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DESIGNING A SCALED EROSION TEST WITH COMPUTATIONAL FLUID DYNAMICS METHODS

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ABSTRACT

The Department of Energy is sponsoring the River Protection Project, which includes the design of a facility to stabilize liquid radioactive waste that is stored at the Hanford Site. Because of its experience with radioactive waste stabilization, the Savannah River Technology Center of the Westinghouse Savannah River Company is assisting in the development and testing of parts of the waste treatment process. One part of the process is the separation of highly radioactive solids from the liquid wastes by cross-flow ultrafiltration. For the projected forty-year life of the filtration facility, wear will occur from a combination of erosion and corrosion due to the flow of slurries. A scaled cross-flow filter facility will be tested with simulated waste to quantify the wear rate so that an effective maintenance schedule can be developed.

This paper discusses the application of computational fluid dynamics (CFD) methods to ensure that the test facility design would capture the erosion phenomena expected in the full-scale cross-flow ultrafiltration facility. An initial literature survey helped identify the principal drivers of erosion for a solids laden fluid. These were the solids content of the working fluid, the regions of recirculation and particle impact with the walls, and the regions of high wall shear.

A series of CFD analyses was then designed to characterize slurry-flow profiles, wall shear, and particle impingement distributions in key pipe bends and fittings representative of the plant. Pipe diameters, lengths, the locations of pipefittings, and slurry velocities were scaled with the CFD calculations to ensure that the erosion drivers were appropriately represented in the test facility. This resulted in a validation of the theoretical determination of those drivers, and allowed the test results to be applied to a prediction of wear in the full-scale filtration facility.

INTRODUCTION

A key concern with radioactive operation of a piping system is the integrity of the pipe, fittings, and accompanying equipment. A breach anywhere in such a system may release contamination, which, at a minimum, will increase operational costs due to clean up and down time, but more importantly would increase the health risks to personnel. It is very important to thoroughly understand the effects of a slurry flow on the piping system so that proper maintenance can be performed to minimize equipment failure and guarantee safe operation. One problem from slurry flow is the wear it exhibits on the pipe wall. That wear results from the solids in the slurry, which causes erosion. The chemicals in the slurry may accelerate corrosion, and the synergistic effect of the combination of both erosion and corrosion, results in an accelerated wear on pipe walls.

The waste treatment and immobilization[†] plant (WTP) to be built as part of the River Protection Project (RPP) at the Department of Energy's (DOE) Hanford Site will contain many pipe systems that will carry slurries. To ensure safe operation the wall thickness corrosion/erosion allowance for in-cell[‡] pipe was set at 2.5 mm over the life of plant, which is currently set at 40 years (This allowance rate is 63.5 µm/year; a thickness equivalent to the diameter of a grain of fine sand.) This allowance represents 45% of the pipe wall thickness for the smallest pipe that will carry the radioactive slurries (78-mm inside diameter, 5.5-mm wall) and 26% for the largest (305-mm inside diameter, 9.5-

[†] Immobilization refers to stabilizing waste by vitrification. Locking the waste in a glass matrix minimizes the risk of indiscriminate access and allows for long term safe storage.
[‡] In-cell refers to the part of the WTP where radioactive operation occurs and therefore access is limited by design to minimize personnel exposure.

mm wall). Most of the pipe systems are expected to safely last the entire life of the WTP and equipment that will wear at higher rates, i.e., pumps, are designed for easy replacement. However, a confidence must be established as to how fast inaccessible pipe will wear due to waste slurries, which are planned for treatment.

As part of the RPP team, the Savannah River Technology Center (SRTC) at DOE's Savannah River Site (SRS), was tasked to experimentally study the effects of the slurry wear for some of the WTP's systems. The highest confidence in experimental results would come from a test done on a full-size facility using the actual waste. Unfortunately, neither could be used. A limited full size facility would still entail hundreds of feet of 0.25-meter diameter pipe with equally large size equipment. The size in itself does not make doing the experiment impossible, however, the expense of the chemically complex slurries would be prohibitive. Using actual waste is also not feasible because of it being radioactive. These test limitations therefore forces the use of a scaled facility with simulated waste slurries, both of which must be properly addressed to obtain full-size representative experimental results.

