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# Design and Testing of a Recirculating Dust Filtration Loop for High-Temperature Particle Receivers

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**Abstract.** Generation 3 particle-base concentrating solar power (CSP) systems utilize solid media in the form of absorptive, sand-like particles as the heat-transfer fluid and thermal-energy-storage medium to increase the maximum operating temperature of CSP technology to over 800°C. The particles fall as a curtain through an open aperture receiver cavity to directly absorb thermal energy from the concentrated solar flux. Abrasion due to particle-to-particle and particle-to-surface interaction within particle based CSP systems creates dust that escapes through the receiver aperture. The dust present in the receiver cavity may result in beam attenuation and mass loss decreasing the efficiency of the receiver. A design for a dust removal loop is presented with preliminary testing demonstrating its ability to reduce the dust present in a 1 $MW_{th}$ FPR with an 8 kg/s mass flow rate. The particle dust removal loop reduced the mass of particle dust present in the receiver by 46% compared to steady operation with ambient temperature particles.

## INTRODUCTION

Generation 3 particle-based concentrating solar power (CSP) system utilize absorptive sand-like particles as the heat transfer fluid (HTF) and thermal energy storage (TES) medium to achieve temperatures in excess of 800°C for the use in a more efficient $sCO_2$ Brayton cycle. The increased thermal to electric efficiency made possible by the higher system operating temperature assists in decreasing the levelized cost of energy (LCOE) produced by CSP systems [1]. Sintered bauxite particles, often utilized in particle-based CSP, fall by gravity through an open aperture cavity receiver to directly absorb thermal energy from the concentrated solar flux [2]. Particle dust created through cyclic abrasion and wear as the particles recirculate through the system can escape from the open cavity receiver [3]. Recent studies have shown that particle dust does not pose a significant health or environmental risk in the area surrounding the FPR [4], but reducing dust emissions is desirable from a receiver efficiency perspective as the particle dust present in the receiver cavity may cause flux attenuation and mass loss.

The design of a particle dust removal system attached to the particle feed duct above the cavity receiver is evaluated, and findings of a dust removal study conducted with the National Solar Thermal Test Facility's 1 $MW_{th}$ prototype FPR located at Sandia National Labs are presented. These studies will inform the design of a dust removal loop for the recently awarded Generation 3 Particle Pilot Plant (G3P3)[5].

## DUST REMOVAL LOOP DESIGN

To remove the particle dust generated in FPR systems, a counterflow of air is introduced into the headspace of the duct conveying the particles from the particle elevator to the top hopper above the receiver, Figure 1. The air entrains the particle dust transporting it to a dust removal section before being reintroduced to the lower section of the duct. The recirculating design of the dust removal section ensures that the heat removed from the particles by the counterflowing air is maintained within the system as venting the dust laden air would result in parasitic heat loss. Particle temperatures of up to 650 °C are expected in the duct, limiting the filtration options available. A stainless-steel cyclonic separator is being considered that features a static assembly without moving parts allowing a 75% filtration efficiency of 1-5 μm particles and a 98% filtration efficiency of >5 μm particles at temperatures in excess of 700°C. The cyclonic separator can be used either independently or as a primary dust removal device extending the life of a secondary high efficiency, high temperature filter downstream of the separator.

