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# Dust deposition mechanism and cleaning strategy for open volumetric air receiver based solar tower sub-systems

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**Abstract**

Desert regions like Rajasthan and Gujarat in India receives abundant solar energy. At the same time these regions are blessed with dust or sand. Solar thermal systems are one of the ways to harness this available energy. Open Volumetric Air Receiver based concentrated solar tower systems are being investigated for applications, like, metal processing. The dust deposition on sub-systems like, heliostat, porous receiver will hinder smooth operation of such a system. Considering this fact, aspects of dust deposition in porous absorber of the receiver and in heliostat are presented. In this direction, experiments and analyses are performed. This revealed that dust deposition on heliostat will be affected by its location among other parameters. The presented analysis shows the required free-stream air velocity for cleaning of such a mirror depending on particle size and location. Experiments on dust deposition in a single pore of an absorber, simulated by a thin and long glass tube of 1.3mm diameter is presented. Furthermore, experiments on dust deposition in one porous absorber reveal its severe consequence. Finally, a strategy for collection of the removed dust particles from these pores is presented to avoid their passage to internals.


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*Keywords:* volumetric air receiver, convective furnace, solar energy, heliostat, CFD, LDV

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## 1. Introduction

Desert regions such as Rajasthan in India, receive high solar irradiation (6-7 KWh/$m^2$/day) and are well suited for the installation of solar thermal systems see e.g. [1]. Open volumetric air receiver (OVAR) based solar tower system has tremendous potential for high temperature process heat applications, for example in metals processing operations, which requires temperatures as high as 800° C see e.g. [2, 3]. Despite the high solar irradiance, desert regions in Rajasthan experience frequent dust storms see e.g. [4, 5]. The significant presence of dust can adversely affect the performance of the OVAR based CSP system, namely, the heliostats or mirrors, absorbers, and the piping and heat exchange systems see e.g. [6, 7]. The effect of dust on the efficiency of heliostats is expected in lieu of reduced reflectivity of collecting heliostat element or mirrors. Strategies are to be adopted to achieve a balance between performance efficiency and cleaning costs. However, very little information is available on the mechanism of dust deposition on heliostats, more specifically on the dust concentration and size distribution on the surface of the heliostat. This will dictate the methodology employed for cleaning heliostats. Another important issue that seems to have been overlooked how dust deposition is related to the distance between adjacent rows of heliostats and the associated field design. Heliostat field design has primarily been governed by optical issues such as shadowing and blockage and not by the manner in which it affects the flow of air between rows of heliostats, see e.g. [8, 9, 10]. The nature of flow between heliostats may (i) influence the manner in which air-borne dust particles are deposited on the heliostats and (ii) aggravate dust deposition by picking dust particles from the ground. The operation of the OVAR system may also be vulnerable to dust storms. This technology is under investigation because of the advantages offered with air see e.g. [2, 3]. As this receiver is open to the atmosphere, dust storms can fully/partially block the pores of the absorbers. Due to the lower thermal conductivity of dry sand ~ 2W/mK [11] high temperature gradients could develop in the absorbers, resulting in localized heating, which, in turn, may result in mechanical damage of the system due to thermal stresses. Even in the absence of dust storms, a fine coating of air-borne dust on the surface of the absorber is expected see e.g. [12, 13, 14]. The consequent adverse effect on heat transfer to the air cannot be ruled out. Dust particles may also enter the piping and heat exchange systems resulting in erosion and adversely affecting heat transfer.

A review of the literature shows that the above-mentioned dust related issues have not received adequate attention. Hence a major initiative on understanding the role of dust on the performance the OVAR based solar system has been launched at the Indian Institute of Technology, Jodhpur, a brief insight into which will be provided in this paper, namely:

- Qualitative investigation on dust deposition on heliostat in an experimental wind tunnel;
- Measured time averaged axial velocity around a heliostat;
- Estimation of the threshold (minimum) free-stream air velocity for initiating the cleaning of heliostat;
- Experiment on dust deposition in the designed porous absorber based OVAR
- A collection strategy of the removed dust from porous absorbers of OVAR.

## 2. Dust deposition on heliostat

This section presents the performed experiments for understanding the deposition of dust on heliostat. Furthermore, analysis is reported for estimation of the required free-stream air velocity for initiation of cleaning process.