Simulated waste slurries developed for RPP are not dealt with in this paper, but details can be found in Eibling and Nash, 2000, and Golcar et al., 2000. In general, all project simulants were developed to match actual waste slurries in both physical and chemical features. The waste slurry that was consider the most abrasive in terms of insoluble solids and the most corrosive in terms of soluble solids was selected for this wear test. This waste was from the Hanford Site tank 241-AZ-101 and special consideration was given to simulate both the caustic nature of the waste supernatant and the concentration, density, hardness, and morphology of the insoluble solids (Elmore, 2000). Specific information on the waste simulant important for this paper is that the insoluble solids have particle sizes from 10 to 40 microns with a concentration of 20 wt%, a slurry density of 1300 kg/m^3, a slurry viscosity of 2 mPa-s, implying a Newtonian fluid[†].

This paper specifically deals with the use of CFD modeling to assist in selecting which parts of a cross-flow filtration facility flow loop to include in a scaled test loop, as well as determining the scaled operating conditions.

CROSS-FLOW FILTRATION FACILITY

Figure 1 shows a schematic of the overall pretreatment filtration system. The closed-loop configuration will have approximately 110 meters of pipe, the majority will be made predominantly of 255-mm pipe (10-inch standard weight).

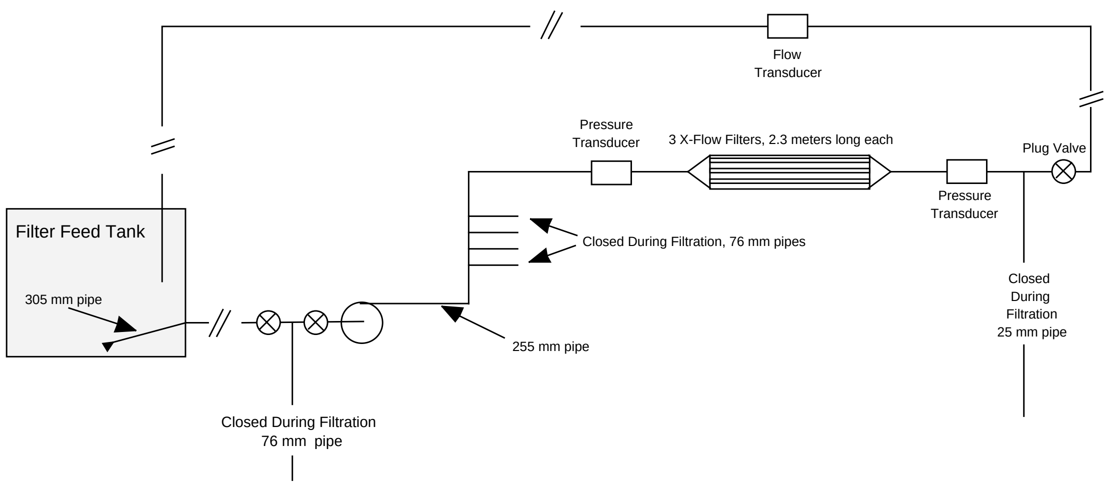


Figure 1. Schematic of the Cross-flow filtration Facility

[†] The slurry is actually Non-newtonian with Bingham characteristics, however the measured yield stress was less than the measurement uncertainty of the Haake rotor rheometer of 0.89 Pa; therefore the slurry was assumed Newtonian in nature.

