

Computational Fluid Dynamics Simulation Approach for Developing a Powder Dispensing Device

Rallapalli Revanth, Shivakumar Bhavi, Vijay Kumar Turaga

Abstract—Dispensing powders manually can be difficult as it requires to gradually pour and check the amount on the scale to be dispensed. Current systems are manual and non-continuous in nature and is user dependent and it is also difficult to control powder dispensation. Recurrent dosing of powdered medicines in precise amounts quickly and accurately has been an all-time challenge. Various powder dispensing mechanisms are being designed to overcome these challenges. Battery operated screw conveyor mechanism is being innovated to overcome above problems faced. These inventions are numerically evaluated at concept development level by employing Computational Fluid Dynamics (CFD) of gas-solids multiphase flow systems. CFD has been very helpful in the development of such devices, saving time and money by reducing the number of prototypes and testing. In this study, powder dispensation from the trocar's end is simulated by using the Dense Discrete Phase Model technique along with Kinetic Theory of Granular Flow. The powder is viewed as a secondary flow in air (DDPM-KTGF). By considering the volume fraction of powder as 50%, the transportation side is done by rotation of the screw conveyor. The performance is calculated for 1 sec time frame in an unsteady computation manner. This methodology will help designers in developing design concepts to improve the dispensation and the effective area within a quick turnaround time frame.

Keywords—Multiphase flow, screw conveyor, transient, DDPM - KTGF.

NOMENCLATURE

CFD	Computational Fluid Dynamics
CPFD	Computational Particle Fluid Dynamics
DDPM	Dense Discrete Phase Model
DEM	Discrete Element Method
DPM	Discrete Phase Model
KTGF	Kinetic Theory of Granular Flow
MIS	Minimally Invasive Surgery
MP-PIC	MultiPhase-Particle-In-Cell

I. INTRODUCTION:

MINIMALLY Invasive Surgery (MIS) has a great advantage over traditional surgery. The prime advantage is patient gets a quicker recovery time from MIS as it is done by making small incisions typically a few millimeters long, as compared to traditional and thereby it will have a lower rate of complications after surgery.

Surgical powder is used during MIS to provide effective control of oozing on surfaces, and it provides a surface for platelet adhesion. To dispense the powder to incision surface, the current models in use are manual and non-continuous in

nature. It is difficult to control powder dispensation from current devices as these are user dependent.

There are a considerable number of experimental and computational studies, including those cited in [3] to [15], in which CFD simulations of fluid-solid multiphase flow systems have been used to access the pattern of solid particles in a fluid flow. Basically, all the multiphase models are divided into two methods. One method is Eulerian-Eulerian approach where both fluid and solid phases are treated as continuous phase. The Eulerian-Eulerian approach is a traditional one which requires less computational time. But in certain situations, this has limitations regarding particle size variation and its effect with fluid particles.

The second method is Eulerian-Lagrangian approach where fluid phase is treated as continuous phase and solid particles are treated as discrete phase and are analyzed by Lagrangian approach. It can provide analysis for a wide range of particle types, sizes, shapes, and velocities. Ansys Fluent software provides typically three main models under Eulerian-Lagrangian approach, namely, Lagrangian Discrete Phase Model (DPM), Dense Discrete Phase Model incorporated with Kinetic Theory of Granular Flow (DDPM-KTGF) and CFD-Discrete Element Method (CFD-DEM). Another one through numeric codes, Computational Particle Fluid Dynamics (CPFD) numerical scheme incorporated with the Multiphase-Particle-In-Cell (MP-PIC) method is used for modeling particle-fluid and particle-particle interactions in CFD.

The way of handling particle-particle interactions, solid particle volume fraction in fluid flow and the numerical method used to solve the equations are the main differences in different Eulerian-Lagrangian Models. If solid particle volume fraction in fluid flow considered to be less than 10%, DPM numeric code is most appropriate for analysis. The particle-particle interaction is assumed to be negligible for calculation in DPM numeric code [1]. DEM is also called soft sphere model based on Cundall and Strack [2]. It is used to explicitly track the particle-particle and particle-wall interaction terms in typical Eulerian-Lagrangian approach. Compared to DPM, DEM will give more accurate predictions for dense phase, but at the high cost of computation. The latest one is Dense Discrete Phase Model incorporated with Kinetic Theory of Granular Flow (DDPM-KTGF) for modeling particle-particle and particle-wall interactions. If solid volume fractions are quite low, the solid particles will be treated in a Lagrangian manner. But for the high solid volume fractions, the particles are treated in a Eulerian manner.

