Erosion Wear Evaluation Using Nektar++

Manuel F. Mejía, Douglas Serson, Rodrigo C. Moura, Bruno S. Carmo, Jorge Escobar-Vargas, and Andrés González-Mancera

1 Introduction

Wear is a common phenomenon on many machines and devices, it is characterised by the removal or loss of material. Erosion wear is a particular wear process which occurs when solid particles or droplets, carried by a fluid (liquid or gas), impact on a solid surface [1]. Turbomachinery such as pumps, turbines and pipe accessories (i.e. tees, elbows, nozzles, valves), are examples of elements affected by the erosion wear, decreasing the performance and the lifetime. In many industrial sectors e.g. energy and mining, and oil & gas; massive amounts of resources are used for maintenance and replacement of affected parts [2–4]. Despite this phenomenon have been broadly investigated [5–14] there are still unsolved challenges in establishing the influence of small eddies during the erosion process leading to modest accuracy levels in the simulation results.

M. F. Mejía (✉)

Universidad de Los Andes, Bogotá, D.C., Colombia

Universidad Central, Bogotá, D.C., Colombia

e-mail: mf.mejia@uniandes.edu.co

D. Serson · B. S. Carmo

Universidade de São Paulo (USP), São Paulo, Brazil

R. C. Moura

Instituto Tecnológico de Aeronáutica, São Paulo, Brazil

J. Escobar-Vargas

Pontificia Universidad Javeriana, Bogotá, D.C., Colombia

A. González-Mancera

Universidad de Los Andes, Bogotá, D.C., Colombia

© The Author(s) 2020

S. J. Sherwin et al. (eds.), *Spectral and High Order Methods for Partial Differential Equations ICOSAHOM 2018*, Lecture Notes in Computational Science and Engineering 134, https://doi.org/10.1007/978-3-030-39647-3_33

Due to the microscopic nature of erosion, the smallest scales in the flow play a fundamental role in the complete process. One of the aspects which has not been carefully studied in erosion wear modelling is the effect that the smaller eddies and secondary flows have on the particles interactions with the surface. In general, these secondary flows could not be represented using linear Reynolds Average Navier Stokes (RANS) simulations, this is mainly because the Reynolds stress imbalance is neglected and the secondary flow does not develop. As was mentioned by Gross and Fasel [15], predictions of the secondary flow require non-linear Reynolds stress, full Reynolds-stress models, Large Eddy Simulations (LES) or Direct Numerical Simulation (DNS). Due to their relatively low computational cost, RANS models are often used to predict erosion using CFD in industrial simulations. The inclusion of smaller eddies and secondary flows in the simulation could be a major breakthrough in the modelling of erosion process. In order to capture in an accurate way the physics related with the small eddies and secondary flows, a numerical technique capable to represent those processes, is needed. As emphasised by Jacobs [16], the use of spectral methods could allow increased accuracy in the simulation due to the potential to simulate a wider range of scales. With this in mind, the purpose of this work is to assess the impact of higher resolution methods on the prediction of erosion wear rate and distribution.

1.1 Spectral Methods

Several numerical techniques are used to solve Navier Stokes (NS) equations. Some of them are finite differences, finite volumes and finite elements. Nevertheless, when high accuracy is required the use of a lot of elements is needed in the modelling, which significantly increase the computational cost [17, 18]. Hence novel methods are subject of research to offer a better rate accuracy and computational cost.

Among novel numerical methods considered nowadays are spectral methods, which have shown to be a powerful tool with high level of accuracy for solving large problems in computational fluid dynamics (CFD), according to the available literature, especially in the studies developed by Boyd [19], Canuto et al. [20–22], Trefethen [23, 24] and Sherwin [25, 26]. Nektar++ is an open-source software framework designed to support the development of high-performance scalable solvers for partial differential equations using the spectral/hp element method [27]. High Order CFD methods have been receiving considerable attention in the past two decades. Traditional CFD software could be replaced by high order code in many applications in few years [28].

