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An Eulerian–Eulerian Formulation for Erosion Modelling: An Alternate Approach

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Abstract
Sand is commonly produced besides petroleum fluids and it presents a major erosional hazard leading to pipe failures. Particle erosion is a complex process in which material is removed due to the repeated particle impacts. Conventionally, a CFD flow solver and computationally intensive lagrangian particle tracking sub–routines, known as Eulerian–Lagrangian (E–L) model, along with empirical erosion equations are used to predict the erosion rates. The present work introduces an Eulerian–Eulerian (E–E) approach in which the multiphase granular model resolves the solid phase and obviates the need of particles tracking. Particle–laden turbulent flow across a flow restrictor, based on an experimental study, is chosen for validation. Numerical experiments are done in Simcenter STAR–CCM+. Comparison with the experimental data demonstrate a good agreement and in particular, the E–E model yields reliable predictions of impact wear locations, erosion rates as those of E–L model. A 90° square bend is also simulated and comparison of erosion rates on the concave wall demonstrate that E–E model can be used as an alternate to computationally expensive approaches.

Keywords: *CFD–based erosion model; Multiphase flow; Eulerian model; Kinetic theory granular model*.

I. INTRODUCTION

A major issue in the Oil and Gas industry is the sand entrainment into production fluids and it leading to particle erosion. Usually, erosion in pipe bends, fittings is more than that of straight sections due to local turbulence and flow transience [1]. Bends, sectional changes introduce a change in the flow direction and the particle's inertia causes it to deviate from the fluid stream leading to a wall impact. As a result, either the particles attrite or the pipe erodes [2]. Therefore, predicting particle erosion is imperative in designing and precluding equipment failures. Literature reports many modelling approaches which are classified into three main categories: Empirical, Mechanistic and Computational Fluid Dynamics (CFD)–based. Researchers have opined that erosion is a complex process and despite rigorous investigations, the mechanism is not fully comprehended and most predictions are a combination of all three above approaches [3, 4]. Finnie [4] proposed the first analytical correlation for erosion in 1958. Thereafter, owing to enormous industrial importance, many investigators have carried out both empirical and/or analytical modelling of erosion mechanisms in bends, elbows, tees and related geometries. Meng and Ludema [5] and more recently, Mazdak et al. [6] provided a critical review of erosion models and emphasized that each model has originated from a specific approach and no single equation exists to suit all the scenarios.

Significant attempts are also made using the numerical methods as well. Shirazi et al. [7] developed a 1D numerical model for fluid and sand phases for simple flow scenarios. Zhang et al. [8] extended it to 2D while accounting tangential impacts and turbulence effects. This model tracked a large number of particles and provided statistically independent results. Jordan [9] further extended Shirazi et al. [7] to multiphase flows and accounted for mixture properties whilst predicting erosion rates. In the early 1990s, commercial CFD packages have gained popularity due to their ability to model complex geometries. Conventionally, a CFD–based erosion model consists of following three steps: Flow and resolution of turbulence, computationally intensive solid particle tracking throughout the domain and lastly, relating the particle impact data to empirical erosion ratio equations such as Ahlert [10], Det Norske Veritas [11], Nelson–Gilchrist [12] and Oka [13]. Wang et al. [14] used the CFD flow solution in elbows to estimate erosion rates. Edwards, McLaury and Shirazi [15] employed a commercial CFD code together with E/CRC erosion equation [10] for a gas–solid flow. Forder et al. [16] modelled deformation due to erosion in control valves using commercial CFD code and obtained a good agreement with experiments. More recently, Wallace et al. [17] used E–L model along with semi–empirical erosion equation for a choke valve geometry. Habib and co–workers [18] extended this model to sudden pipe contractions. Li et al. [19] accounted for particle–particle interactions for erosion in choke valve.

There is a continued interest in prediction of erosion rates to estimate the life of equipment. Huge computational requirements force most of the CFD–based or numerical approaches to settle for one–way coupling. That is, flow is unaffected by particle motion. This neglects the transience of erosion mechanism and cumulative effects of numerous factors. In this article, an E–E approach is presented in which the multiphase granular model [20] is used to compute the solid phase's collision frequency and volume fractions and thus obviates the need of computationally expensive particles tracking Model is validated using particle–laden turbulent flow across a flow restrictor in Simcenter STAR–CCM+.

II. EROSION MECHANISMS AND THEIR MODELLING

There are two erosion mechanisms: Impact wear and Abrasive wear. Impact wear occurs due to a direct particle impact on a surface and it prevails during light–particle loading combined with an abrupt change in flow direction. In an abrasive wear, particles are scoured along the surface due to local flow conditions in high–particle loading cases.

A. Eulerian–Lagrangian (E–L) Model

In Simcenter STAR–CCM+, the following continuity and momentum equations for continuous phase are solved using an Eulerian framework [21].