The actual design of the filtration flow loop is not complete and is will be revised as the overall WTP design and process is finalized. However, major changes are not expected to the current design characteristics of the full size cross-flow filtration system, which are:

Average slurry flow rate:	0.151 m^3/s
Average slurry velocity:	3 m/s (255-mm pipe)
Average slurry velocity:	2 m/s (305-mm suction pipe)
Filter units:	3 in series
Filter orientation:	horizontal
Each filter unit:	244 tubes
Each filter tube	2.29-meter porous length, 12.7-mm inside diameter
Average slurry velocity in tubes:	5 m/s
Slurry from the filter feed tank:	well mixed
Operating Temperature:	25°C to 30°C
Flow loop material:	304L stainless steel
Filter tube material:	316L stainless steel
All loop bends:	standard short-radius welded fittings

Equipment that is not defined are the valves, instruments, and pipe orientations. Most of the valves are assumed to be the type which do not impact pipe flow and therefore are ignored. The exception is the valve downstream of the filter units, which will be used to control filter pressure; it may be a gate-type plug valve. Instruments may disturb the flow by either having recesses in or protrusions out of the pipe wall. Pipe orientations will change as the design is finalized.

EQUIPMENT SELECTION CFD MODELING

The very first step taken to evaluate slurry wear in the cross-flow filtration system was to choose parts of the flow loop which may have higher levels of wear than a straight pipe. As seen in Fig. 1, the elemental parts included a 90° elbow, branch non-flowing pipes, filter bundle entrance and plenum, filter bundle exit and plenum, an arbitrary bluff body, and a plug valve. The pump was not included in the modeling evaluation because the complexities of a pump requires a good knowledge of its design; a knowledge that was not available. Moreover, the pump will be designed so that the impeller and its housing are easily accessible for inspection and replacement. Further, some of the flow loop parts needed to be modeled together because of their joint effect on slurry flow patterns, e.g., the double elbow section, S-type bend, with branch pipes, just downstream of the pump. Some considerations for this section were to determine affects on erosion because of: the closeness of the elbows to each other, single or multi-branch pipes, location of branches to an elbow, etc. For the full-size flow system the following piping arrangement were evaluated:

- 90° short radius elbow in isolation
- Two 90° short radius elbows joined with a straight pipe containing multiple branches (see Fig. 1 immediately downstream of the pump).
- Two 90° short radius elbows joined with a straight pipe containing a single branch.
- A single filter tube
- A filter tube surrounded with other tubes
- Filter plenum entrance
- Filter plenum exit
- Bluff body
- Plug Valve

This equipment was first evaluated with CFD modeling at full size to determine which needed to be included (e.g., would an elbow in isolation or two elbows closely joined give the more conservative slurry wear results). Further, full-size results could then be used to determine flow conditions needed at smaller scales to obtain similar results. This methodology is discussed later in the paper.

COMPUTATIONAL FLUID DYNAMICS METHODOLOGY

Designing a scaled experiment to measure the slurry wear rate in a full-size slurry flow system required a method to select: the parts of the system which would experience significant wear, the parts which could give conservative results for other similar parts, and the proper scaling criteria. Due to the complexities of the erosion and corrosion processes, accurate quantitative results were not expected from CFD modeling. However, CFD modeling is expected to be very important for using small-scale test results to determine slurry wear rated in a full-size system. CFD modeling was used to obtain guidance on the equipment to include in the experimental test loop, as well as on the appropriate scaled flow conditions.

There are many mechanisms, which cause slurry to wear pipe walls, but for flow loop design purposes, two specific mechanisms were considered: wall shear stress and particulate impingement. The erosion process under the uniform particle slurry flow is assumed to be caused by abrasive friction and particle collision. For the slurry flow laden with large particles such as sand, the latter process may be important in elbow components or at flow obstructions in the pipe. For the calculations of the continuous slurry flow field, three-dimensional transport and continuity equations were solved in an Eulerian reference system. In this situation, the Reynolds number of the flow condition is found to be about 5×10^5 in terms of component diameter, which corresponds to fully turbulent regime. Two-equation turbulence model with turbulent kinetic and dissipation equations known as the κ–ε model was used to include the effects of particle dispersion due to turbulent eddies present in the continuous phase. For the simulations of the particle impingement trajectory, a force balance, including inertia, solid-fluid interfacial drag, and gravitational terms, was used in a Lagrangian reference system to calculate the trajectory of the discontinuous particles in the slurry.

