

TWO DIMENSIONAL TRANSFER CHUTE ANALYSIS USING A CONTINUUM METHOD

Paul McILVENNA¹ and Dr Ruth MOSSAD²

¹ Connell Hatch Pty Ltd, Brisbane, Queensland 4004, AUSTRALIA

² The University of Southern Queensland, Toowoomba, Queensland 4350, AUSTRALIA

ABSTRACT

The performance of transfer chutes is vital to the productivity of conveyor belt systems in the bulk solids industry yet no traditional design method is able to reliably predict the flow characteristics. The discrete numerical method has come to be regarded as the primary tool for particle flow modelling, but many design engineers in industry may not be aware that continuum methods are also suitable for some types of chute analysis.

This paper reports an investigation into a continuum model based on kinetic theory as an alternative to the discrete element method for basic transfer chute analysis. Fluent software has been used to perform two-dimensional modelling of chutes and the result is compared to traditional design methods. The conclusions suggest that continuum models may have an important part to play in the future of chute design.

INTRODUCTION

Transfer chutes are an essential part of every belt conveyor system for handling bulk solids. They are relatively low cost items in the system, but if they don't perform correctly the efficiency of the whole handling system can be severely reduced. Engineers have felt that detailed analysis of chutes is not justified since the associated design costs are significant when compared to the cost of replacing the chute if it performs below expectations. A section of a typical transfer chute is illustrated in Fig. 1.

Mechanical engineers are often presented with the problem of selecting the best transfer chute geometry with limited literature and design methods available. Two major sources of information in Australia are the bulk solids handling departments of both the University of Newcastle and the University of Wollongong. For examples of their work see Alan Roberts (1989 & 1998). The vacuum of detailed design experience translates into conservative designs and hence more cost than necessary to the owner. In many cases, simple rules-of-thumb are used to provide a design that permits the flow of material without blockage, but does not necessarily fulfil other performance criteria such as minimum chute/belt wear, minimum dust generation and lowest material cost.

The owner is not the only stakeholder to be considered. In today's conservative engineering environment further demands are being placed on engineers to work towards sustainable development and therefore minimise raw

material requirements. Other environmental concerns such as dust emissions are also being more closely regulated than before. As well as these pressures, increasing demands are being made by end-users for performance based contracts with specific criteria (such as wear and dust generation). These demands are shaping the future of chute design and to meet these demands, accurate methods of analysis need to become available to the regular chute designer.

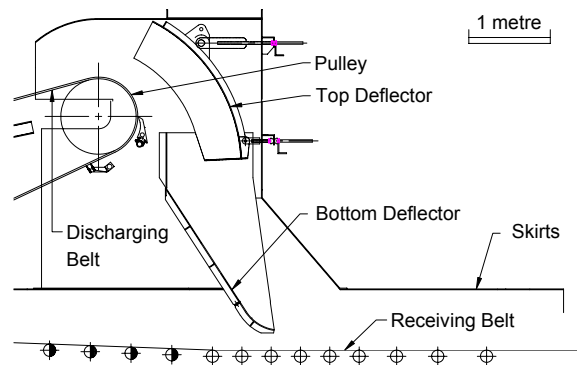


Figure 1: Transfer Chute - Section

Numerical methods employing discrete element modelling are becoming the accepted standard for bulk solids flow analysis and rightly so due to the ability of the models to predict a large number of flow properties. Unfortunately such codes can be expensive to operate and at present they are not widely used in transfer chute design. It can be anticipated that as the capability of software and hardware increases and their cost decreases, these codes will gradually become routine for chute design engineers.

However, there is an important aspect that makes continuum methods especially attractive: consulting engineers may already be using CFD software for other fields of engineering e.g. HVAC analysis, and the same software can be used for analysis of continuum granular models.

The purpose of the present research was to investigate a continuum design method and apply it to chute analysis. Firstly, the capabilities of DEM and continuum methods will be discussed, followed by an example of a continuum method analysis performed by the author using Fluent. The results are discussed briefly and the outputs of the method are highlighted.

