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Preliminary Discrete Element Modeling of a Falling Particle Curtain for CSP Central Tower Receivers

R.Zanino[1,a)], C. K. Ho[2], D. Romano [1] and L. Savoldi[1]

[1]*Dipartimento Energia, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy*
[2] *Solar Technologies Department, Sandia National Lab*
P.O. Box, 5800, Albuquerque, NM 87185-1127, USA.

[a)] Corresponding author: roberto.zanino@polito.it

Abstract. Current methods used to simulate the curtain thickness in a falling particle receiver lead to a poor agreement with the experiments. Here the Discrete Element Method (DEM) is proposed to address the problem, including both the top hopper and the interactions between particles in the model. Some first promising results are presented, showing an acceptable agreement between simulation and experiment for an ad-hoc set of input parameters. A sensitivity study provides a first assessment of the effects of the main input parameters of the model (boundary conditions at the release, particle Young's modulus, restitution coefficients and effective particle diameter) on the predicted curtain thickness.

INTRODUCTION

This study is based on the concept of a *falling particle receiver*, conceptually proposed 30 years ago at Sandia National Laboratories (SNL), in Albuquerque (NM) USA [1].

An advanced realization of this concept was recently developed and experimentally tested at SNL [2]. The project goal is to develop a cheap and reliable replacement for molten salts as the thermal medium. In fact, commonly used nitrate salts cannot withstand temperatures higher than ~600 °C without experiencing chemical decomposition. This limits the operating temperature of the power cycle, thus limiting the thermal-to-electric efficiency. On the other hand, in the case of a falling particle receiver, a curtain made of a sand-like ceramic (Accucast) spheres, see Fig. 1, of diameter $D \sim 280$ μm, gets directly irradiated by the concentrated radiation coming from the solar field. The very stable composition of the particles allows them to reach temperatures as high as 1000 C and they can be used both for electricity production and as thermal storage.

A first measurement campaign took place at SNL at the end of 2014, aimed at collecting data about the (fluid) dynamics of the falling particles: the particle falling speed was evaluated at different heights from the release, together with the curtain profile (thickness, in the direction of concentrated solar radiation, and width), for different slot aperture thickness, by means of high-definition pictures and video. In [2], a first attempt to replicate the physical curtain behavior using an ANSYS Fluent® simulation was presented, based on the Discrete Phase Model (DPM). Whereas good results were obtained for the simulated particle falling speed, basically that of a free falling body with negligible drag, the curtain thickness, which significantly affects its opacity, was not correctly reproduced by the model: the simulated particle curtain thickness was considerably less than the experimentally measured thickness.

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FIGURE 1. Curtain test facility at SNL, with details of the curtain during operation [2].

This study aims at expanding the work presented in [2]. The DPM used in [2] to compute the particle flow allows air-particle interactions, but neglects particle-particle interactions. While in previous tests [3] it was claimed that this is a good approximation for the problem at hand, we consider here that the interaction between the particles should contribute to the increasing thickness of the curtain observed in [2]. Furthermore, a very straight-forward injection method was used in the simulations presented in [2]: the release event was modeled as particle injection from the aperture present at the bottom of the top hopper. In reality, the particles undergo strong inter-particle interactions in the top hopper because of the large solid fraction, then they interact with the metal aperture, and only at that time they begin falling less constrained. These interactions can cause a non-negligible initial momentum in the horizontal direction that may cause additional spreading and thickening of the curtain.

Since the curtain thickness computed in [2] was quite different from the experimental data, a somewhat different approach is proposed and attempted in this study:

a) *Introduce a more precise model*: the Discrete Element Method (DEM), an engineering numerical method to simulate in a Lagrangean framework the motion of many interacting solid particles, has been applied instead of the DPM, as implemented in the StarCCM+ code [4]. This method allows air-particle, particle-particle and particle-structure interactions, thus better representing the forces that particles exchange with one another.
b) *Introduce a more precise geometry*: in the actual release event, similar to an hourglass, a stockpile of particles starts flowing down from the top hopper, through a narrow aperture, see Fig. 2. The simplification made in [2], of a purely vertical release of the particles from the aperture height, neglects the horizontal momentum that the particles retain when they start flowing after being stockpiled. Therefore, we include a buffer volume on the top part of the computational domain, attempting to mimic the actual top hopper.

