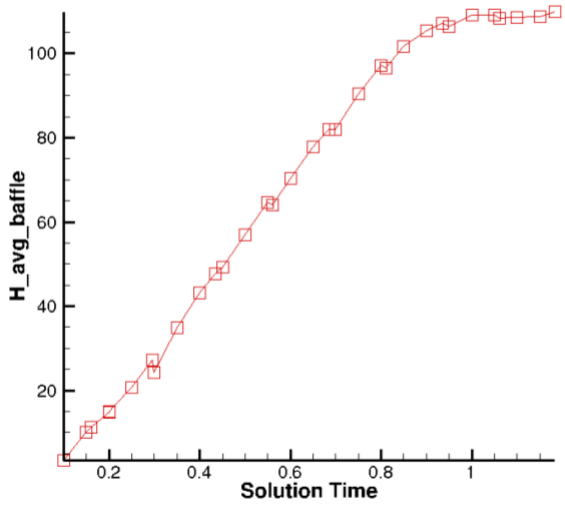

Figure 4. Baffle Configuration 1: The average heat transfer coefficient for all baffles during the simulation.

Close inspection of the hydrodynamic profile for Baffle Configuration 1 (Figure 2(a)) shows that low solids concentrations persist throughout the system and particularly after converging baffles. To avoid regions of high void fraction the particles must be consistently forced into contact with the walls. Therefore, a geometry change was made to remove the converging baffles in lieu of only diverging type baffles. In addition, the vertical spacing between baffles was reduced to maintain more uniform contact. It is also noted, that the decrease in vertical spacing caused an increase in the number cut cells per system height. The boosted cut cell density ultimately forced a reduction of system size in the y-direction, from 1[m] to 15[cm], to avoid overflow of memory on the root processor. The hydrodynamics and heat transfer results for Baffle Configuration 2

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(Figures 5-7) now show significantly more desirable profiles and a bolstering of the overall system heat transfer coefficient to 215$\left[\frac{W}{m^2K}\right]$.

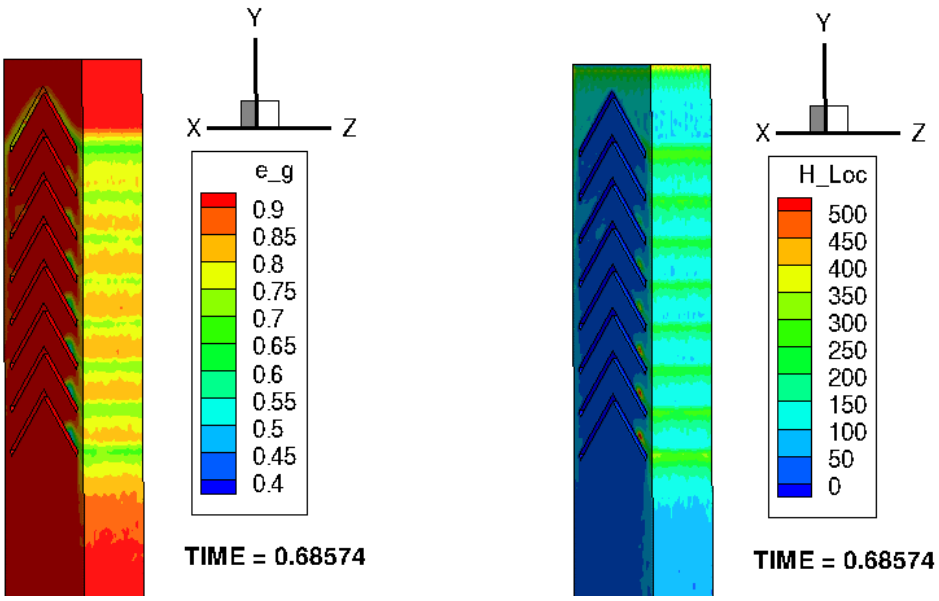

Figure 5. Baffle Configuration 2: (a) Gas fraction (e_g) and (b) local heat transfer coefficients (H_Loc).