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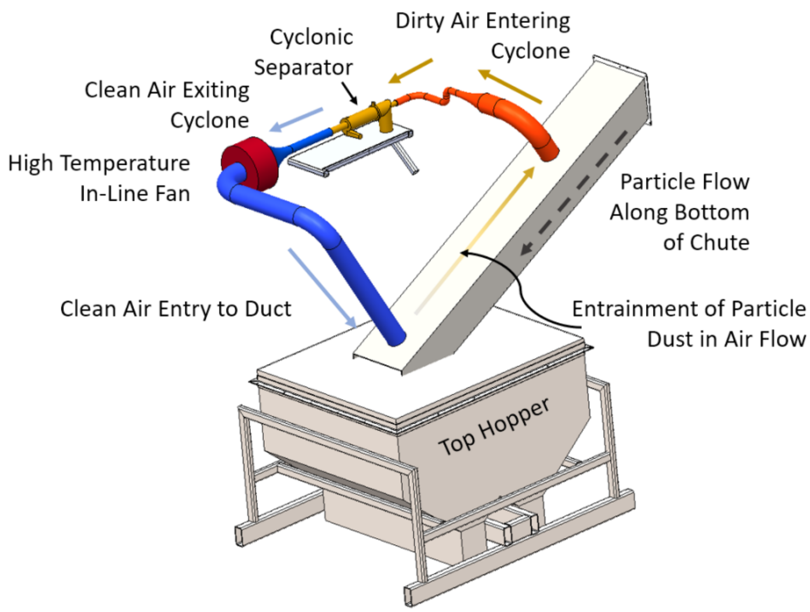


**FIGURE 1**. Particle dust removal loop design consisting of the particle duct, cyclonic separator, and high temperature fan.

## METHODOLOGY

An experimental study utilizing a single pass open-loop design was conducted with the 1 $MW_{th}$ falling particle receiver apparatus. A 3 m (10-ft) long pipe section extending from the particle elevator to the top hopper, shown in Figure 2, was used to test the counterflow dust collection technique. In this pipe section, ambient temperature particles flowed from a 17 cm diameter pipe to a 25 cm diameter pipe. Ambient temperature air was introduced into the pipe via a 15 cm diameter tube with a 2.2 kW blower near the particle outlet at the bottom of the pipe providing a measured 150 CFM of air flow. The air traveled upward counter to the gravity-driven particle flow to entrain particle dust and vent it to atmosphere through another 15 cm diameter tube near the particle inlet. The particle inlet corresponds to the top of the duct connected to the particle elevator. Particles flowed along the bottom of the pipe at a flow rate of 8.5 kg/s corresponding to 1/3 of the pipe volume in the 17 cm diameter section.

Three tests were conducted. The first experiment featured Anderson (Mark III) impactors which measured the mass concentration of .4-21 µm particles in three locations: the particle inlet, particle outlet, and cavity receiver. The air outlet can be seen below the particle inlet and air inlet can be seen above the particle outlet in Figure 2. The particle dust concentration was documented with the blower on and the blower off for 1-hour intervals each, to determine the difference in particulate mass

The second and third experiment feature an Aerodynamic Particle Sizer (APS) measuring the concentration of .5-20 µm particles within the receiver cavity alone. The dust removal configuration used in the first experiment was also used in the second and third experiments. Particulate concentration within the cavity receiver was documented with and without dust removal over three 30 minute on/off intervals. Following the on/off testing, the dust ventilation system continuously removed particle dust for a 2.5-hour period over which the particle concentration within the cavity receiver was continuously measured.