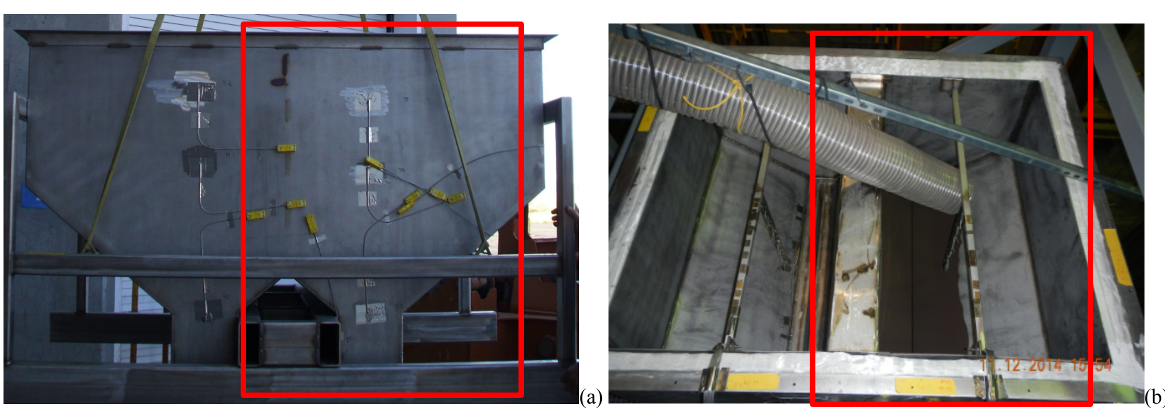

FIGURE 2. Side (a) and top (b) view of the double-hopper used in the tests. Only one half of the device (red rectangle) is considered.

In the rest of the paper we will focus on the prediction of the curtain thickness as a function of the distance from the aperture. Only the particle dynamics is of interest here and isothermal conditions are assumed.

As opposed to previously applied models where the interactions between the particles where neglected, see e.g. [5], [6], the DEM should in principle provide a more accurate simulation of the particle fluid dynamics, at the expense, however, of significant computational time. An additional issue, which we will start addressing below and which non-negligibly contributes to the preliminary nature of the present work, is related to the fact that the DEM results depend on a number of input parameters whose optimization for the case at hand could not be achieved here. Therefore, in the results section below, we shall mainly present and discuss the trends of the results as these input parameters are varied, postponing the actual calibration of the model to future work.

THE DEM MODEL

In this paper we rely on the DEM model implemented in the commercial software STAR-CCM+ [4], where inter-particle (contact) forces are included in the equations of motion (extension of Lagrangean modeling to include relatively dense particle flows). The particles, that can move in the computational domain as rigid bodies, in the model are "soft", i.e., they are allowed to overlap. The calculated contact force is proportional to the overlap, and depends on the particle material and geometric properties.

The main parameters that allow tuning the interaction between the particles are:

- Young's modulus E
- the so-called "restitution coefficients" Rn and Rt, which, according to the Hertz-Mindlin model in STAR-CCM+, give the energy dissipation due to the damping of the normal and tangential components of the contact force, respectively [4]. $Rn = Rt = 1$ indicates a perfectly elastic collision.

In view of the very high computational cost of the DEM simulations, we reduce the computational domain to a slice (10 mm wide, compared to the total aperture width of ~1200 mm) of the top hopper. We consider only the case of the largest slot aperture tested (width of ~ 11 mm).

For the sake of reducing the computational cost, we develop two models, corresponding to different values assumed for the "effective" particle diameter $D_{eq} > D$:

- Model A: D_{eq} = diameter of a sphere with volume equal to that of 20 real particles;
- Model B: D_{eq} = diameter of a sphere with an equivalent volume equal to that of 40 real particles.

Two domains will be alternately considered,

- The full domain, including (for completeness) a slice of the top hopper;
- A reduced domain, excluding (for simplicity) the hopper.

In both cases, symmetry allows to consider only half of the domain, cut at the mid-plane along the width of the curtain.

The boundary conditions in the case where the top hopper is included assume a particle injection of 0.034 kg/s from the top of the simulated portion of the hopper, which would return the total measured mass flow rate in case the whole hopper was considered. Symmetry conditions are imposed at the surfaces created to scale-down the computational domain. No further constraints on the particle mass flow rate are imposed on the particle release surface.