Wall Shear Stress

The stress on pipe walls due to the shearing action of a flowing slurry was thought to be an important feature of erosion because of the softness of the wall material, stainless steel. Erosion of a surface can also depend on the angle at which particles approach the surface. Literature that deals with the direction of a particle towards an eroding surface fall into two categories: particle trajectory angles that cause ductile wear or brittle wear. Those types of wear will not be discussed here but they refer to the way material is removed from a surface. Ductile wear is defined when a surface has the highest wear rate at an impingement angle of about 30° and brittle wear is at an angle of about 90°. Finnie, 1995 states that ductile wear occurs between 20-30°, but he adds that it is always the predominate type of wear when particles are less the 10 microns in diameter and move at "slow" velocities. Using 304L stainless steel Burstein and Sasaki, 2000 state that sand particles attacking surfaces at oblique impingement angles (40-50°) remove the passive oxide layer more effectively than at 90°. In fact, Foley and Levy, 1983 showed that 304 stainless steel does indeed wear fastest with a particle angle of 30°. Singh et al., 1991 showed that both 304 and 316 stainless steels have the same rate of wear when impinged with an air jet containing SiC particles that were 160 microns in diameter, and had angular shapes. Both metals wore the fastest when the impingement angle was at 30° and it was the slowest at 90°. This information is very useful when designing a test because it indicates where attention must be directed to evaluate the maximum wear locations. That is, wear measurement must not be concentrated only at a section of a flow loop where the flow makes an abrupt 90° change. This was well demonstrated by Smith and Elmore, 1992, who studied the wear on a steel specimen from a perpendicularly (90°) oriented slurry jet, only to find that another steel specimen, which only received oblique-angle particle attacks, unexpectedly showed more wear. The conclusion is that, for ductile materials like stainless steel, measurements should be made where particles hit a surface at lower angles. Since small angles of attack are important for stainless steel, the shear being transmitted to a surface is thought to be important for erosion.

The CFD model used in this paper contains the assumptions that the volume concentration of the discrete phase and the particle size are small so that particle-particle interactions and the effects of the particle volume fraction on the continuous phase are negligible. Thus, the mixed slurry fluid is assumed to be homogeneous considering that the discontinuous solid phase is distributed uniformly. The characteristics of turbulent fluid-wall interactions were considered by the standard κ–ε model. In this model, it is assumed that the friction due to the wall shear stress mainly governs the erosion.

Particle Impingement

While a knowledge of the wall shear stress pattern in a flow system is useful in developing insights on high stress locations, it may not be directly applicable to locations of high wear rates. The difference between these two locations will increase as slurry solids become heavier and larger; that is, as the flow path of particulates become increasing different from fluid streamlines. Erosion primarily occurs from the mechanical interaction of the solid particles impinging on the surfaces of wall boundary. Subsequently, corrosion is accelerated as impacted surfaces are exposed to the slurry chemistry. To estimate where high erosion locations exist, it is important to model the movement of those particles.

Particle size has been studied by several investigators but there is not a consistent story. At one extreme, Zhong and Minemura, 1996 determined that erosion rate increases with size but the effect is "small" until a particle reaches 1000 microns. Iwai and Nambu, 1997 determined that erosion rate only becomes independent of particle size above 300 microns. Mishra and Finnie, 1981 found that independence kicks in for particles larger than 100 microns. Mills and Mason, 1981 say that the cut off occurs at 50 microns. Finally, Gandhi et al., 1999 found that the erosion rate is always affected by particle size, albeit "weakly." However, Finnie, 1995 quantified the relative effect of particle size on erosion rate and states that a 10-micron particle is only 25% effective as a 100 micron size. This wide range of results seem to be confusing, but in the context of the present need where the target particle sizes range from 10 to 40 microns, all the studies seem to imply less than 50 microns is considered small. (See also Fig. 8-6 in Shook and Roco, 1991). This definition of "small" can be used to determine the range of particle sizes for which the computational approximation of homogeneous flow is valid.