### *2.1 Experiments*

Experiments are performed with single, double heliostat set-up to understand flow based deposition as shown in Fig. 1. These experimental heliostats are inclined at an angle of 25° that compares well with latitude of Jodhpur. Each heliostat model comprise of a glass plate (G), stand (S) and base (B). The dimensions are provided on fig. 1. A uniform inlet air velocity of 16 m/s is used for all the experiments. The air is laden with incense ash particles which are deposited on the mirror (heliostat). The size of ash particles is around 20 – 60 μm measured by scanning electron microscope (SEM), which is comparable to the deposited dust on solar panels placed at the roof of IITJ building.The inlet air velocity is close to basic wind speed at a height of 10m in an open terrain (IS 875 Part 3)

[16]. The gap between two consecutive heliostats is $h = 74mm$, the height of the prototype model in stow position. The experimental set up is shown in fig. 2. For the data collection and analysis procedure from dusty mirror plate, refer to [17]. In fig. 2 the measured and subsequently processed dust deposition profiles on the heliostat are presented.

Dimensions (mm)
G: 60 x 60 x 3
S: 18 x 6 x 50
B: 68 x 74 x 20

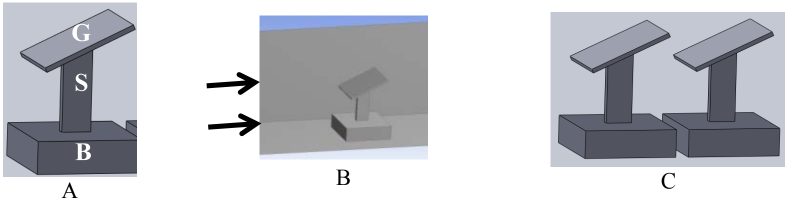



Fig. 1. (a) Model heliostat with dimensions (b) Single heliostat and (c) Double heliostat in wind tunnel

Qualitatively uniform deposition of dust is observed on the one heliostat experiment as in fig. 2A. The observation remains practically unchanged for the first heliostat in two heliostat experiment as well, see fig. 2B. This is indicated by colors. Whereas localized deposition of dust is observed in the second heliostat, which is shown in fig. 2C.

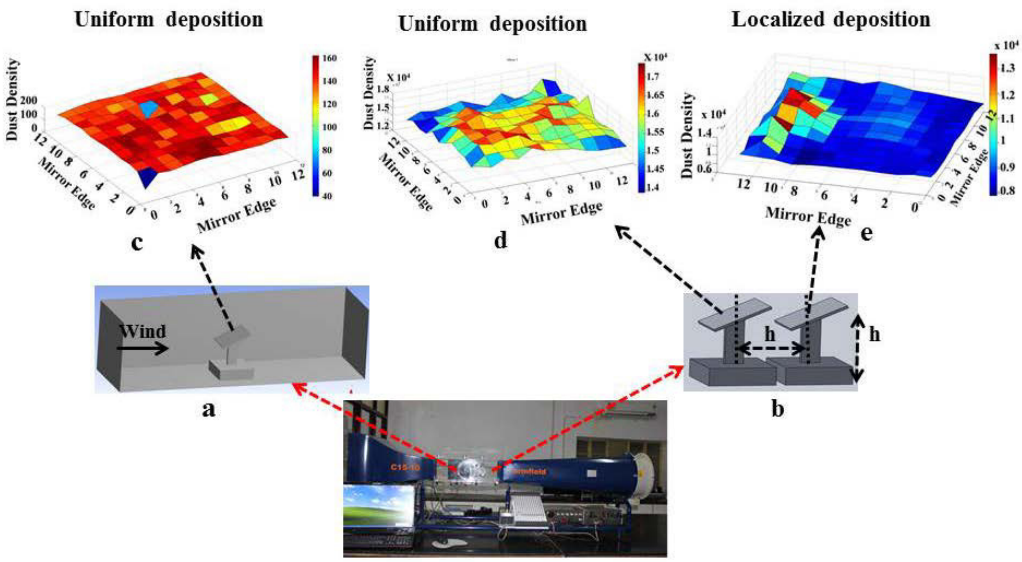



Fig. 2. Measured dust deposition profiles on single and double heliostat experiment; a) Single; b) double heliostat setup; c) dust density on single heliostat; d) first heliostat e) second heliostat of double heliostat setup.