GRANULAR FLOW MODELS

There are two types of numerical algorithms for modelling bulk granular flows: the Discrete Element Model and the Continuum Model. At the numerical level, these methods are like chalk and cheese, because the domain of the former model consists of every individual particle in the flow space, whereas the latter is defined by the space through which the particles travel.

Discrete Element Models

The discrete element method follows the traditional notion of real particle motion involving collisions with walls and other particles, and linear motion between these collisions. The calculations for each particle include rotation and torque, contact forces, drag and lift forces, and momentum exchange. Refer to literature such as Cundall (1979) for further information.

Discrete element models in a granular flow context are not to be confused with the normal finite element term: “discrete element” which has a broader application not confined to particles (remember: a continuum model also has discrete *volume* elements). Perhaps “discrete particle models” would be a less confusing term, however industry seems to have adopted Discrete Element Method (DEM) as the designation for this type of work.

All discrete particle models contain a large number of variables and consequently, a large number of particle properties must be provided by the analyst. Properties such as particle hardness, geometry, elasticity, plasticity, drag coefficients, for example, are some of these properties that require extensive testing each time a new material is modelled. Obtaining these properties requires the help of specialist equipment.

Compromises are usually made in the model particle size vs. real particle size because the method is very demanding on computing resources. Despite these difficulties, it must be stated that discrete element models are capable of certain processing features not possible with a continuum method. Particle fracture and size degradation (comminution), tracking of a specific particle, and granular mixing patterns are examples of the specialised outputs from the discrete element method.

Following is a summary of the DEM method from a chute design perspective:

- Domain consists of moving elements, where element displacements, velocity and accelerations only change under gravitational influence or during collisions with walls and other particles. The chute space is defined by the collision surfaces (walls).
- Minimum particle diameter is limited by available computing resources. This restricts the application of DEM to relatively lumpy bulk solids.
- Ability to model breakage of particles (comminution)

Continuum Models

Granular flows can be modelled as a continuous gas-solid flow stream, rather than as a large number of separate particles in space. The flow is expected to deform according to global properties such as granular viscosity and frictional shear resistance.

The kinetic theory for behaviour of a granular phase is developed by drawing an analogy between random granular motion and gaseous molecular behaviour. An overview of the theory and references to its sources is available in Gidaspow (1994). As in gaseous behaviour, the intensity of the particle velocities determines the stresses, viscosity and pressure of the solid phase i.e. the kinetic theory is used to define the constitutive relations for the solid phase.

Today, applications of the kinetic theory approach are used effectively for the numerical analysis of fluidised beds and other fine particle problems with relatively dense solid-gas ratios.

The major considerations of Continuous Models from a chute design perspective are:

- The domain consists of fixed volume elements which define the internal chute space. The external surfaces of the chute space (walls, inlets, etc.) are assigned appropriate properties.
- The contents of the elements change when a flow is introduced into the chute space. The flow is influenced by gravitational forces, aerodynamic forces (optional), surface interactions and internal viscous forces.
- No minimum particle size limit.
- Practical max size limited by random nature of a few particles (this randomness hard to predict anyway).

CFD SOFTWARE

FluentTM is a computational fluid dynamics software based on the integral volume method and is packaged with three multiphase models – Volume of Fluid (VOF), Discrete Particle (Lagrangian), and Eulerian.

The Discrete Particle model is designed for sparse particle trajectories such as tracking bubble motion, and the VOF model is based on standard fluid models and is not suitable for bulk solids modelling.

In the Eulerian model a momentum equation is solved for each phase and it includes external body forces, lift forces, virtual mass forces and interaction forces between the phases. Lift forces arise due to velocity gradient in the primary phase (air in our case), virtual mass forces occur when a secondary phase accelerates relative to a primary phase, and interaction forces depend on friction, pressure, cohesion and other effects. The continuity equation is used to calculate the volume fraction for each phase with the condition that the sum of the volume fraction of all phases should equal one. There is a minimum of two phases in the Eulerian Model – one gas phase (e.g. air) and one granular phase. The maximum number of possible phases is limited by the computer’s processing power. For a detailed explanation of the variables and their mathematical relations refer to the Fluent manuals.