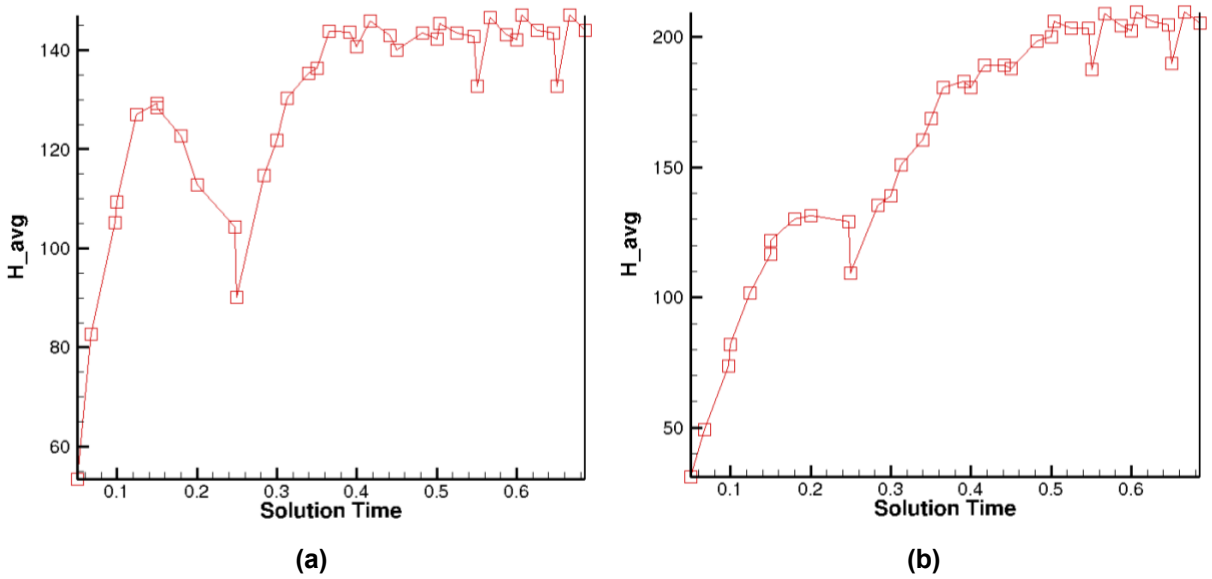

Figure 6. Baffle Configuration 2: (a) The average heat transfer coefficient for the East XY plane wall during the simulation. (b) The average heat transfer coefficient for the West XY plane wall during the simulation.

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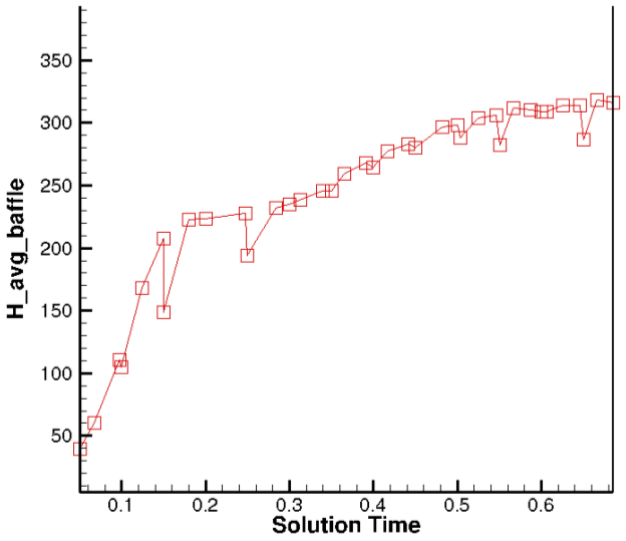

Figure 7. Baffle Configuration 2: The average heat transfer coefficient for all baffles during the simulation.