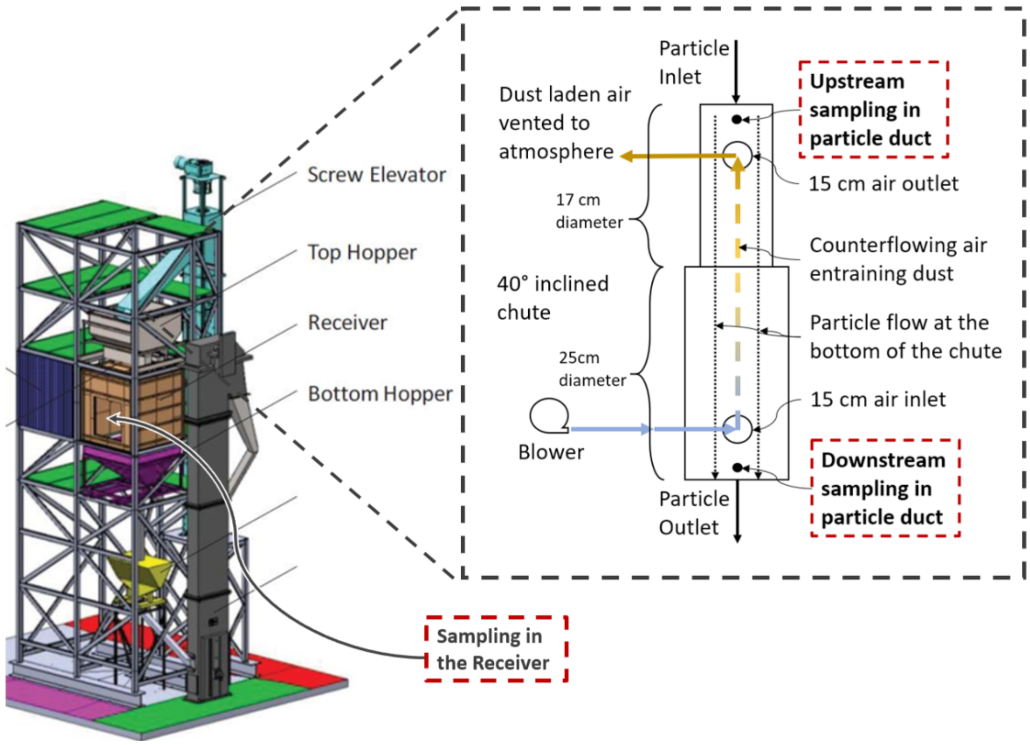


**FIGURE 2.** Falling particle receiver system (Left) with dust removal system blowout (Right) and cascade impactor sampling locations

## INSTRUMENTATION

Two particle sampling probes were used in this study, the Anderson (Mark III) impactor and the Aerodynamic Particle Sizer (APS), detailed below. The Anderson Impactors continuously capture particle dust to determine the total particulate mass gathered over a given collection interval. Gravimetric analysis of the dust collected within the impactor provides a single discrete measurement of the average particulate mass gathered at the probe location during the measurement interval. The APS continuously measures the particulate concentration in 10 second sampling intervals providing a continuous measurement of the particle dust present.

### Anderson (Mark III) Impactor

The Anderson (Mark III) impactor is an eight stage, multi-jet cascade impactor, designed to measure aerodynamic particle size distributions from 0.4 to 21 microns at a nominal flow rate of 14 liters per minute. The impactor is constructed of 316 stainless steel with glass fiber substrate collection media, which can withstand temperatures of 815 °C and 500 °C, respectively. During operation, particulates enter the inlet cone and cascade through eight successive orifice stages each with higher orifice velocities. As particles flow through each stage, successively smaller particles are inertially impacted onto the collection plates. Remaining submicron particles (<0.4 μm) are collected with a 50 mm backup filter. For the recirculating dust removal loop study, the cascade impactors were place in various locations along the chute and receiver, shown in Figure 3. The impactors were run for approximately 1-hour per location to collect enough material to gravitationally measure for post-analysis.

**FIGURE 3.** Anderson impactors at various locations during the first dust removal study: Top of chute/before dust removal loop (Left), bottom of chute/after dust removal loop (Middle), receiver (Right) with the particle flow direction shown by the black dotted lines and the air flow direction shown by the solid blue lines.