Air is treated as an ideal gas in incompressible flow. All the boundaries around the particle curtain, which are not symmetry surfaces, are set as pressure outlets. The air is passive in the sense that there is no wind in the simulation and the air is therefore simply entrained by the falling particles.

In the simulations without the top hopper, a particle injection of 0.034 kg/s is imposed on the release surface – the injection occurs with null vertical speed and with a "normal" speed distribution in the horizontal direction perpendicular to the aperture characterized by a given peak value, see below.

The simulations are intrinsically transient, as a consequence of the Lagrangean approach adopted to model the particles, and run for ~1 s. This can be compared with the average time (~ 0.5 s) needed by a particle to free fall from the aperture to the floor of the bottom hopper. A quasi-steady state condition is therefore achieved in the simulation.

PRELIMINARY RESULTS

We perform first the analysis on the full computational domain, using model A and including the (slice of the) hopper as shown in Fig. 3.

The figure qualitatively confirms the enlargement of the curtain thickness with drop length. In the inset of Fig. 3 it is seen how each particle in the proximity of the aperture has a non-negligible horizontal component of the velocity in the direction of the curtain thickness, which will contribute to the thickening of the curtain as the particles start falling from the aperture.

From the post-processing of this simulation we learned that the particle mass flow rate through the aperture (which was not an input parameter in this case) is about 4 times the mass flow rate in the simulations below, which do not include the top hopper, where on the contrary the mass flow rate value was set in input to a value suitable for the comparison with the measurements. In perspective it should therefore be interesting to repeat this simulation with comparable mass flow rates to those used in the reduced domain, because such simulation could then be used also to provide some justification for the assumed distribution of inlet velocities for the particles released from the aperture, in the case of the reduced domain.