While Baffle Configuration 2 showed marked improvements over Baffle Configuration 1, it was still believed that solids fractions were too low near boundary walls. From previous work with gravity driven flows, it was known that solids at the inlet of the simulation begin to accelerate under the force of gravity and cause the void fraction to increase exponentially as fall height increases. In addition, void fraction profiles as a function of fall height are strongly related to initial conditions. Therefore, by increasing the solids fraction at the simulation inlet, it was hypothesized that the dilution of particles before contact with the first baffle could be reduced. Hydrodynamic and heat transfer results for this third and best baffle configuration are shown below in Figures 8-10 below. This final compounding of configurational modifications yielded an overall heat transfer coefficient of 601$\left[\frac{W}{m^2K}\right]$. Time averaging of the overall heat transfer coefficient for Baffle Configuration 3 between 0.60000-0.66427[s] led to a time average overall heat transfer coefficient (TAOHTC) of 592, a standard deviation of 14.2, and a sample size of 6. From Equation 3, it follows that, with 95% confidence, the TAOHTC is statistically greater than 400 ($-11.7 < 192$). Furthermore, by altering the target value to force the left side of Equation 3 equal to the right side of Equation 3 an upper bound for the TAOHTC can be found, which is 603$\left[\frac{W}{m^2K}\right]$.

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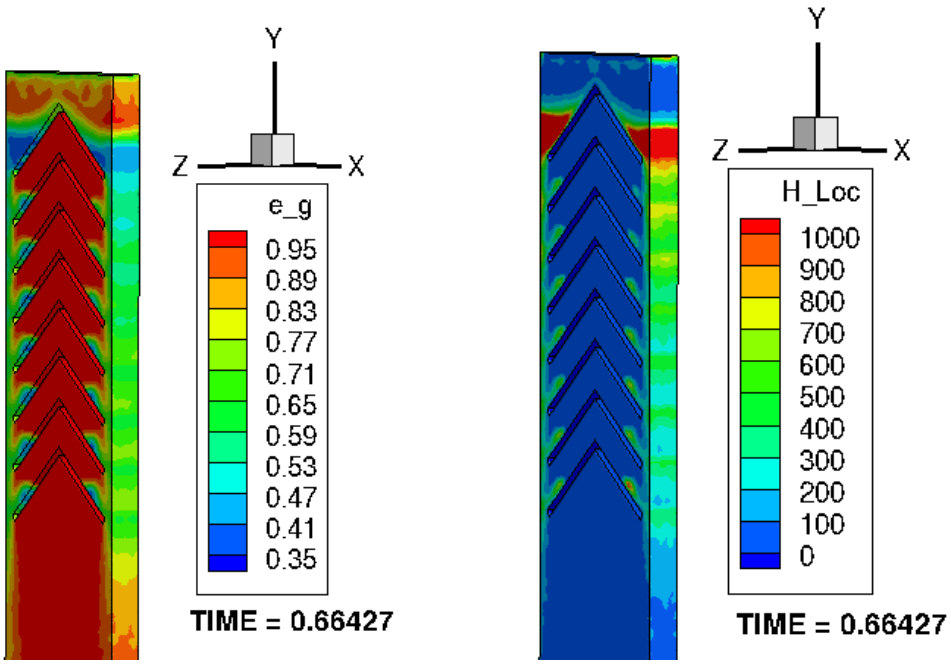
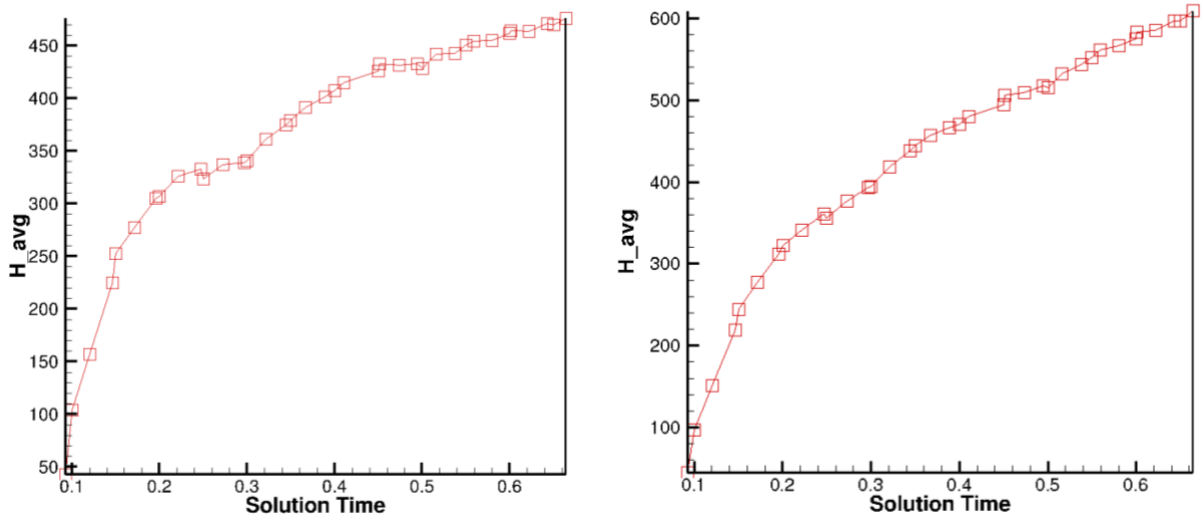