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Titus et al. [3] had studied the effect of particles in a liquid slurry flow by considering Eulerian-Eulerian approach. They examined the influence of particle size (90 μm to 270 μm) and also the particle volume fraction (10% to 40%) on the radial distribution of particle concentration and velocity and frictional pressure loss. By considering k -epsilon (k - ϵ) turbulence model, they got satisfactory results as compared to experimental data. Vidyapati et al. [4] had used the DEM approach to study the transitional rheology of dense granular material in an annular Couette cell. They had modelled simplified 3-D model to study flow characteristics. They found that the refined order parameter (ROP) with Kinetic theory model predicts the total granular stress within the error range of 15% for assemblies with a solid volume fraction up to 0.57. The parameters like drag function, solid shear viscosity and granular temperature are investigated in a cylindrical spouted bed by Hosseini et al. [5]. They had applied a Eulerian-Eulerian Two-Fluid Model incorporating with kinetic theory of granular flow and concluded that representative unit cell drag model and the Syamlal viscosity model were most suitable for prediction of gas and solid flow patterns in cylindrical spouted beds, particularly, for solid axial velocity and voidage in the spout zone. Balzer et al. [6] focused on the closure of the solid stress based on the kinetic theory to improve the operating conditions of existing circulating fluidized bed combustor units. The important assumption is that the particles are freely moving between collisions. But in the real case of gas-solid flow, the carrier gas acts on each particle through the drag force. By introducing this drag force in the kinetic theory, they tried to modify the closures and direct numerical simulations were able to validate these modifications. By using the DEM and statistical analysis, Li et al. [7] had studied the gravity-driven dense granular flows numerically. Based on the values of SOE (span of energy magnitude) and σ (standard deviation), gravity-driven dense granular flows are subdivided into three sub-regimes: an extremely slow flow, an intermittent flow, and a consistent flow. These respectively represented a quasi-static, intermediate, and liquid-like states of dense granular materials under gravity. Above these were for solid concentration from 62% to 65%.

Qinghong et al. [8] had proposed a unique model named as coupled Eulerian fluid phase-Eulerian solid phase-Lagrangian discrete particle phase (CEEL) hybrid approach where transport equations of fluid phase and Eulerian solid phase are solved in a Eulerian framework and the discrete particle phase is represented through the Lagrangian framework.

Eulerian solid phase and discrete particle phase were symbolized by new term called as ghost phase. By using kinetic theory of granular flow, Eulerian solid phase was modelled. Discrete particle phase was modelled by using the discrete element method. The ghost field used as a medium to transfer the mass, momentum and kinetic energy between Eulerian solids phase and discrete particle phase. Simulations are executed in a dense gas-solid bubbling fluidized bed. Oyegbile et al. [9] had focused on the hydrodynamic analysis of the granular particle interactions in a rotor-stator particle agglomeration reactor using the Eulerian-Lagrangian one-way

coupling i.e., DPM-KTGF modelling approach. They found out that granular pressure at a low solid concentration relies primarily on the kinetic mechanism rather than particle-particle collisions which implies that discrete phase velocity does not vary significantly with the restitution coefficients especially at low solids loading. Hashemisohi et al. [10] had observed that separation between solid and gas phase were more, when the coefficient of restitution as one of the parameters was decreased in DDPM model. The particle volume fraction within bubbles went from 5% to 30%, when the coefficient of restitution went from 0.90 to 0.99. Single bubble and freely bubbling fluidized beds were modelled by using DDPM coupled with KTGF approach. Upadhyay et al. [11] investigated the six different drag models to predict the solid particles flow in a circulating fluidized bed (CFB) reactor. By using the root mean square error (RMSE) calculation, the discrepancy between the six different simulation predictions was calculated. The comparative study between DDPM-KTGF and DDPM-DEM was conducted by Hwang et al. [12] on dense flow cyclone. He had observed that models consisting of a high solid volume fraction could be analyzed by using DDPM-KTGF with lower computational time as compared to DEM approach. Horizontal screw conveyor's performance was studied by using the DEM approach by Patinge et al. [13] and Owen et al. [14]. Owen et al. [14] had observed that there was a significant increase in power draw for increasing non-sphericity of the particles. Effect of clearance was studied by Patinge et al. [13]. The clearance is the distance between the screw's outer diameter and the case.