1.2 Particles Tracking

To the best of the authors' knowledge, there is no work that uses high order methods to evaluate erosion wear rate. This research aims to assess the impact of higher resolution methods on the prediction of erosion wear rate and distribution. It

comprises the solution of fluid flow using incompressible NS solver with implicit LES modelling, the implementation of a Lagrangian particle tracking model and the later data processing through traditional erosion rate models but using the available high order information. This could allow the evaluation of traditional rate models with more spatial resolution and accuracy.

The Lagrangian particle tracking model is based on one-way coupling approach, that is the most simple case when just the iteration between the fluid and each particle is taking into account in just one way. That means that the particles are moved by the fluid but the fluid flow is not perturbed by the particles. Moreover, the effects of the collision between particles are also neglected. The one-way coupling model is valid for volume concentrations of particles lower than 10^{-6} [29, 30].

The problem of predicting particle motion in a fluid flow can be predicted by solving an evolution equation in time:

$$\frac{d \mathbf{v}_p}{dt} = F(\mathbf{u}, \rho, \rho_p, C_d, \dots) \quad ; \quad \frac{d \mathbf{x}_p}{dt} = \mathbf{v}_p \quad (1)$$

where $\mathbf{v}_p$ and $\mathbf{x}_p$ are the particle velocity and position and F is a function of the velocity of the fluid $\mathbf{u}$, the density of the fluid ρ and particle density ρ_p , among others.

To start, it is necessary to obtain the velocity on a certain point from the eulerian velocity field. This process consists of finding the element containing the particle and interpolating the velocity with the element information. In a higher-order velocity element field, the use of linear interpolation is inaccurate and could vanish the advantage won with the use of high order methods. On the other hand, using high order interpolation could be computationally expensive. Therefore, special attention to this procedure is required [16, 31, 32].

1.3 Erosion Wear Evaluation

Once the information about the collisions is complete, the erosion wear model is used to predict the pattern of material removed. The general erosion equation, based on the work of Finnie [33–38] can be presented as

$$W = k F_s V_p^n f(\theta) \quad (2)$$

W is the erosion rate or material removed by collision, k is a wall material dependent constant, F_s is the particle geometric factor, V_p and n are the collision velocity and the velocity exponent, and $f(\theta)$ is a function of collision angle. Several authors define these values for different materials configurations and test cases. Three of the most used models, which include experimental results are the jet impingement test [39–45], elbow erosion [46–49], and the works of the Wong et al. [4, 46, 50, 51].

2 Implementation

This section describes the implementation of erosion wear in Nektar++. To achieve this objective is important to have in mind the partition of the problems into two parts. The first one is the particle tracking as a filter within the Nektar++ incompressible Navier Stokes solver. A filter in Nektar++ is a module for calculating a variety of useful quantities from the field variables as the solution evolves in time [27].

The second one is implemented as a FieldConvert module to evaluate the erosion of each collision and generate the fields on the boundaries walls. FieldConvert is a utility embedded in Nektar++ with the primary aim of allowing the user to work with the Nektar++ output files, some of the modules within FieldConvert allow the user to postprocess the output data [27].

2.1 Particles Tracking

The first step was the implementation of a ODE time solver. Several options are available, but having into account the discrete time flow fields calculated with the Navier Stokes incompressible solver, and to avoid the use of temporal interpolation, the selected option was the Adams-Bashforth (AB) and Adams-Moulton (AM) schemes.

The implementation was tested with a benchmark case presented in [31]. In this model, the particle velocity is the fluid velocity at certain point and the evolution equation is reduced to one equation; Eq. 1 is reduced to:

$$\frac{d \mathbf{x}_p}{d t} = \mathbf{u} \quad (3)$$

To solve this system a Time-Marching Method was implemented, meaning that the future values are evaluated using the present and past values of the variables. Explicit AB and Implicit AM methods were implemented using first to fourth integration order. The error values obtaining using AB and AM with different order presents features from this kind of methods.