Volume Fraction

Since the granular flow is modelled as a continuum and not as discrete particles, the concentration of particles in every element in the model is represented by a volume

fraction. The momentum and transport equations are calculated for each phase individually.

Virtual Mass Effect

The ‘virtual mass effect’ occurs when a secondary phase accelerates relative to the primary phase. The inertia mass of the primary phase exerts a virtual force on the accelerating secondary phase particles.

Solids Shear Viscosity

The shear viscosity is a combination of the collisional, kinetic and frictional viscosities. The frictional viscosity is predominant where the flow has low deformation rates and the secondary phase volume fraction is near the packing limit.

Bulk Viscosity

The bulk viscosity represents the resistance of the granular phase to compression and expansion. The restitution coefficient defines the material’s resistance to compression and expansion, and is similar to the concept of ‘bulk modulus’ of solid materials.

Wall Friction

The wall friction behaviour is entered into the software as one of the boundary conditions of the chute walls. Fluent can accommodate full-slip, no-slip, fixed or variable shear wall conditions. Full-slip means that the material will slide (slip) freely over the wall surface with no shear at all, assuming ideal flow. No-slip means that the material in contact with the wall will ‘stick’ to the wall with no sliding at the wall interface. This wall condition is a more realistic assumption since most homogeneous, viscous fluids, such as water, exhibit this property. Finally, the fixed-shear wall condition allows the user to apply a fixed shear stress to the wall interface. It is possible to write a user-defined function for a variable shear on the wall using the C programming language to apply the correct wall shear, however the time scale of the project did not accommodate this task. Therefore a fixed wall friction angle independent of consolidation pressure was used.

CHUTE DESIGN WITH THE EULERIAN MODEL

In order to evaluate the Eulerian model on a real chute design, a chute installed on a coal shiploader in the central coast of Queensland was selected (see Fig. 1). An early version of the chute (not shown) had a top deflector with a combination of curved and straight surfaces and was prone to blockage. It was later replaced by the revised design shown in Fig. 1 with a curved surface only. For the sake of brevity, a drawing of the earlier design has not been included, but the reader can compare the shape of the deflectors in Fig. 2 (early design) and Fig. 3 (revised design). Both designs were modelled to see if the 2D analysis could indicate where the first design was inadequate.

Because it was an early investigation of the Eulerian model, only two dimensional problems were considered. The modelling and analyses were performed using Fluent v6.0 at the University of Queensland, St Lucia Campus, on an SGI Origin 3000 computer. The average processing time for each analysis was about two hours.

Table 1: Typical Model Variables

Variable	Units	Value
Solver		Segregated
Flow Regime		Laminar
Time		Unsteady
Time Step	sec	0.001
Nominal Mesh Spacing	mm	75
Chute Wall Boundary		No-slip
Particle Diameter	mm	25
Particle Density	kg/m ³	1300
Granular Bulk Viscosity		Lun-et-al
Restitution Co-efficient		0.5
Frictional Viscosity		Schaeffer
Angle of Internal Friction	deg	30
Packing Limit		0.6
Volume Fraction Discretisation		2nd Order

The unsteady solver is necessary for chute analysis with the Eulerian model. A time step of 0.001s was adopted to avoid instability which occurred at higher time steps when the advancing flow reached the impact locations where deformation rates are quite high.

The air volume fraction of the entire model was first initialised to unity, and then a flow of bulk material was introduced into the chute from the conveyor belt inlet. To avoid unrealistic divergence of the flow at the inlet, the conveyor pulley and part of the moving belt were included in the model.