Screw conveyors are used in wide industrial units for transporting materials from one location to another location. Based on research carried out by Minglani et al. [15] regarding screw conveyors, horizontal screw conveyor was chosen as a handling unit for transporting of surgical powder from hopper side to trocar's end. Based on the above observations from previous studies and high computational cost involving for DEM approach, DDPM-KTGF approach has been used to numerically investigate the three-dimensional screw conveyor.

II. HORIZONTAL SCREW CONVEYOR: GEOMETRY

The full three-dimensional screw conveyor has been modelled in design software. The microscopic dimensions were considered for designing purpose, as it is to be used for transferring the surgical powder to injury location. The schematic representation of screw conveyor as shown in Fig. 1 and its specifications were given in Table I. To understand the flow in the screw fluid domain only and to reduce the mesh count, inlet/hopper design was not considered for analysis. Screw conveyor CFD model is divided into three domains:

1. Rotary Domain,
2. Stationary Domain and
3. Outlet Domain.

By using Boolean operation, solid screw geometry was subtracted from overall fluid domain. It is shown in rotor domain, Fig. 2. The full geometry nomenclature is shown in Fig. 2.

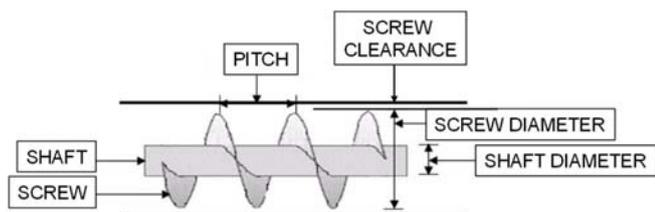


Fig. 1 Schematic representation of Screw Conveyor

TABLE I
 SCREW CONVEYOR SPECIFICATIONS

Screw Diameter (D) (mm)	2.64
Shaft diameter (d) (mm)	0.81
Pitch (P) (mm)	2.70
Maximum Screw Clearance (c) (mm)	0.05
Screw Length (l) (mm)	250

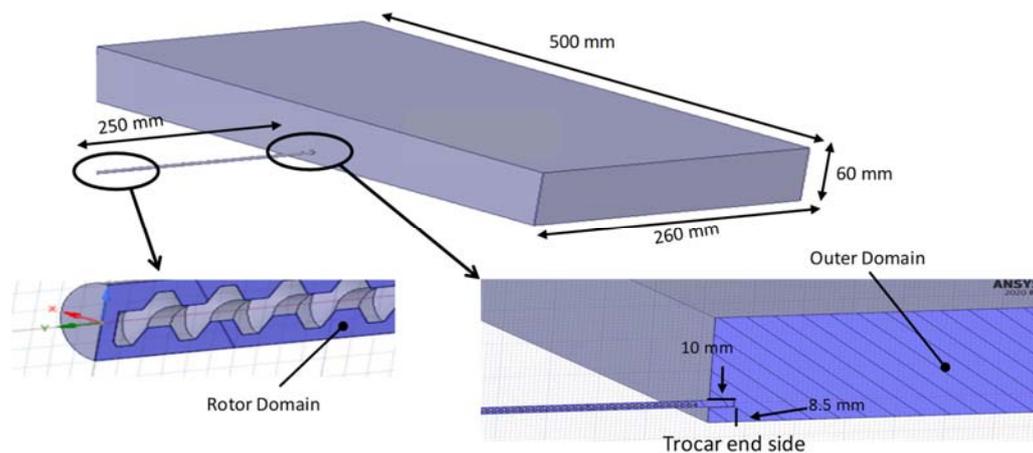


Fig. 2 Screw Conveyor domain measurements

III. BOUNDARY CONDITION AND SOLVER SETTINGS

The three flow domains were meshed separately in the ANSYS MESH tool. The screw conveyor fluid domain was divided into two parts due to its rotation part domain. The stationary domain was meshed by using hexahedral cells. Both rotor and outlet domain were meshed using patch conformal tetrahedral cells. During meshing, skewness parameter was assessed to check the tetrahedral element mesh quality. The number of elements and skewness were shown in Table II.