## TSI Aerodynamic Particle Sizer (Model 3321)

In a second study, a TSI Aerodynamic Particle Sizer (APS, Model 3321) was used in combination with a TSI Diluter (Model 3302A) for real-time measurements inside the receiver cavity. The instrument measured aerodynamic diameters from 0.5 to 20 µm at a sampling air flow rate of approximately 5 ± 0.2 LPM and used time-of-flight particle sizing technology. Time-of-flight (ToF) is a method that measures average particle velocity between a timing zone with two narrowly focused laser beams. For this to work, a larger/heavier particle will lag behind the air and will have a lower velocity in the timing zone. The magnitude of this lag, along with a suitable calibration, determines the aerodynamic particle diameter[6]. A diluter was necessary in this study to reduce total particulate concentration in order for the APS to accurately measure particle size. The diluter caused some loss in particulates larger than 10 µm in diameter; however, particulate sizes in that range were not the dominating particulates in the chute or receiver, so the reduction in measurement accuracy was likely minimal. The diluter was used at a dilution ratio of 20:1, which was based on a calibrated pressure drop across a laminar-flow capillary tube. The APS program used the efficiency curve, generated by the manufacturer, to back calculate total concentration and particle size, Figure 4.

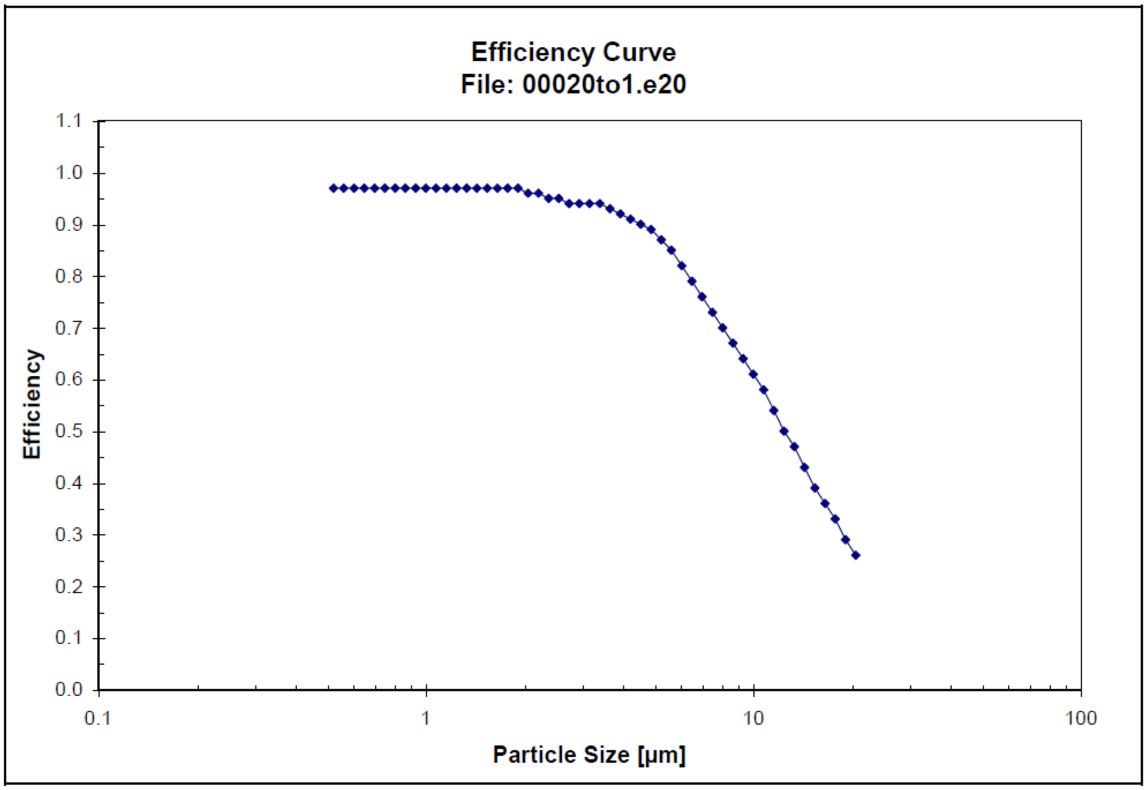


**FIGURE 4.** TSI Diluter Efficiency Curve at a Dilution Ratio of 20:1

## RESULTS

The first test, featuring the Anderson impactor particle sampling probes, measured the difference in the average particulate mass present in the receiver and upstream and downstream of the dust filtration loop between two 1-hour sampling intervals. The dust removal loop was activated during the first interval and deactivated in the second. Figure 5 depicts the total particulate mass gathered during each interval for the downstream, upstream, and receiver probes (the downstream particulate mass with dust removal is present but not visible). The mass of particulate was reduced by 99% at the downstream probe, 96% at the