Table 2: Wall Types

Physical Wall Type	Fluent Wall Type	Value
Chute Sides	Fixed Wall	Full Slip or No Slip
Material Inlet	Inlet	Vol Frac. (coal) = 0.7
Discharging Conveyor Belt	Moving Wall	v = 4.3 m/s
Receiving Conveyor Belt	Moving Wall	v = 4.3 m/s
Skirt Exit	Pressure Outlet	Atm. Pressure
All Other Open Sides	Pressure Inlet	Atm. Pressure

For the material inlet, it was important to match the velocity of both phases (coal and air).

RESULTS

Qualitative results obtained from the Eulerian model met the expectations for prediction of flow shape including local recirculation zones near the impact surfaces. A typical plot of volume fraction of the original design is illustrated in Fig. 2. This figure shows the advancing flow of coal at a real time of 2.5 seconds.

A volume fraction plot of the revised design is illustrated in Fig. 3. The colour/shades in the plots in Fig 2 & 3 represent the average particle spacing.

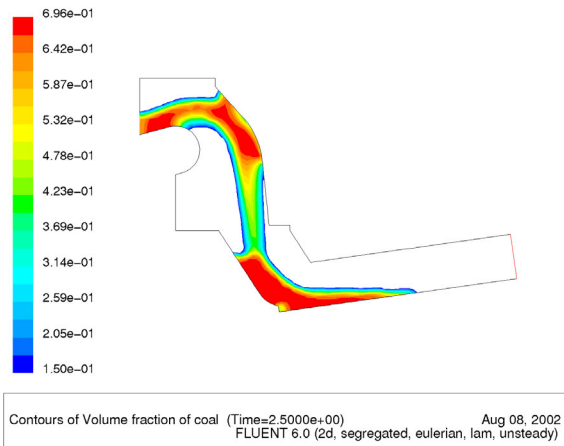


Figure 2: Volume Fraction – Original Design

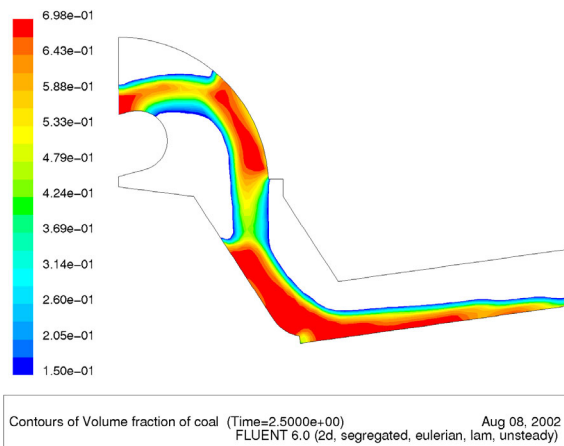


Figure 3: Volume Fraction – Revised Design

The outlet boundary at the skirt exit was difficult to model correctly using the standard wall types. A pressure outlet proved to be the most useful but still generated slight air ‘surges’ propagating from the skirt exit back into the chute. These surges can be seen clearly in the velocity vector plot in Fig. 4. The velocity vectors should be interpreted in conjunction with the material stream outline in Fig. 2 because the velocity plot does not eliminate the regions of very low probability of particles.

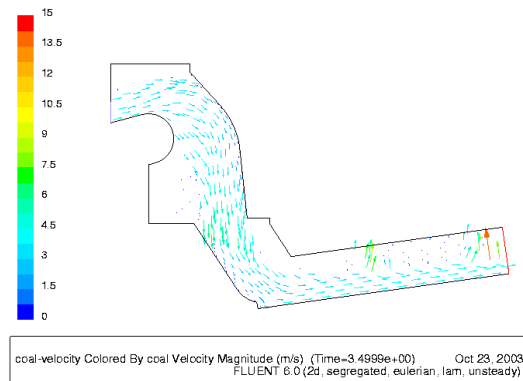


Figure 4: Velocity Vectors of Coal Phase

The results have indicated some possible causes for the better performance of the revised design. Wall shear stresses on the bottom deflector (Fig. 5) and bottom

conveyor belt (Fig. 6) are significantly lower in the revised design meaning less resistance to the flow and therefore a lesser chance of generating blockages. The lower shear stress on the conveyor belt indicates that a longer belt life can be expected from the revised design. Shear stresses on the top deflector (Fig. 7) are marginally higher in the new design indicating a higher wear rate, but that is a small price to pay for a chute that functions properly.