The next step was the implementation of the solid particles. In this case, the momentum equation is evaluated on each particle, resulting:

$$\frac{d \mathbf{v}_p}{d t} = F_d (\mathbf{u} - \mathbf{v}_p) + \mathbf{g} \frac{\rho_p - \rho}{\rho_p} \quad ; \quad \frac{d \mathbf{x}_p}{d t} = \mathbf{v}_p \quad (4)$$

$$F_d = \frac{3}{4} \frac{C_d Re_p \rho_p}{v d_p^2} \quad (5)$$

$$Re_p = \frac{(\mathbf{u} - \mathbf{v}_p)d_p}{\nu} \quad (6)$$

$$C_d = \begin{cases} 24/Re_p, & Re_p < 0.5 \\ 24/Re_p \left(1 + 0.15Re_p^{0.687}\right), & 0.5 < Re_p < 1000 \\ 0.44, & Re_p > 1000 \end{cases} \quad (7)$$

where F_d is the drag force, Re_p is the Reynolds Number based on the diameter of the particle, $\mathbf{g}$ is the gravity acceleration, and C_d is the drag force evaluated on each particle.

Figure 1 shows a diagram of the evolution equation. Current position, velocities and forces are evaluated to get the future positions (BP, OP) until the next position is located outside of the domain (NP). When this happens, the evolution algorithm stop and a function is used to evaluate the collision point (CP) and the position after collision (NP') using the high order information about the walls.

2.2 Erosion Wear Evaluation

Erosion rate per collision (Eq. 2) has to be integrated over each element of the eroded surface. For each particle collision, more material is removed from the surface, the elemental erosion rate has to take into account this cumulative effect over the surface.

As mentioned before, the set of parameters used in this work, has been based on experimental data. One of the most used parameter set is the one proposed by Erosion group of the University of Tulsa [38, 48, 52]. The erosion rate takes the form of Eq. 2, $F_s = 1$ for sharp (angular), 0.53 for semi-rounded, or 0.2 for fully rounded sand particles. V_p is the impact velocity and $n = 1.73$. The angle function has the form:

$$f(\theta) = \begin{cases} a\theta^2 + b\theta, & \text{for } \theta \leq \phi \\ x \cos^2(\theta) \sin(w\theta) + y \sin^2(\theta) + z & \text{for } \theta > \phi \end{cases} \quad (8)$$

Fig. 1 Evolution of particle tracking

All the parameters and empirical constants depend on the material being eroded. For velocity in ft/s, the steel-sand parameters are: $a = 38.4$, $b = 22.7$, $\phi = 1$, $x = 0.3147$, $y = 0.03609$, $w = 0.2532$ and $z = 0$ [53].

3 Test Case

To test the new feature in Nektar++, a Backward Facing Step (BFS) model was developed based on the experimental setup of [30, 32, 54] showed in Fig. 2. In the model developed in this work, the simulations were done with the addition of gravitational effects on the $-y$ direction. In original experiments the air at the inlet is a well development turbulent flow ($\bar{u} = 10.5$ m/s), this is used as inlet condition and, to complete the model, a zero pressure condition at the output. The additional boundaries were set as walls. A zero velocity field was set as initial condition. The particles used have a $70\text{ }\mu\text{m}$ diameter and 8808 kg/m^3 density.

Figure 3 (top) shows a snapshot of the velocity field when the statistically stationary regime is reached ($t = 8$ s), next the particles are released and were convected by the flow. Particular trajectories are shown in grey lines in Fig. 3 (bottom). In the same figure, results of the particle collision with the walls, computed with Eq. 2, are also shown.

From the results presented Fig. 3, the typical BFS velocity profiles can be recognised. It is important to note the details behind the step, the main flow originates the secondary eddies and defines the limit of the recirculation zone ($x/H = 7$ from the step) where backflow occurs. Additionally, interesting details appear in between each main velocity flow ripple and the walls along the x -direction.

It is noteworthy that particle tracking is evaluated using a steady velocity field, therefore the existence of several irregularities is expected, for instance, particle trajectories inside recirculation zone. Erosion rate depends on the number of collisions at specific points. It is a localised phenomenon that does not occur continuously in the domain. Its distribution shows a strong dependence on the flow dynamics.