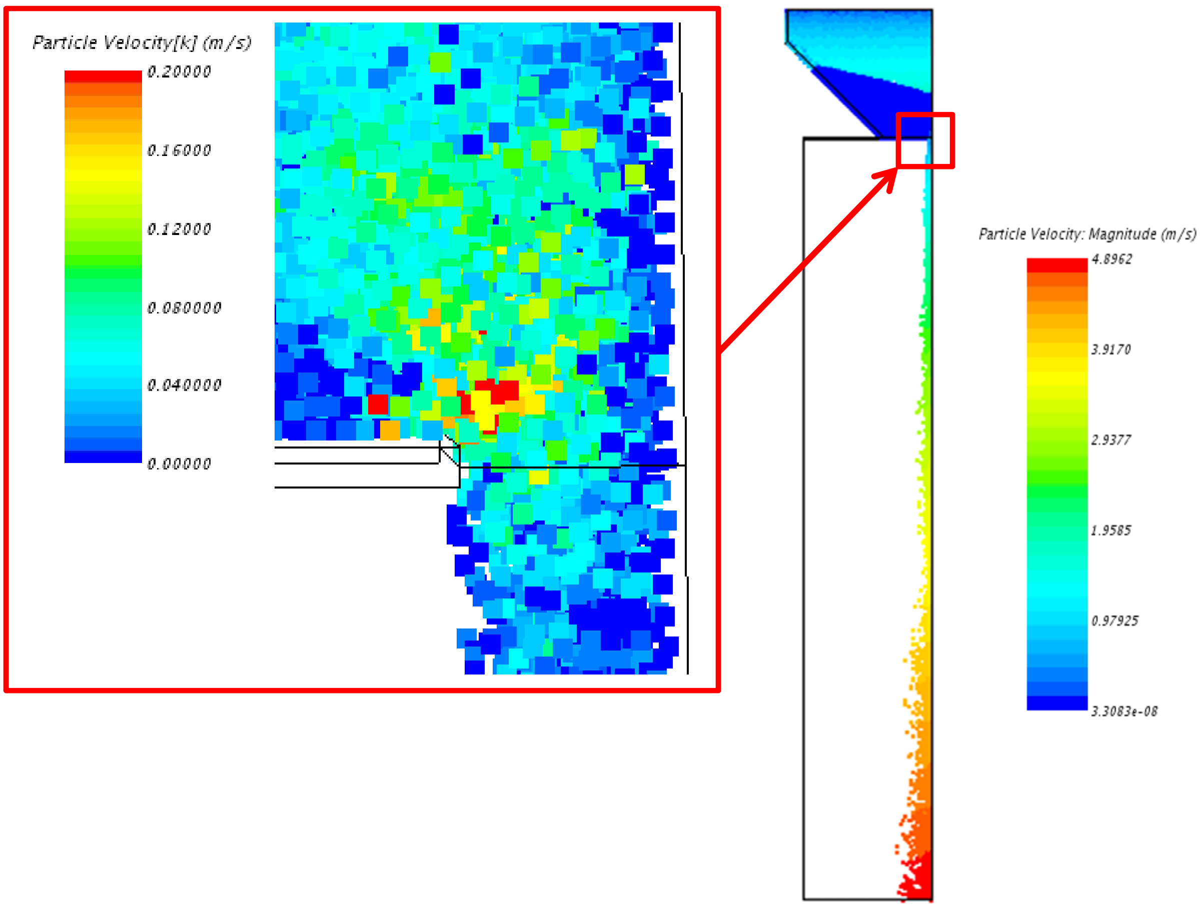

FIGURE 3. Computed results for the DEM simulations including the slice of the top hopper (Model A; $Rn = Rt = 0.5$; $E = 1$ MPa). The progressive thickening of the curtain and the acceleration of the particles are shown on the right. The inset on the left shows a zoom around the aperture region, where each particle is coloured based on the component of its velocity in the direction of the curtain thickness.

As the computational cost of the simulations including the top hopper is significant, we proceed from here onwards to the above-mentioned simplification of the computational domain, excluding the top hopper.

In Fig. 4a we compare the computed curtain thickness distribution with the experimental data (the experimental value is deduced from the high-definition pictures with uncertainty error-bar). Here and below the curtain thickness is estimated from the results of the simulation using the following procedure: we track the particle trajectory and we detect the location of the intersections of the trajectories with the horizontal plane at the heights where we want to evaluate the curtain thickness. The actual computed curtain thickness corresponds to the region extension where

98% of the particles intercept each horizontal surface, and the error bars cover the region where 96% and 100% of the particles intercept the surface, respectively.

The effect of increasing the peak value of the horizontal velocity component across the curtain thickness, imposed to the particles leaving the aperture, is shown to be as expected, with lager values leading to consistently thicker curtains. A good agreement with the experiment is apparently reached for one particular combination of parameters. However, it should be noticed that a detailed calibration procedure (see below) will have to be implemented and followed, when one aims at a validation of the model, which is beyond the scope of the present paper.