TABLE II
 ELEMENTAL MESH QUALITY

Domain	No. of Elements	Maximum Skewness
Stationary	378104	0.868
Rotary	6846107	0.899
Outlet	250717	0.841

More than 6.8 million elements were used to capture the curvature portion of rotary geometry, as shown in Fig. 3.

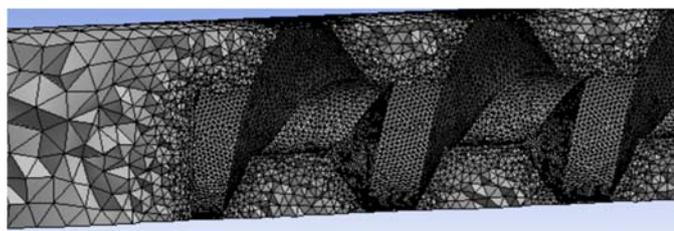


Fig. 3 Rotor Mesh section view

ANSYS FLUENT was used as a solver. By using the sliding mesh technique, the three mesh domain's interfaces were

combined in fluent. To simplify the model for running transient DDPM-KTGF model, laminar model was selected. The volumetric space of screw conveyor was assumed to be completely filled by the surgical powder having 50% volume fraction. For fluid domain model, 3D, transient, laminar models (gravity has been taken into account) were selected for analysis. CFD simulations were conducted by assigning 150 rpm rotation to rotary domain, thereby powder moved forward and released at the trocar end side. Surgical powder properties are shown in Table III. Entire simulation was solved for 1 sec time frame to understand the powder flow at the trocar's end side. Coupling between the velocity and pressure was implemented through phase-coupled SIMPLE scheme. Second order scheme was selected for pressure. Other important simulation parameters are shown in Table IV. Adaptive time step (multiphase specific method) was employed to carry out the simulation. The transient CFD calculations were performed, where initially time step of 0.00001 s was used and thereby 0.0005 s was used to capture air-powder flow behavior.

TABLE III
 SURGICAL POWDER PROPERTIES

Density	400 kg/m ³
Diameter	0.4 mm

IV. RESULTS AND DISCUSSION

Flow behavior at the trocar's end was examined quantitatively by measuring solid flow velocity and solid volume fractions at different planes. All the results are extracted at the time frame of 1 second.

TABLE IV
 MODELLING PARAMETERS

Granular Properties	
Solid- solid restitution coefficient	0.90
Granular Viscosity	Syamlal-O'Brien method
Packing Limit	0.80
Transient solver calculation and convergence criteria	
Time step	0.0005 s
Convergence criteria	none
Maximum iterations per time step	20
Discretization schemes settings	
Momentum	First order upwind
Volume fraction	First order upwind
Transient formulation	First order implicit

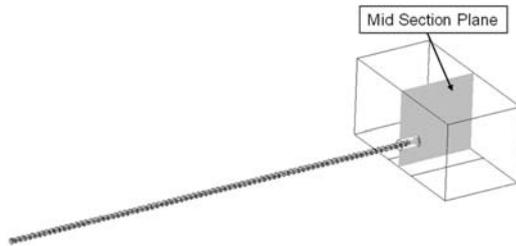


Fig. 4 Mid-section plane

Solid velocity was plotted at mid-section plane as shown in Fig. 4.

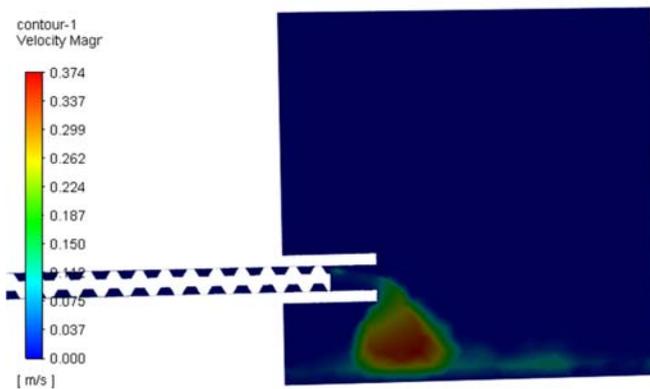


Fig. 5 Velocity at mid-section Plane

Fig. 5 shows a contour plot of velocity at mid-section. Maximum velocity was observed as 0.374 m/s at the mid-section. This shows how the powder flows out from the screw conveyor outlet. The maximum velocity is based on providing screw conveyor rotation of 150 rpm.