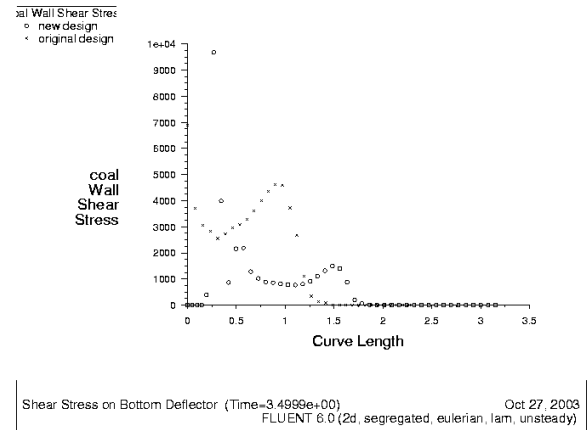


Figure 5: Shear Stress on Bottom Deflector

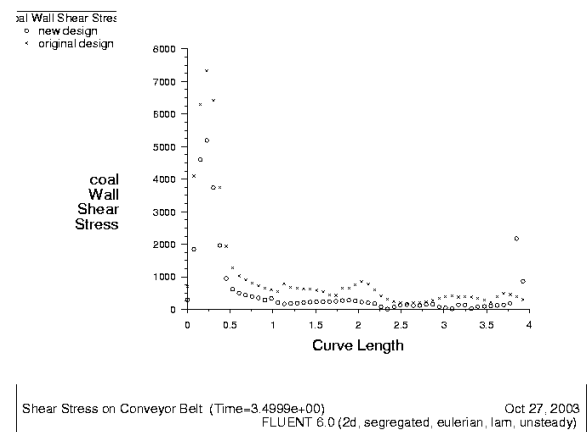


Figure 6: Shear Stress on Bottom Conveyor Belt

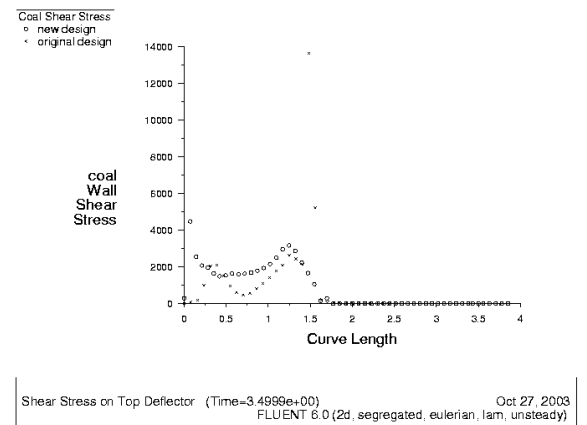


Figure 7: Shear Stress on Top Deflector

The basic stream velocities have been compared to a traditional design method involving Korzen's impact mechanics and one-dimensional linear motion equations. From the experience of the author and colleagues, this method yields velocities that are higher than observed in the field. The difference between this method and the Fluent results is illustrated in Fig. 8. If the real wall condition were modelled with a custom function the result should lie between the No-Slip and Full-Slip curves, which are both lower than the results from the traditional method and correspond to the velocities experienced in practice.