Fig. 2 Geometry of the Backward Facing Step setup. The initial velocity was set to get a $Re = 18,600$

Fig. 3 BFS case results. Top: Velocity field at a statistically stationary condition. Bottom: Distribution of the particles inside the flow (gray lines). The colours in the walls indicate the location of the normalised erosion rate

4 Conclusion and Future Work

This work presented a method developed to assess the erosion wear rate using a high-order (spectral) element based technique on a modified test case implemented in Nektar++. The methodology proposed in this study has a potential to increase the accuracy when solving this kind of problems. Future research activities are going to be focused on the determination of accuracy improvements and optimisation of the proposed methodology. Several more cases have to be tested to produce solid conclusions about the implemented methodology, as well as a detailed comparison with experimental test cases.

Despite the methodology implemented had several important simplifications, as the use of one-way coupling and the few forces taken into account, allowed quicker implementations and results. This work would be an interesting starting point to implement this kind of simulations using Nektar++. However, to run more realistic cases, additional research efforts are required for the implementation of two-way and four-way coupling and the effects of other forces over each particle.

References

1. Kulu, P., Kleis, I.: Solid Particle Erosion: Occurrence, Prediction and Control. Springer, London (2008)
2. Neopane, H., Cervantes, M.: Sediment erosion in hydraulic turbines. Global J. Res. Eng. Mech. Mech. Eng. **11**, 17–26 (2011)

3. Walker, C.I., Robbie, P.: Comparison of some laboratory wear tests and field wear in slurry pumps. *Wear* **302**(1–2), 1026–1034 (2013)
4. Wong, C.Y., Solnordal, C., Graham, L., Short, G., Wu, J.: Slurry erosion of surface imperfections in pipeline systems. *Wear* **336**, 72–85 (2015)
5. Karimi, A., Schmid, R.K.: Ripple formation in solid-liquid erosion. *Wear* **156**(1), 33–47 (1992)
6. Zeng, C., Xiao, Y., Wang, Z., Zhang, J., Luo, Y.: Numerical analysis of a Pelton bucket free surface sheet flow and dynamic performance affected by operating head. *Proc. IMechE* **231**(3), 182–196 (2017)
7. Padhy, M.K., Saini, R.P.: Study of silt erosion mechanism in Pelton turbine buckets. *Energy* **39**(1), 286–293 (2012)
8. Bajracharya, T.R., Acharya, B., Joshi, C.B., Saini, R.P., Dahlhaug, O.G.: Sand erosion of Pelton turbine nozzles and buckets: a case study of Chilime Hydropower Plant. *Wear* **264**(3–4), 177–184 (2008)
9. Kumar, P., Saini, R.P.: Study of cavitation in hydro turbines—a review. *Renew. Sust. Energ. Rev.* **14**(1), 374–383 (2010)
10. Xiao, Y.-X., Han, F.-Q., Zhou, J.-L., Kubota, T.: Numerical prediction of dynamic performance of Pelton turbine. *J. Hydrodyn. B* **19**(3), 356–364 (2007)
11. Zhu, H., Pan, Q., Zhang, W., Feng, G., Li, X.: CFD simulations of flow erosion and flow-induced deformation of needle valve: effects of operation, structure and fluid parameters. *Nucl. Eng. Des.* **273**, 396–411 (2014)
12. Chongji, Z., Yexiang, X., Wei, Z., Yangyang, Y., Lei, C., Zhengwei, W.: Pelton turbine needle erosion prediction based on 3D three- phase flow simulation. *IOP Conf. Ser. Earth Environ. Sci.* **22**(5), 052019 (2014)
13. Finnie, I., Kabil, Y.H.: On the formation of surface ripples during erosion. *Wear* **8**(1), 60–69 (1965)
14. Dutta, S.: Bulle-effect and its implications for morphodynamics of river diversions. Ph.D. Thesis. University of Illinois at Urbana-Champaign (2017)
15. Gross, A., Fasel, H.: Hybrid RANS/LES simulations of turbulent channel and diffuser flows. In: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Aerospace Sciences Meetings. American Institute of Aeronautics and Astronautics (2010)
16. Jacobs, G.: Inertial particle behavior in an unsteady separated flow. In: 46th AIAA Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings. American Institute of Aeronautics and Astronautics (2008)
17. Sengupta, K., Mashayek, F., Jacobs, B.: Direct numerical simulation of turbulent flows using spectral methods. In: 46th AIAA Aerospace Sciences Meeting and Exhibit, pp. 7–10 (2008)
18. Olige, J., Kreiss, H.O.: Comparison of accurate methods for integration of hyperbolic equations. *Tellus* **24**, 199–215 (1972)
19. Boyd, J.P.: Chebyshev and Fourier Spectral Methods, 2nd edn. Dover Publications, Mineola (2000)
20. Canuto, C., Hussaini, M.Y., Quarteroni, A., Zang, T.A.: Spectral Methods: Fundamentals in Single Domains. Scientific Computation. Springer, Berlin (2007)
21. Canuto, C, Hussaini, M.Y., Quarteroni, A., Zang, T.A.: Spectral Methods in Fluid Dynamics. Springer, New York (1987)
22. Zang, T.A., Canuto, C., Hussaini, M.Y., Quarteroni, A.: Spectral Methods: Complex Geometries and Applications to Fluid Dynamics, 1st edn. Springer, Berlin (2007)
23. Trefethen, L.N.: Finite difference and spectral methods for ordinary and partial differential equations, 1st edn. Cornell University, Ithaca (1996)
24. Trefethen, L.N.: Spectral Methods in Matlab, 1st edn. Cornell University, Ithaca (2000)
25. Karniadakis, G.E.M., Sherwin, S.: Spectral/hp Element Methods for Computational Fluid Dynamics. Oxford University Press, New York (2005)
26. Karniadakis, G.E., Sherwin, S.J.: Spectral/hp Element Methods for CFD. Oxford University Press, New York (1999)