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

Momentum Equation

$$\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot (\rho \mathbf{V} \otimes \mathbf{V}) = -\nabla \cdot (p\mathbf{I}) + \nabla \cdot \mathbf{T} + \mathbf{f}_b \tag{2}$$

Additional closure equations are solved for turbulence, such as $k-\epsilon$ model or $k-\omega$ model wherever necessary. The discrete phase or sand particles are tracked in space–time coordinates as they are transported under the influence of continuous phase using Lagrangian framework. Path of each single particle, say i^{th} particle, is resolved by numerically integrating below linear equation of motion.

Particle's Linear Equation of Motion [21]

$$\frac{d\mathbf{V_i}}{dt} = \mathbf{F}_{\text{Drag}} + \mathbf{F}_{\text{Virtual Mass}} + \mathbf{F}_{\text{grad(p)}} + \mathbf{F}_{\text{Body Force}} + \mathbf{F}_{\text{Lift}} \tag{3}$$

Amongst all the forces, drag plays a pivotal role. Virtual mass is dominant for high fluid to particle density ratios. Pressure gradient force acts on the particle's surface and body forces include gravity effects. Lift or Saffman force is dominant in high shear flows. This particle data in conjunction with empirical erosion ratio equations predict the wear patterns and erosion rates. Oka et al. [13] is listed below and other models, all nomenclature can be obtained from referred articles [10, 11, 12, 13, 21]. E–L model accounts for near–wall particle impacts as against to mean values for more realistic results.

Oka Correlation [13]

$$e_r = e_{90} g(\beta) \left(\frac{u_{rel}}{u_{ref}}\right)^{k_2} \left(\frac{D_{part}}{D_{ref}}\right)^{k_3} \tag{4}$$

B. Eulerian–Eulerian (E–E) Model

The underlying continuous fluid flow and solid sand particles are modelled as inter–penetrating continua. Governing laws as given in Equations (1), (2) are solved for each of the phases to resolve their respective flow characteristics, volume fractions and in addition, Granular stress τ_s equation based on Kinetic Theory Granular Model (KTGF) is solved to account for solid inelasticity.

Granular Stress Equation

$$\tau_s = -p_s + \mu_s \left(\nabla \mathbf{u}_s + (\nabla \mathbf{u}_s)^T + \left(\mu_{b,s} - \frac{2}{3}\right)(\nabla \cdot \mathbf{u}_s) \right) \tag{5}$$

Granular Temperature Equation

$$\frac{3}{2}\left[\frac{\partial}{\partial t}\alpha_s \rho_s \theta_s + \nabla \cdot (\alpha_s \rho_s \theta_s \mathbf{u}_s)\right] = \nabla \cdot (k_s \nabla \theta_s) + \tau_{s,k} : \nabla u_s - \gamma_s - J_s \tag{6}$$

It assumes that the solid viscosity and stress are functions of granular temperature θ_s [20]. Near–wall particle phase's data and erosion ratio equations estimate erosion rates. However in E–E model, particle impacting, rebounding are not accounted.

III. SIMULATION SETUP AND VALIDATION

A. FLOW RESTRICTOR

Geometry in use is a flow restrictor, tested under erosive conditions using water–sand flow (0.39% w/w) by Wallace et al. [17]. It is mounted between lengths of 53.1 mm diameter piping as shown in Figure 1[A] with a flow rate of 28.09 kg/sec. Sand density is 2650 kg/m^3. Static pressure measurements are made at 106 mm upstream and 318 mm downstream of restrictor. Also, overall mass loss was recorded by weighing the restrictor periodically over a 14 hour test period.

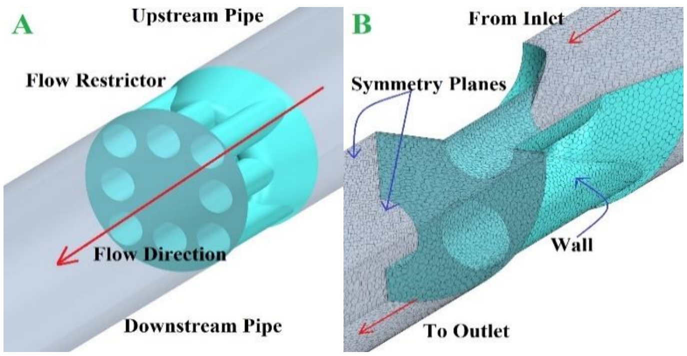

Figure 1: [A] Restrictor geometry. [B] Calculation mesh and boundary arrangement.

A 3D poly mesh is generated in Simcenter STAR–CCM+ with boundary arrangement as shown in Figure 1[B]. Due to symmetry, only a quadrant of it is analysed. A steady, segregated flow solver with $k-\omega$ turbulence is chosen for water phase and sand is entrained using lagrangian injectors and boundary volume fraction in E–L and E–E models, respectively, with a velocity matching that of liquid phase. Mainly, drag, pressure gradient, virtual mass and turbulent dispersion forces are accounted for solid phase and every effort is made to make both setups similar for an accurate comparison.