upstream probe, and 21% in the receiver while the dust removal loop was active. The upstream probe likely experienced a reduction in particulate mass due to air passing the dust exhaust port and escaping through the particle elevator providing "clean air" to the probe. The less substantial drop in the particulate mass in the receiver compared to the upstream and downstream probes may be due to the presence of the top hopper between the receiver and the dust removal loop which potentially reintroduced particle dust or generated dust through particle abrasion. This suggests that the particle dust removal loop should be positioned as close to the receiver as possible to prevent the re-entrainment of dust into the particles. The APS was used to measure the particle concentration in the receiver for the remaining experiments.

The correlation between the concentration of dust in the receiver and the status of the dust removal loop was determined through the continuous measurement of the receiver dust concentration while the dust removal loop was cycled on and off. Figure 6 shows the particle dust concentration as a function of time with the state of the dust removal loop delineated by the vertical dashed lines. Particles were circulated in the system for 1 hour prior to the cycling of the dust removal loop to provide a baseline concentration measurement and ensure the dust present was independent of startup effects. In the hour prior to the dust removal loop's activation the concentration of dust in the receiver was relatively constant followed by a decline in concentration during subsequent periods of active dust removal. For periods between active dust removal, with the counterflowing air switched off, the concentration of dust increased. The correlation between the decrease in particle dust concentration and presence of active dust removal provides confidence that the dust removal has a direct effect on the dust present in the receiver.

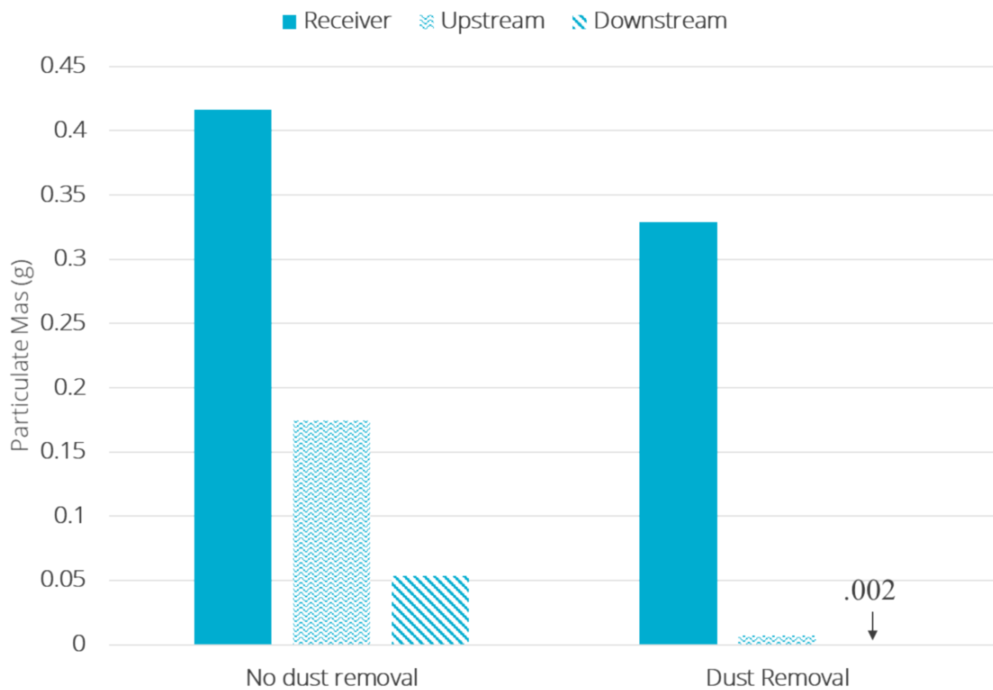


**FIGURE 5.** Particulate mass collected by cascade impactor probes with and without dust removal upstream and downstream of the dust removal loop and in the receiver