In experiments with single and double heliostat the inlet velocity condition remained the same. The localized deposition is therefore attributed to the effect of disturbed flow on the second heliostat due to the presence of first heliostat in this controlled experiment. For a better understanding of the dust deposition flow measurement around a single heliostat is presented in fig. 3. The flow measurement is performed with laser Doppler velocimetry (LDV) technique, refer to [18] for more details. The measured time averaged axial velocity upstream and downstream of the experimental heliostat is shown in fig. 3. This clearly shows attenuation effect of heliostat on the flow, which is inferred from the reduced velocity in the mid-plane region and increased velocity over the heliostat. Furthermore, sudden strong change in velocity downstream of heliostat (say, around 5 mm) results in strong turbulence generation as a consequence of energy conservation. This was also demonstrated in the CFD analyzed flow field around heliostat in [17]. It can be inferred from the presented velocity profiles, that, after a certain distance the effect of blockage will disappear and consequently the localized deposition of dust, see [18].

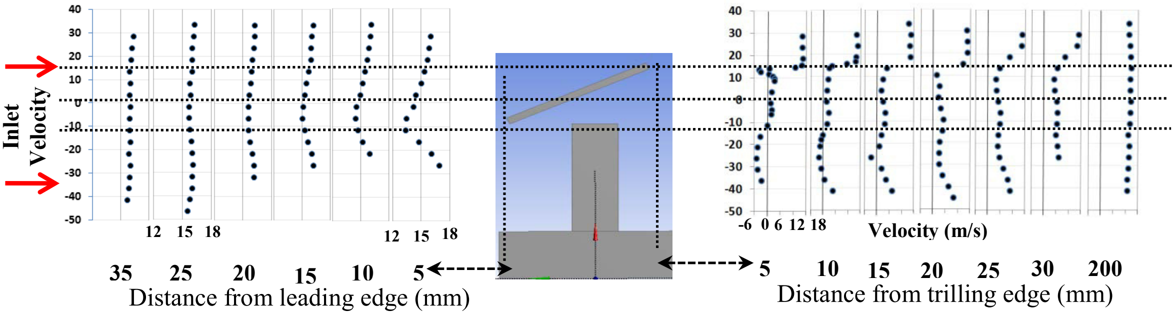



Fig. 3. LDV measured to mean axial velocity (in m/s) around heliostat

## 2.2 Threshold velocity

The minimum required velocity to lift off a dust particle or initiation of saltation process from a surface is called threshold velocity [19]. It should be emphasized that in arid regions locations like Rajasthan use of water for cleaning must be avoided. Considering this fact, analysis is performed with air as cleaning media. At the initiation of saltation process or lift-off, moment of drag and lift forces about a fix point becomes equal to moment of gravity and inter-particle forces as discussed in [19]. In case of dry sand, most likely available in desert regions, Vander Waal force is dominant and remain effective up to 1 nm range. Therefore, it represents the inter-particle forces between sand particles. In the analysis, sand particles are assumed to be spherical in shape with tetrahedral arrangement. Using these, threshold velocity is approximated as:

$$u = \left( \frac{\left( \left( \frac{8}{3\sqrt{3}} \right) \pi \rho_p g r^3 + \frac{\mathrm{Ar}}{6z^2} \right)}{\left( \rho_a C_d A' \right)} \right)^{\frac{1}{2}} \tag{1}$$

Here, *r, A* and *S* are radius of particle, Hamakar constant and separation between particle surfaces respectively. $C_d$ is drag coefficient, $\rho_a$ and $\rho_p$ are density of air and dust particle, respectively and A' is the projected area of particle. Analysis of the deposited dust particles on a flat plate at a height of about 10 m shows the size distribution is 20 - 60µm [18]. Considering this observation the particles are expected to be in boundary layer regime. Accordingly, using the estimated threshold velocity (*u*) the required free-stream air velocity (*U*) is calculated as follows:

For laminar flow, velocity profile in boundary layer is given by Karman [20] as below ($10^3 < \mathrm{Re} < 10^6$)

$$u(x,y) = U\left( \frac{2y}{\delta(x)} - \frac{y^2}{\delta(x)^2} \right) \text{with } \delta(x) = \frac{5x}{\mathrm{Re}_x^{1/2}} \tag{2}$$

For turbulent flow (1/7th power law) [20]: ($10^6 < \mathrm{Re}$)

$$\left( \frac{u}{U} \right)_{turb} = \left( \frac{y}{\delta} \right)^{\frac{1}{7}} \text{with } \frac{\delta(x)}{x} = \frac{0.16}{\mathrm{Re}_x^{1/7}} \tag{3}$$

Here, $x$ is distance from leading edge and $y$ is height from surface at $x$, $u(x,y)$ is threshold air velocity, $U$ is the required free-stream velocity to lift-off dust particles from surface, $Re_x$ is the local Reynolds number at $x$ with $\delta(x)$as the thickness of boundary layer at $x$. As expected, threshold free- stream velocity will depend on particle size as well as location of a particle as shown in fig. 4. This clearly shows the required high free-stream air velocity for cleaning of small size dust particles moving towards the trailing edge of mirrors. Consequently, cleaning of corner regions may pose bigger challenge with small dust particle size, say < 50µm, in diameter.