27. Cantwell, C.D., Moxey, D., Comerford, A., Bolis, A., Rocco, G., Mengaldo, G., De Grazia, D., Yakovlev, S., Lombard, J.-E., Ekelschot, D., Jordi, B., Xu, H., Mohamied, Y., Eskilsson, C., Nelson, B., Vos, P., Biotto, C., Kirby, R.M., Sherwin, S.J.: Nektar++: an open-source spectral/element framework. *Comput. Phys. Commun.* **192**, 205–219 (2015)
28. Wang, Z.J., Fidkowski, K., Abgrall, R., Bassi, F., Caraeni, D., Cary, A., Deconinck, H., Hartmann, R., Hillewaert, K., Huynh, H.T., Kroll, N., May, G., Persson, P.-O., van Leer, B., Visbal, M.: High-order CFD methods: current status and perspective. *Int. J. Numer. Methods Fluids* **72**(8), 811–845 (2013)
29. Elghobashi, S.: On predicting particle-laden turbulent flows. *Appl. Sci. Res.* **52**(4), 309–329 (1994)
30. Greifzu, F., Kratzsch, C., Forger, T., Lindner, F., Schwarze, R.: Assessment of particle-tracking models for dispersed particle-laden flows implemented in OpenFOAM and ANSYS FLUENT. *Eng. Appl. Comput. Fluid Mech.* **10**(1), 30–43 (2016)
31. Coppola, G., Sherwin, S.J., Peiro, J.: Nonlinear particle tracking for high-order elements. *J. Comput. Phys.* **172**, 356–386 (2001)
32. Jacobs, G.B., Kopriva, D.A., Mashayek, F.: Towards efficient tracking of inertial particles with high-order multidomain methods. *J. Comput. Appl. Math.* **206**(1), 392–408 (2007)
33. Finnie, I.: Erosion of surfaces by solid particles. *Wear* **3**(2), 87–103 (1960)
34. Finnie, I.: Some observations on the erosion of ductile metals. *Wear* **19**(1), 81–90 (1972)
35. Padhy, M.K., Saini, R.P.: A review on silt erosion in hydro turbines. *Renew. Sust. Energy. Rev.* **12**(7), 1974–1987 (2008)
36. Finnie, I.: Some reflections on the past and future of erosion. *Wear* **186–187**, 1–10 (1995)
37. Hutchings, I., Shipway, P.: *Tribology: Friction and Wear of Engineering Materials*. Butterworth-Heinemann, London (2017)
38. Parsi, M., Najmi, K., Najafifar, F., Hassani, S., McLaury, B.S., Shirazi, S.A.: A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications. *J. Nat. Gas Sci. Eng.* **21**, 850–873 (2014)
39. Sugiyama, K., Harada, K., Hattori, S.: Influence of impact angle of solid particles on erosion by slurry jet. *Wear* **265**(5), 713–720 (2008)
40. Gnanavelu, A., Kapur, N., Neville, A., Flores, J.F., Ghorbani, N.: A numerical investigation of a geometry independent integrated method to predict erosion rates in slurry erosion. *Wear* **271**(5), 712–719 (2011)
41. Eifrid, K.D., Wright, E.J., Boros, J.A., Hailey, T.G.: Correlation of steel corrosion in pipe flow with jet impingement and rotating cylinder tests. *Corrosion* **49**(12), 992–1003 (1993)