Restitution coefficients developed by Forder et al. [16] are used through user code. Impact erosion rates are predicted using Oka et al. [13] and coefficients are adjusted for sand–carbon steel combination. Necessary post–processing for pressure drop, wear locations and erosion rates are setup and simulations are converged. Results are tabulated as shown in Table 1. Pressure drop values from the simulations compare favourably with those from test. E–E model slightly over predicts due to a strong numerical coupling among phases.

Table 1: Comparison of test, E–L and E–E approaches

	Test	E–L	E–E
Pressure Drop (bar)	5.44	5.82	7.83
Erosion Rate (gm/hr)	0.58	0.75	0.49

It is vital to state that in both the models, flow is validated and it is imperative as erosion predictions are largely dependent on underlying flow field. Using Oka model, predicted wear patterns are as shown in Figure 2[A] and 2[B] for E–L and E–E models respectively.

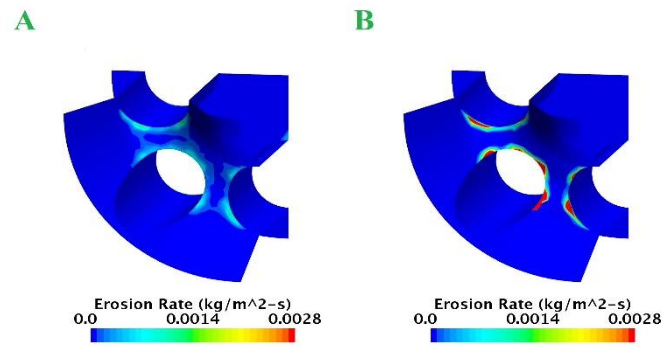

Figure 2: [A] E–L model erosion rate. [B] E–E model erosion rate.

B. 90° SQUARE ELBOW DUCT

Side of square cross–section and inner radius of the elbow section are both one inch in dimension. Boundaries making up the computational domain are as shown in the Figure 3[A]. With sufficient entry and exit lengths, geometry is discretized using polyhedral cells in Simcenter STAR–CCM+ as shown in the Figure 3[B].

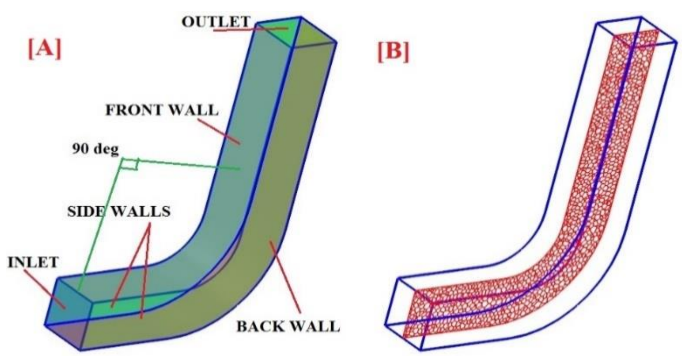

Figure 3: [A] Boundary arrangement. [B] Mesh scene.

Air being the continuous phase, enters the domain through an inlet boundary at 0.47772 g/s for both E–L and E–E setups and 0.25 mm spherical sand particles with 2650 kg/m^3 density are released into the domain at 2.6 g/s. In E–L model, inlet boundary acts as lagrangian injector where as in E–E model, boundary volume fraction is adjusted to equate mass flows. Outlets are modelled as pressure outlets. For both the cases, flow is stabilized before the release of sand to enhance numerical stability. In this case, Neilson–Gilchrist impact wear model is chosen and wear patterns are predicted. Results presented below are impact wear patterns for E–E and E–L models as shown in Figure 3[A] and 3[B] respectively.

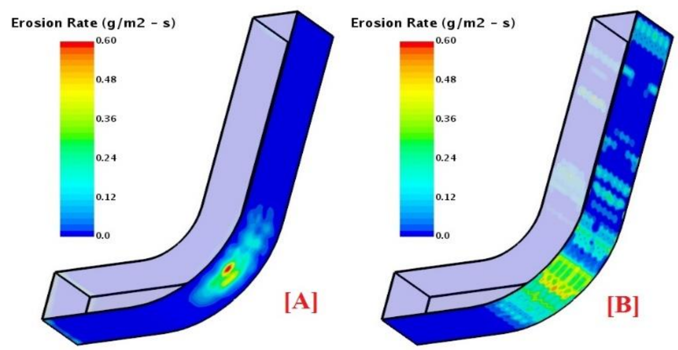

Figure 3: [A] E–E model, [B] E–L model.

IV. CONCLUSIONS

It is vital to note that although both models are fundamentally different but predicted similar erosion patters for restrictor as well as square duct cases. The hot spots, both qualitatively and quantitatively, are in good agreement. Overall, the predicted patterns are realistic in nature and plausible. As stated earlier, the computational time and effort required for E–E model is substantially less as it obviates the need for particle tracking. Therefore, this model can be used by industries as alternate to computationally expensive conventional approaches.

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