Note that an implicit assumption in particle size is that all the particles are uniform in size. At times this is an unavoidable simplification, but it is important to remember that in real systems the transported particles have a non-uniform size distribution. Most studies state the mean particle size, without giving information on the actual distribution of particle sizes within a group. However, a group of particles having all the same size and another, which has a wide range of sizes - with a mean size equal to the uniform-size group, may give different wear results. In fact, wear results from the two different groups of particles would not be expected to match because the interaction energy and the rate of material removal are nonlinear with particle size. Some experiments performed for particles with a broad quasi-logarithmic size distribution suggest that the "equivalent wear diameter" for slurry pipes or pumps is larger than the mean particle size (Roco and Cader, 1990; Roco and Minani, 1989). The "equivalent wear diameter" refers to a particle diameter that is assigned to a group of particles, which has a range of sizes, that would cause the same wear rate as a group of particles that all have that same (assigned) size. The difference between actual diameters and equivalent wear diameter should be taken into account when discussing erosion rates based on a mean particle diameter.

Neilson and Gilchrist, 1968 showed that the erosion mainly depends on the wall material, the particle velocity, and the angle of attack. In this model, it is assumed that erosion is mainly controlled by particle impingement against the pipe wall. Slurry flow was modeled as a continuous phase using three-dimensional mass continuity and momentum equations in an Eulerian frame of reference. The particles in the slurry were simulated as a dispersed phase in a Lagrangian frame of reference to compute their trajectories and the shape of the particle was assumed to be spherical. The coupling between the two phases was considered to include its impact on both the discrete phase trajectories and the continuous phase flow. We assumed that the volume concentration of the discrete phase is small so that particle-particle interactions and the effects of the particle volume fraction on the continuous phase are negligible. When a particle is introduced into a slurry stream with a low concentration of solids, the response of the particle depends on the relative velocity of the particle and the fluid. This relative velocity determines the interfacial drag, which determines the motion of the particle. Further, it is assumed that there are no particle-particle interactions within the slurry flow field.

Neilson and Gilchrist, 1968 showed that the erosion coefficient, $\xi_{erosion}$, mainly depends on the incident particle speed, v_{in}, particle size, d_p, and the incident angle, β_{in}, which is the angle between a plane tangent to the surface at the impact and the direction of motion of the incident particle. The form of the empirical relation used for the present erosion model is,

$$\xi_{erosion} = k v_{in}{}^{n} f_d\left(d_p\right) f_\beta\left(\beta_{in}\right) \quad (1)$$

In Eq. (1), k and n are constants assumed to depend on the physical characteristics of the materials involved, and $f_\beta(\beta_{in})$ describes the dependence of erosion on the particle incidence angle. In the calculations, the parameter f_β is set at 0.96, as recommended by Fluent, Inc. and n is assumed to be zero. f_d and k are assumed to be unity, since confirmed information on material characteristics of the current facility design is not available now. Using the empirical constants, then the erosion rate is estimated by summing up the impingement impact of individual particle over the entire number n of particles corresponding to the mass flowrate m_p of the particles.

$$R_{erosion} = \sum_{i=1}^{n} \frac{m_{p,i}\xi_{erosion,i}}{A_i} \quad (2)$$

A in Eq. (2) is the area of wall face associated with the impact angle of the particle path. The main assumptions in the erosion calculations were made as follows:

- The particle collisions with the wall are elastic. This is realized through a coefficient of restitution, which is the ratio of the approach to recoil velocities and is specified as an input parameter to the code. In the present analysis, when a particle impinges a wall boundary, this ratio is assumed to be unity so that both the normal and tangential conditions result in no momentum dissipation.
- The particle-particle interactions and the effects of the particle volume fraction on the continuous fluid phase are negligible assuming that the discrete solid phase is sufficiently dilute (particle concentrations of less than 10 vol% in the present analysis. The slurry under study has a concentration of approximately 7 vol%).
- The particle shape contained in a slurry flow is spherical. The particle size is uniform and 10 microns in diameter.
- The particles have no direct impact on the generation or dissipation of turbulence in the continuous phase.