Following the dust removal loop cycling study, the continuous removal of dust was considered to determine the maximum receiver dust reduction possible for this dust removal loop. For the 2.5 hours of continuous dust removal following the dust removal cycling, the concentration of dust remained relatively constant with the variability in particle concentration during the experiment attributed to the presence gusty wind conditions around the FPR potentially causing periods of higher system ventilation. The particle dust generated through abrasion in the top hopper is a potential cause for the continuously elevated particle dust concentration despite continuous filtration. Given that the FPR system used as the test apparatus has been run for >160 hours of on-sun testing, the particle dust built up in the top hopper may also be significant, resulting in the re-entrainment of particle dust into the particle flow.

The average concentration of particle dust present in the receiver during active dust removal was 43% lower than the baseline average concertation recorded prior to the dust removal loop cycling.

In addition to measuring the total concentration of dust present in the receiver, the APS also measured the concentration of individual particle sizes providing the particle size distribution depicted in Figure 7. The density (assumed to be the same as the CARBOBEAD HSP 40/70 parent particles) and the apparent particle volume based on aerodynamic diameter was used to determine the mass distribution of the particle dust. The particle size distribution of the dust present in the receiver documented in this study corroborated the findings of a previous dust characterization study [3] that utilized a fluidized bed of HSP 40/70 particles as a source of dust generation. While the previous study noted a high concentration of particulate below 1 μm, particle sizes below 1 μm were not included in the study as the majority of the particulate mass was composed of 1-10 μm particles. With this information the 43% decrease in the total dust concentration is correlated to a 46% decrease in the mass of dust in the receiver.

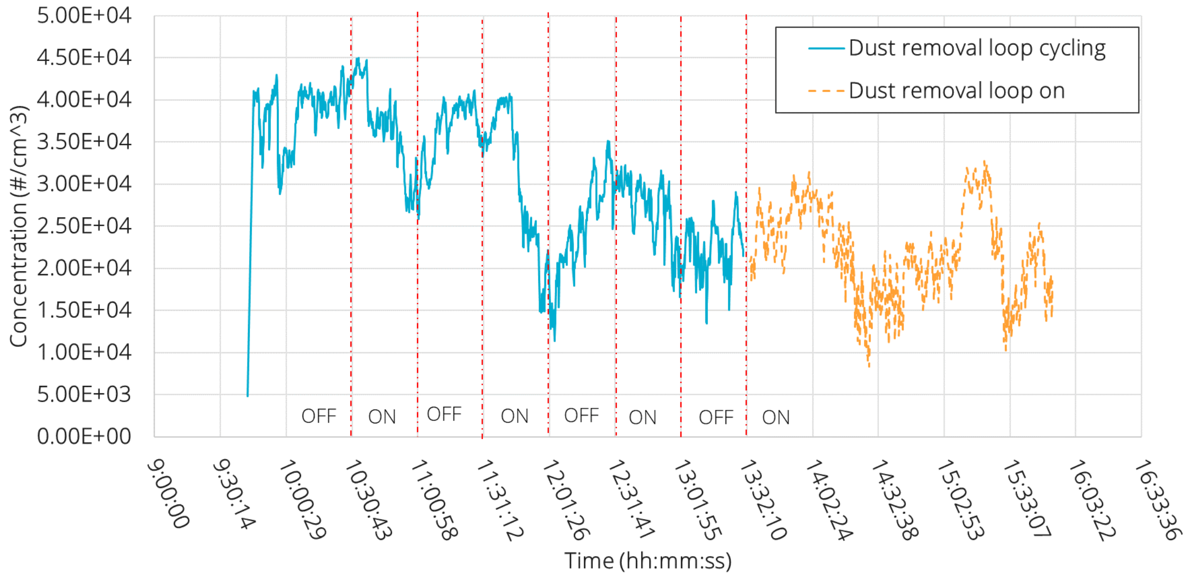


**FIGURE 6.** Particle dust concetration in the receiver during dust removal loop cycling and during continuous dust removal