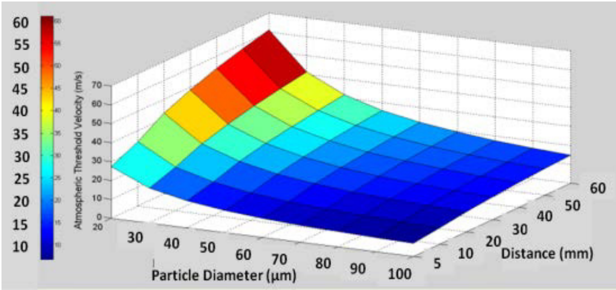
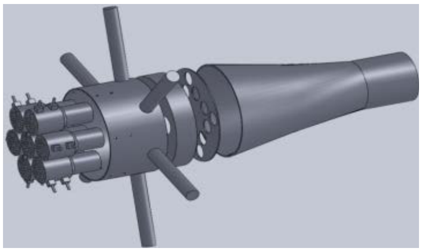



Fig. 4. The required free-stream air velocity for lift-off in laminar flow condition

## 3. Dust deposition and cleaning of OVAR

As explained, the open volumetric receivers (OVAR) works under atmospheric pressure condition using atmospheric air heat transfer fluid. The concentrated radiation from heliostat is focused onto porous absorber in this receiver. Porous absorbers are made of metals (like, steel, Inconel) or ceramic (like, SiC) with interlocking shapes, knit wire packs, and foam or foil arrangement [2]. An open volumetric air receiver designed at IIT Jodhpur is shown in fig. 5a. The detailed design basis of this receiver is presented in [21]. This receiver comprise of 7 porous circular absorbers at the front of the receiver as shown in fig. 5. The performed experiments to demonstrate dust deposition on these pores are presented here after.



A

B

Fig. 5. (a) The designed open volumetric air receiver and (b) porous absorber

### 3.1 Experiments

In order to understand the extent of dust deposition in absorber pores, experiments are performed. The schematic of experiment is shown in fig. 6. This shows a region full of sand, reflecting a sand dune, a 60 mm long glass tube of 1.3 mm diameter reflecting single pore of the absorber. These experiments are performed up-to 30 minutes with air velocity of about 4 m/s with a sand size ranging from 75-106µm. It is to be emphasized that this free-stream velocity is estimated for lift-off of sand particles as explained. Photographs are taken at 5, 10 and 30 minutes for visual inspection. Higher velocity is expected at a height >10 m in an open terrain or in the desert of Jaisalmer. The blower is placed at a distance of about 673 mm from the plate with sand so as to assure the required velocity and its uniformity, as far as possible. The glass tube is placed at a distance of 15mm from the plate.

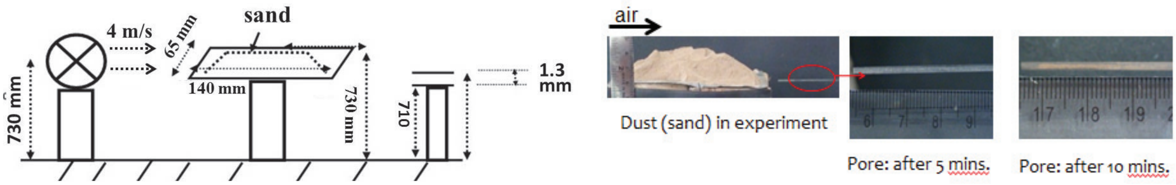
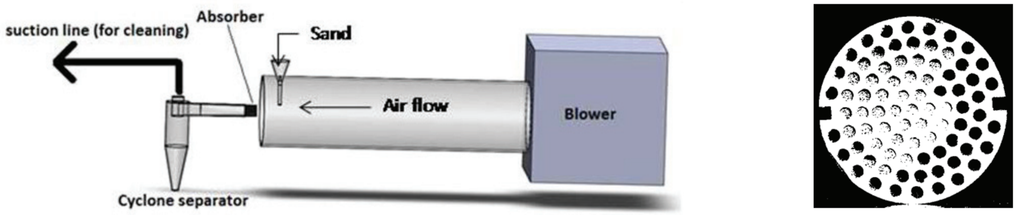