Based on the modeling assumptions, coupled calculations of the continuous phase and discrete phase equations were performed to provide the test conditions and to select key components of the test loop. All converged solutions were achieved using the segregated and iterative solution technique.

BENCHMARKING RESULTS AND SELECTION OF DESIGN COMPONENTS

From the literature information, the principal drivers for erosion for a solids laden fluid were identified. These were the solids content of the working fluid, the regions of recirculation and particle impact with the component walls, and the regions of high wall shear. The CFD models for wall shear and particle impingement erosions were developed using Fluent^{TM} and calculations performed to estimate slurry-flow patterns, wall shear, and particle paths in key pipe components and fittings representative of the facility. The CFD methods were also applied to ensure that the scale-down test facility design could capture the erosion phenomena expected in the full-scale cross-flow filtration facility.

The model predictions were benchmarked against the literature data for hydraulic transport and erosion tests. Three sets of representative experiments were chosen to test the CFD models presented in this paper. They are the hydraulic tests obtained for sharp-edged (so-called miter) and 90° standard elbows (Toda et al., 1972), and the erosion test data for the straight pipe (Hisamitsu et al., 1985). All these tests were performed using a sand-water slurry. For the hydraulic experiments through the elbows, 30.2 mm pipe diameter and about 990 micron particles were used. Solid concentrations for the sharp-edged and standard elbows were 8 and 20 weight percent, respectively. The results of the model predictions are compared with the test data in Fig. 2, and agree with the experimental data to within about 15%.

For the erosion experiment Hisamitsu et al., 1985 used a straight pipe with an inside diameter of 75 mm through with the slurry flowed at 2.83 m/s. The slurry had a nearly-uniform size distribution of sand of an approximate diameter of 0.67 mm with a specific gravity of 2.7 and the concentration of solids was 11 vol.%. Erosion was measured at 8 points along the pipe circumference with an ultrasonic thickness meter. Using the parameters from this straight pipe experiment predictions were made with the particle impingement model. Those predictions are compared with the test data in Fig. 3[†]. The results show that the model predictions qualitatively agree with the data, taking into consideration the very complex nature of two-phase turbulent flows. Detailed quantitative benchmarking with the scaled tests to be conducted at SRS will be performed to quantify the erosion rate for a full-scale facility. This results in a validation of those calculations, and will allow the test results to be applied to a prediction of erosion in the full-scale filtration facility.

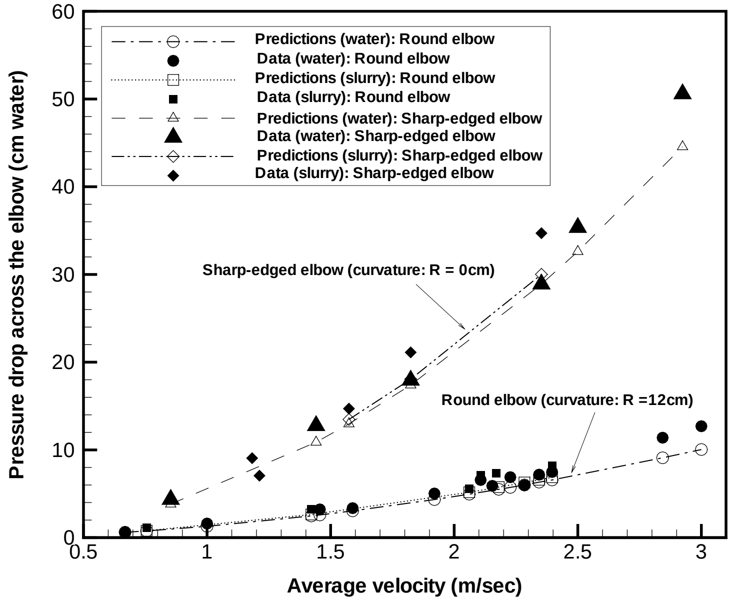


Figure 2. Comparison of predictions using the standard κ–ε turbulent model with discrete solid phase to the experimental hydraulic data of Toda et al., 1972