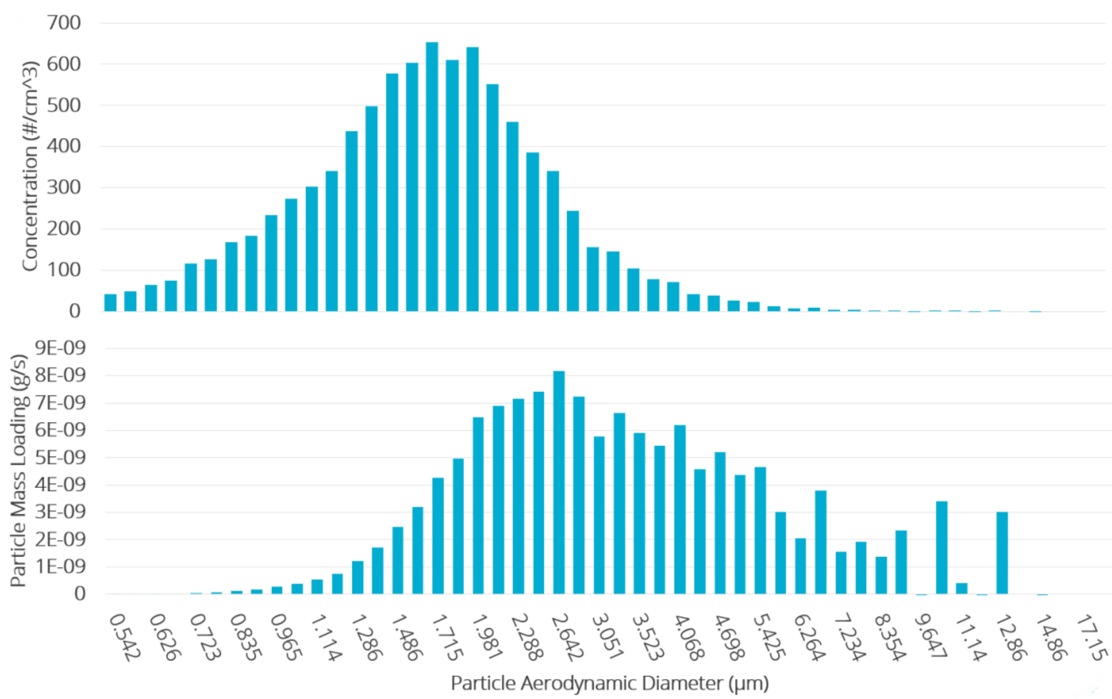


**FIGURE 7.** Particle dust concetration in the receiver (top) and particle mass loading in the receiver (bottom)

## CONCLUSION

Generation 3 particle based CSP systems generate dust through the cyclical abrasion of the particle heat transfer fluid and thermal energy storage media which can escape through the open aperture of the falling particle receiver resulting in undesirable effects such as reduced receiver efficiency. A recirculating dust removal loop design which separates the dust from the particle flow while minimizing heat loss was presented. An experimental study was conducted featuring a single-pass open-loop dust filtration system utilizing a 1 $MW_{th}$ falling particle receiver apparatus with an 8 kg/s particle mass flow rate. A 99% reduction in the mass of particle dust downstream of the dust removal loop was documented. Particulate mass in the receiver was reduced by up to 46%. Future studies will investigate the dust mitigation with the closed-loop design and integrated cyclonic separator.

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