(a) (b)

Figure 8. Baffle Configuration 3: (a) Gas fraction (e_g) and (b) local heat transfer coefficients (H_Loc).



(a) (b)

Figure 9. Baffle Configuration 3: (a) The average heat transfer coefficient for the East XY plane wall during the simulation. (b) The average heat transfer coefficient for the West XY plane wall during the simulation.

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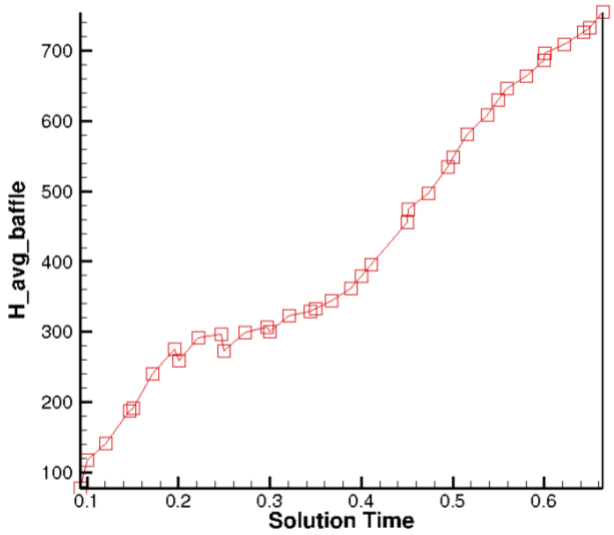

Figure 10. Baffle Configuration 3: The average heat transfer coefficient for all baffles during the simulation.

The effect of baffle apex angle upon the system heat transfer coefficient was explored once a new baseline had been developed (Configuration 3 above). It should be noted that while the baffles significantly contribute to the heat transfer in the simulations, they are not the intended main source of heat transfer in the real system. Therefore, the focus for enhancing heat transfer should be placed upon the domain walls and not the baffles. *When altering the baffle apex angle it was found that the heat transfer with the domain walls was not a strong function of apex angle, but that the heat transfer with the baffles was.* Specifically, that more obtuse baffle angles led to higher baffle heat transfer coefficients due to enhanced particle-baffle contacts.

References:

[1] Morris, A., Hrenya, C., Ma, Z., Pannala, S., & O'Brien, T. (2015). Discrete element and continuum heat transfer simulations of a solar receiver that uses solid particles as a heat transfer fluid. Nuclear Engineering Division 2015 - Core Programming Area at the 2015 AIChE Annual Meeting.

[2] Morris, A. B., Pannala, S., Ma, Z., & Hrenya, C. M. (2016). Development of soft-sphere contact models for thermal heat conduction in granular flows. AIChE Journal, 62(12). https://doi.org/10.1002/aic.15331.

[3] Morris, A. B., Pannala, S., Ma, Z., & Hrenya, C. M. (2015). A conductive heat transfer model for particle flows over immersed surfaces. International Journal of Heat and Mass Transfer, 89, 1277–1289. https://doi.org/10.1016/j.ijheatmasstransfer.2015.06.004.

[4] Morris, A. B., Ma, Z., Pannala, S., & Hrenya, C. M. (2016). Simulations of heat transfer to solid particles flowing through an array of heated tubes. Solar Energy, 130((2016)), 101–115. https://doi.org/10.1016/j.solener.2016.01.033

Subject Inventions Listing: None.

ROI #: None.

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