Fig. 6. An experiment depicting dust deposition on single pore of a porous receiver

It is inferred from the performed experiment that:

- Air carries sand and deposits in pore indicated by the glass tube;
- A large extent of the glass tube is blocked by the deposited dust after 10 minutes;

It can be argued that, single pore provides less resistance to dusty air flow. Therefore, using a complete porous absorber may even provide faster deposition of dust and therefore blockage of pores. To evaluate this argument experiments are performed with one porous absorber as in fig. 5b. The schematic of experiment is shown in fig. 7a. The experimental conditions are presented in table1. In this experiment a free-stream velocity of 6m/s is considered. Such a velocity is expected at a height of more than 10 m above the ground. The size of dust particles are selected in view of e.g. [18].




A B

Fig. 7. (a) Schematic of dust deposition experiment; (b) Photograph of dust deposited absorber

In the performed experiments the rate of injection of the smaller dust size is 5 times lower than that of larger dust size. From the required experimental time and the rate of injection of dust, it can be inferred that larger dust sizes will block the pores even earlier than that of smaller dust sizes. Deposition of 10g dust in absorber indicates 100% blockage. Consequently, 2 g of the deposited dust indicates 20% of blockage. The blocked porous absorber is shown in fig. 7b. Experiments also revealed deposition on the front surface of absorber [15].

Table 1: Experimental condition and outcome of dust deposition on porous absorber

| S.no. | Velocity of air (m/s) | Dust particle size range (µm) | Weight of injected dust taken(g) | Experiment duration (sec) | Dust injection rate (g/s) | Deposited dust (g) | Blocked porosity(%) |
|---|---|---|---|---|---|---|---|
| 1 | 5.9 | 75-106 | 100 | 65 | 1.54 | ~ 2 | ~20 |
| 2 | 5.9 | <53 | 60 | 196 | 0.31 | | |

As expected, pore blockage will reduce convective heat transfer to air from absorber surface, which is undesirable. The consequence will be high absorber material temperature and eventual damage of the system. Therefore, a cleaning device for porous OVAR is needed. Furthermore, a device is needed for collection of the removed dust in order to prevent its passage to system internal. Based on literature review, cyclone separator is considered for dust collection and is shown in fig. 8. This is expected to work in-situ with the receiver and even at a high altitude with minimum human interference. Fig. 8 shows the detailed drawing with dimension of a so called 2D2D cyclone separator design. The selection of this 2D2D design is based on a detailed literature review for high dust collection efficiency [22]. The dimensions are selected for the required air mass flow rate of 4-6 g/s in the receiver and the desired corresponding averaged inlet air velocity in the range of 9-15 m/s.

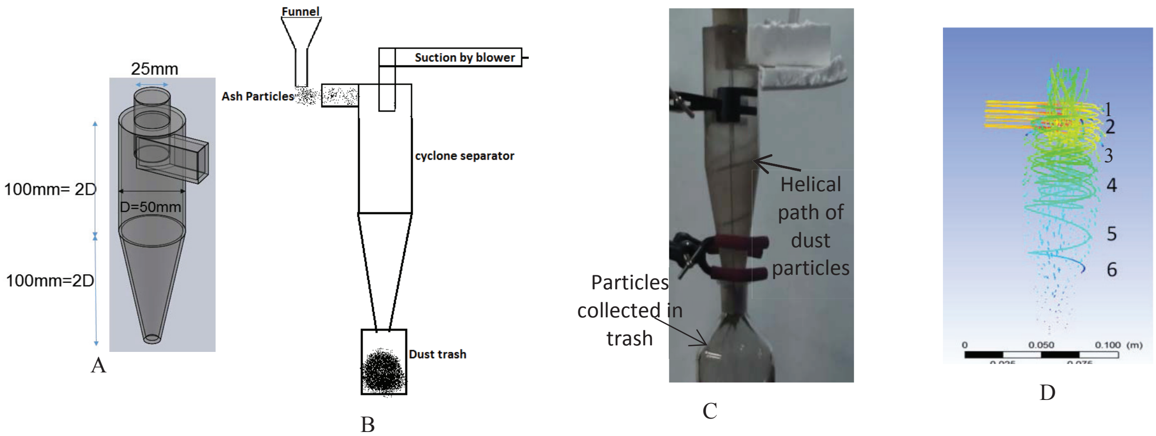



Fig. 8. (a) Designed 2D2D cyclone separator, (b) Schematic of an experiment for estimation of collection efficiency (c) Helical path of dust particles as observed in experiment and (d) CFD analysed helical streamline of air.