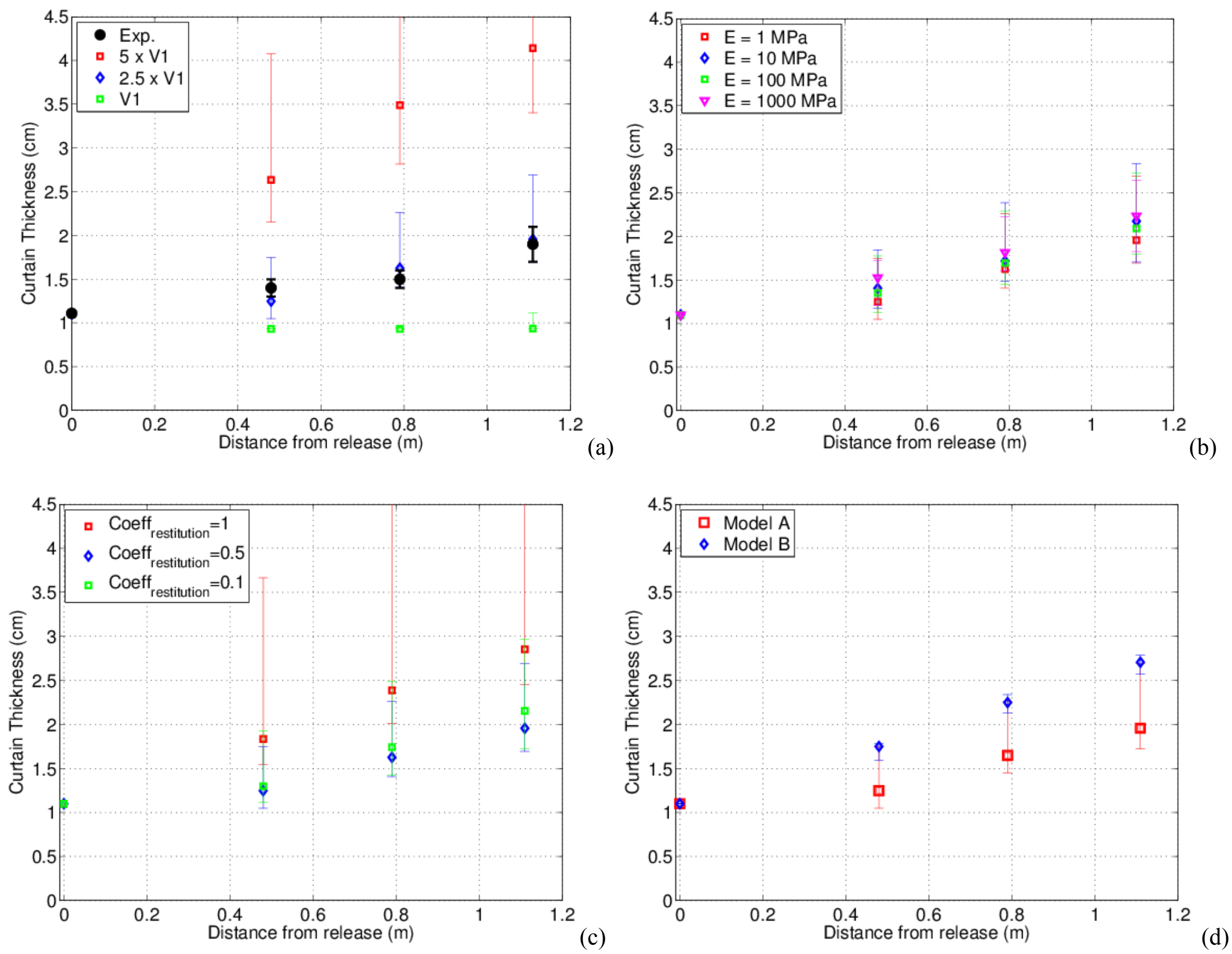

FIGURE 4. (a) Comparison between measured and computed curtain thickness at different distances from the release (Model A; *Rn* = *Rt* = 0.5; *E* = 1 MPa). The effect of increasing the peak value of the velocity component across the curtain thickness, imposed to the particles leaving the aperture, is shown. *V1* = 1 cm/s. Computed curtain thickness at different distances from the release: (b) Model A, *Rn* = *Rt* = 0.5: the effect of different assumed values for the Young's modulus *E* of the particles is shown. (c) Model A, *E* = 1 MPa: the effect of different assumed values for the restitution coefficients *Rn* = *Rt* is shown; (d) *E* = 1 MPa, *Rn* = *Rt* = 0.5: the effect of different assumed values for the effective particle diameter (models A vs. B) is shown.

The effect of the assumed Young's modulus of the particles on the computed results is shown in Fig. 4b. It is seen that an increase of *E* leads to a thicker curtain, although the effect is not very strong. We do not know the value of *E* for the real (Accucast) particles, but, as a reference, the *E* of fine ceramics may be of the order of hundreds of GPa. On the other hand, simulations become increasingly expensive (long) as *E* increases, so that we have not, for the time being, tried higher values of *E*.

In Fig. 4c we investigate the effect of the two restitution coefficients (always assumed equal in this paper, for the sake of simplicity) on the predicted curtain thickness. It is seen that, as expected, for completely elastic inter-particle collisions the thickest curtain is achieved, while at low *Rn*, *Rt* some saturation occurs.

Finally, in Fig. 4d the effect of increasing the particle diameter from the value assumed in Model A up to the value in Model B (for the sake of reducing the computational cost), is shown. It is seen that a reduction in D_{eq} leads to a reduction of the curtain thickness.

CONCLUSIONS AND PERSPECTIVE

The first promising results for the simulation of the curtain thickness in a falling particle receiver using the Discrete Element Method have been presented in the case of an isothermal curtain, showing that the prominent experimental feature of an increasing curtain thickness as the distance from the release increases can be reproduced both qualitatively and quantitatively for an ad-hoc set of input parameters and a reduced computational domain.

The preliminary sensitivity study of the predicted curtain thickness to the main input parameters of the model (boundary conditions at the release, particle Young's modulus, restitution coefficients and effective particle diameter) has been presented.

In future work, the model shall be calibrated based on measured data at a given value of the aperture and the full domain simulations (including the top hopper) shall be performed for experimentally relevant conditions. Then, with fixed values of the different input parameters, the model will be validated against measured data obtained with different values of the aperture.

The inclusion of the effects of solar radiation, wind and the possible recirculation of the particles will be addressed in future work.

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