Fig. 6 shows a contour plot of volume fraction of a solid at mid-section. As packing limit was limited to 0.8 as per boundary condition shown in Table IV, maximum volume fraction was predicted to be 0.799 and it was observed at the curved portion of rotating part of the screw conveyor.

Fig. 7 shows the plot of volume fraction with a reduced scale to visualize the powder dispensation from the trocar's end side. As simulation is done for 1 second, Fig. 7 shows settling of powder at the flat plate (located at the bottom side of trocar's end side).

The variation of the solid volume fraction is shown at different section planes in Fig. 8. Each plane was taken at a gap of 10 mm. This shows the rotation of screw conveyor driving the powder to trocar's end side. High solid volume fraction is observed at the screw rotation part's downside location.

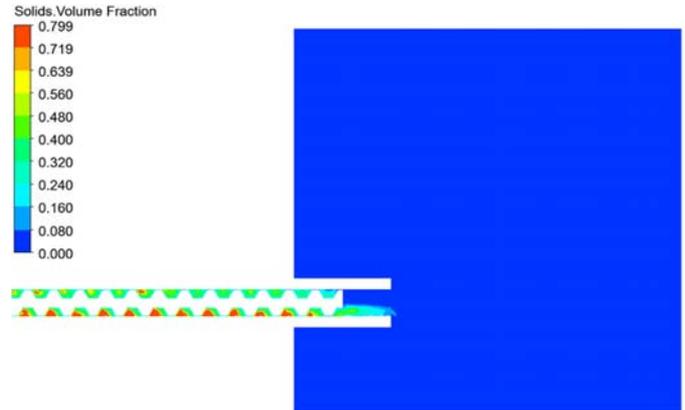


Fig. 6 Solid Volume fraction (global scale) at mid-section plane

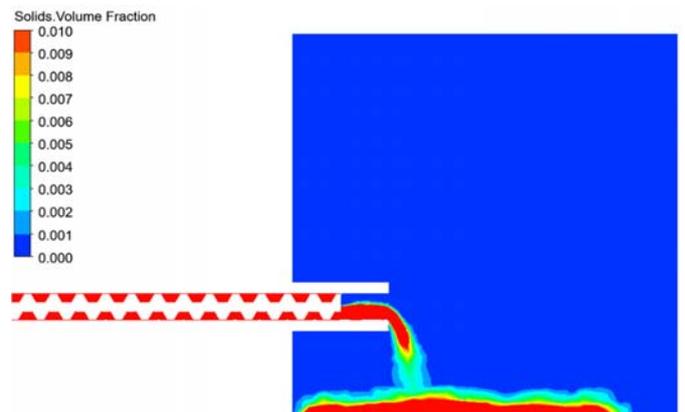


Fig. 7 Solid Volume fraction (localized scale) at mid-section plane

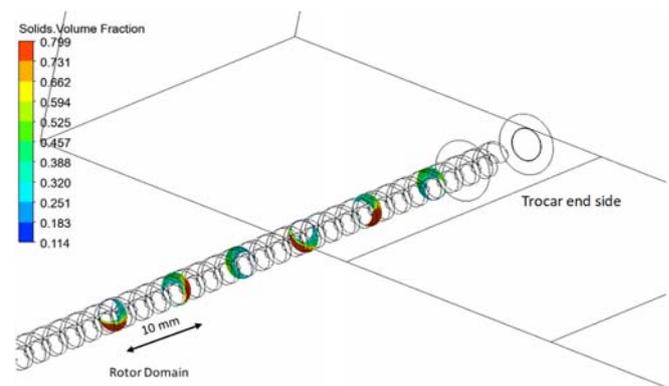


Fig. 8 Solid Volume fraction (global) at different section planes

V. CONCLUSIONS

1. Solid volume fraction was high, as observed at the downside of rotating part, as compared to topside.
2. Maximum velocity was observed to be 0.374 m/s at the mid-section plane.

3. Volume fraction of powder at the trocar's end was about 1%.
4. Experimental validation needs to be done to validate the computational analysis.

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