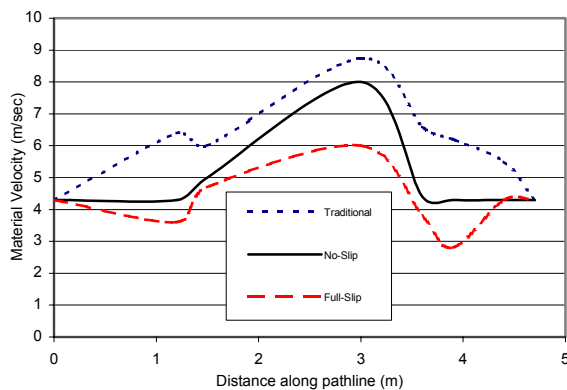


Figure 8: Streamline Velocity from Different Methods

In one of the test cases, the particle diameter was increased to 50mm and this produced an unexpected result. A 'bunching up' in the form of an arch was evident between the discharge pulley and the deflector (Fig. 9). The most likely cause of this problem is that the particle size was too large for the chute.

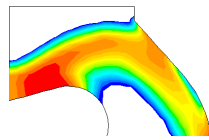


Figure 9: 'Bunching' due to excessive particle size

The accuracy of the model outputs has not yet been verified and a check of grid dependency has not been completed due to time constraints before publication.

CONCLUSION

Upon completion of the project, the following conclusions were drawn:

- continuum methods have good potential for basic transfer chute analysis;
- although two dimensional modelling is limited, it gives meaningful results that cannot be obtained by traditional design techniques;
- continuum methods are appropriate numerical methods able to be applied to the modelling of fine powders in chutes; and
- within the context of transfer chute analysis, the most significant variables in the Eulerian model are the time step, the particle size and wall friction model.

Despite the inability to provide detailed individual particle data (for which DEM methods are required) the

continuum model is useful for many chute design tasks such as predicting flow shape, stream velocity, wear index and location of flow recirculation zones. It is a numerical method available with the potential for efficiently modelling multiple phases.

REFERENCES

- BAGNOLD, R.A., (1954) *Proceedings of the Royal Society of London*, A225, 49.
- CLEARY, P. and SAWLEY, M., (1998), "Three-dimensional Modelling of Industrial Granular Flows". *Second International Conference on CFD in the Minerals and Process Industries*, Melbourne.
- GIDASPOW, D., (1994), "Multiphase and Fluidized Flow: Continuum and Kinetic Theory Descriptions". Academic Press, Boston.
- HUQUE, S.T. and McLEAN, A.G., (2002), "Belt Conveyor Transfers – A Brief Review", *Bulk Solids Handling*, Vol. 22 No.3.
- KORZEN, Z., (1998), "The Dynamics of Bulk Solids Flow on Impact Plates of Belt Conveyor Systems", *Bulk Solids Handling*, Vol. 8, No. 6, December.
- LUN, C. K. K., SAVAGE, S. B., JEFFREY, D. J., and CHEPURNIY, N. (1984), "Kinetic Theories for Granular Flow: Inelastic Particles in Couette Flow and Slightly Inelastic Particles in a General Flow Field". *J. Fluid Mech.*, 140:223-256.
- McILVENNA, P., (2002) "The Application of Granular Kinetic Theory to Transfer Chute Design", *B.Eng. Thesis*, The University of Southern Queensland, Toowoomba.
- NORDELL, L., (1998), "Particle Flow Modelling: Transfer Chutes & Other Applications", *Master of Engineering Course: Centre for Bulk Solids Handling and Particulate Technologies*, April.
- ROBERTS, A.R., (1989), "Concepts of Boundary Friction, Adhesion and Wear in Bulk Solids Handling Operations", *3rd International Conference on Bulk Materials, Storage, Handling and Transportation*, Newcastle, June.
- ROBERTS, A.W., (1998), "Transfer Chute Performance and Design", *Master of Engineering Course: Centre for Bulk Solids Handling and Particulate Technologies*, April.
- SCHAEFFER, D. G. (1987). "Instability in the Evolution Equations Describing Incompressible Granular Flow". *J. Diff. Eq.*, 66:19-50.
- SYAMLAL, M. and OBRIEN, T.J., (1987), "A Generalized Drag Correlation for Multiparticle Systems", *Morgantown Energy Technology Centre DOE Report*. "User Manuals", *Fluent Version 6.0*. Fluent Incorporated, USA.