42. López, A., Nicholls, W., Stickland, M.T., Dempster, W.M.: CFD study of jet impingement test erosion using Ansys Fluent® and OpenFOAM®. *Comput. Phys. Commun.* **197**, 88–95 (2015)
43. Gnanavelu, A., Kapur, N., Neville, A., Flores, J.F.: An integrated methodology for predicting material wear rates due to erosion. *Wear* **267**(11), 1935–1944 (2009)
44. Sugiyama, K., Nakahama, S., Hattori, S., Nakano, K.: Slurry wear and cavitation erosion of thermal-sprayed cermets. *Wear* **258**(5–6), 768–775 (2005)
45. Oka, Y.I., Hayashi, H.: Evaluation of erosion resistance for metal–ceramic composites and cermets using a water-jet testing apparatus. *Wear* **271**(9–10), 1397–1403 (2011)
46. Solnordal, C.B., Wong, C.Y., Boulanger, J.: An experimental and numerical analysis of erosion caused by sand pneumatically conveyed through a standard pipe elbow. *Wear* **336–337**, 43–57 (2015)
47. Asgharpour, A., Zahedi, P., Khanouki, H.A., Shirazi, S.A., McLaury, B.S.: Experimental and numerical study on solid particle erosion in elbows mounted in series. In: *ASME 2017 Fluids Engineering Division Summer Meeting*, p. V01BT06A015. American Society of Mechanical Engineers, New York (2017)
48. Shirazi, S.A., Shadley, J.R., McLaury, B.S., Rybicki, E.F.: A procedure to predict solid particle erosion in elbows and tees. *J. Press. Vessel. Technol.* **117**(1), 45–52 (1995)
49. Vieira, R.E., Mansouri, A., McLaury, B.S., Shirazi, S.A.: Experimental and computational study of erosion in elbows due to sand particles in air flow. *Powder Technol.* **288**, 339–353 (2016)

50. Wong, C.Y., Solnordal, C., Swallow, A., Wu, J.: Experimental and computational modelling of solid particle erosion in a pipe annular cavity. *Wear* **303**(1), 109–129 (2013)
51. Boulanger, J., Wong, C., Solnordal, C., Zambari, M.S.A., Shaffee, A., Johar, Z., Jadid, M.: A simplified computational approach to multi-phase erosion. *International Conference on CFD in the Minerals and Process Industries*, CSIRO, vol. 11 (2015)
52. Chen, X., McLaury, B.S., Shirazi, S.A.: Application and experimental validation of a computational fluid dynamics (CFD)-based erosion prediction model in elbows and plugged tees. *Comput. Fluids* **33**(10), 1251–1272 (2004)
53. Ahlert, K.R.: Effects of particle impingement angle and surface wetting on solid particle erosion of AISI 1018 steel (1994)
54. Fessler, J.R., Eaton, J.K.: Turbulence modification by particles in a backward-facing step flow. *J. Fluid Mech.* **394**, 97–117 (1999)

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.