Fig. 8 shows the designed cyclone separator and schematic of an experiment to evaluate its dust collection efficiency. Also, the employed plexiglass model of this cyclone separator in experiment is shown in fig. 8c. The collection efficiency is the ratio of collected to injected mass of dust particles. In the performed experiments dust is seen to be moving in a helical path as in fig. 8c. This is attributed to the direction of the resultant of centripetal, centrifugal, buoyancy and gravity forces that act on a particle. Also, detailed computational fluid dynamics (CFD) analysis using a validated tool clearly shows the presence of similar helical path of air near the wall region. The helical movement of dust particles leads to their separation near the wall region in lieu of viscous effect.

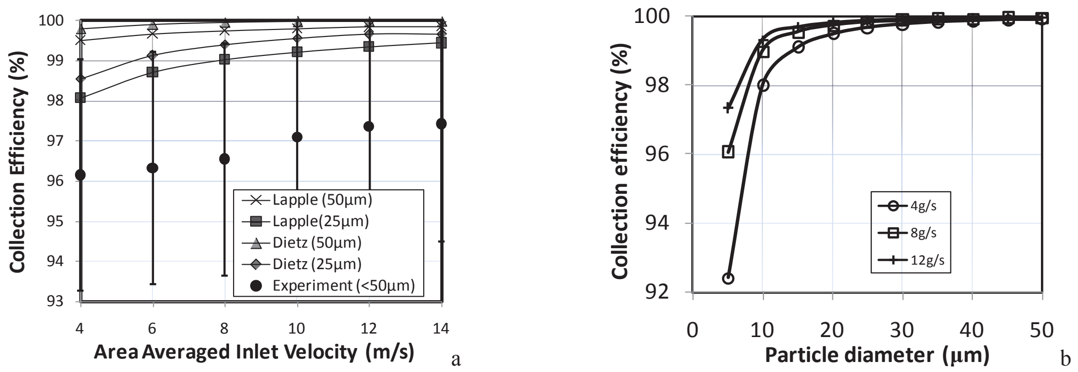



Fig. 9. (a) Comparison between experimentally measured and model evaluated dust collection efficiency (b) Collection efficiency v/s particle diameter for the designed OVAR for various mass flow rate of air.

The measured collection efficiency is shown in fig. 9a and is compared with well-known Shepherd and Lapple [23] and Dietz [24] models. Following are observed:

- For particle size < 50µm the collection efficiency of designed cyclone separator is more than 96% for the considered area averaged inlet velocity;
- The model estimated collection efficiency increase with particle size (25 to 50 µm) and area averaged inlet velocity.
- The differences between experimental and model estimated values are < 4%.

Considering the above, it can be stated that both these models provide acceptable prediction of the collection efficiency. Further analysis using Shepherd and Lapple model in fig. 9b reveals the dust collection efficiency > 92% for particle size > 10 µm for the designed cyclone separator. The considered mass flow rate in this analysis includes the operating condition of the designed OVAR. From these observations it is concluded that such a system will allow collection of the removed dust from OVAR. It worth mentioning that use of this collection system may even allow removal of dust from pores by suction of air at a high velocity. Currently, installation of this dust collection system with the design OVAR based system is under investigations.

## 4. Conclusions

Desert regions with abundance of solar energy are usually blessed with dust or sand. Deposition on sand over mirrors and in other sub-systems will severely affect the performance and operation of a solar thermal system. As for example, dust deposition on sub-systems of open volumetric air receiver based concentrated solar thermal system is presented. In this direction, the performed experiments with dust deposition on mirrors or heliostat show uniform and non-uniform distribution. It is inferred that the location of heliostat or mirrors will influence such a deposition. Detailed flow measurement indeed revealed a possible influence of strong velocity attenuation or enhanced level of turbulence downstream of heliostat. Also, dust deposition experiments in porous absorber revealed that pores are expected to be blocked, especially, during a dust storm if adequate measures are not taken. Analysis and experiments with cyclone separators show that such a system can be utilized for collection of removed dust from pores of receiver. At the same time, it is realized that such a system may even allow cleaning by means of suction of air through pores. In future, this aspect will be discussed by incorporating an open volumetric air receiver with cyclone separator in the designed in-house test bed.

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