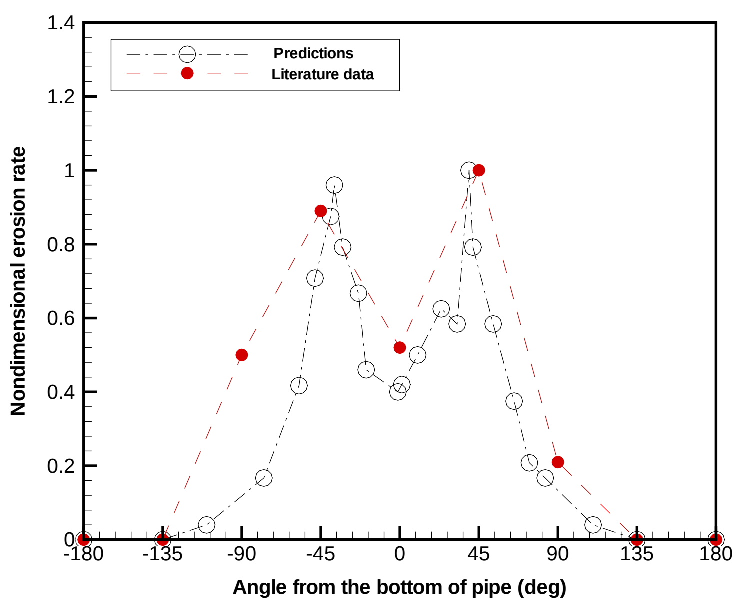


Figure 3. Comparison of predictions, using the standard κ–ε turbulent model with discrete solid phase, to experimental erosion data for horizontal pipe of Hisamitsu et al., 1981 (Pipe diameter = 75 mm, average fluid velocity = 2.83 m/sec, particle volume concentration = 11%, particle size = 0.67 mm).

[†] Figure 3 shows experimental and predicted erosion rate data in a non-dimensional form by normalizing the local rates with the maximum experimental and predicted erosion rates in the pipe, respectively.

The CFD methods were applied to the selection of key components to ensure that the erosion mechanisms expected in the full-scale facility are appropriately represented in the scaled test facility. The modeling calculations for the full-scale facility were performed for the slurry flowing at 3 m/s for the 255-mm inside-diameter pipe and 5 m/s for the 12.7-mm inside-diameter filter tubes. Other parameter used were: a specific gravity of 1.3, an insoluble solids loading of 20 wt%, and a particle diameter of 10 microns. All the main components shown in Fig. 1 were studied to simplify the components without losing key erosion phenomena and slurry flow characteristics. They include isolated elbow, S-type pipe with single or multiple branches, single or multiple filter tube arrangement, and bluff body attached to the inner wall of horizontal pipe. The results for maximum wall shear and the normalized erosion rate[†] are shown in Table 1. The maximum erosion location for each of the key components is also shown in the table[‡]. Locations of the maximum erosion for the selected components are illustrated in Fig. 4.

Table 1. Maximum wall shears for the models of the key components considered in the analysis associated with erosion (filter tube inside diameter = 12.7 mm)

Cases	Isolated elbow	S-type elbow with branch	Pipe with branch	7-tube filter		Pipe with bluff body
				Inlet	Exit	
Max. wall shear (Pa)	72.0	66.2	40.0	171.5	115.8	51.0
Max. erosion location due to impingement (see Fig. 4)	Outer elbow	Outer elbow	Leg inlet	Upstream tube sheet	Downstream tube sheet	Front bluff
Relative scale for max. erosion rate	~0.4	~0.9	~0.1	1.0	~0.1	~0.3

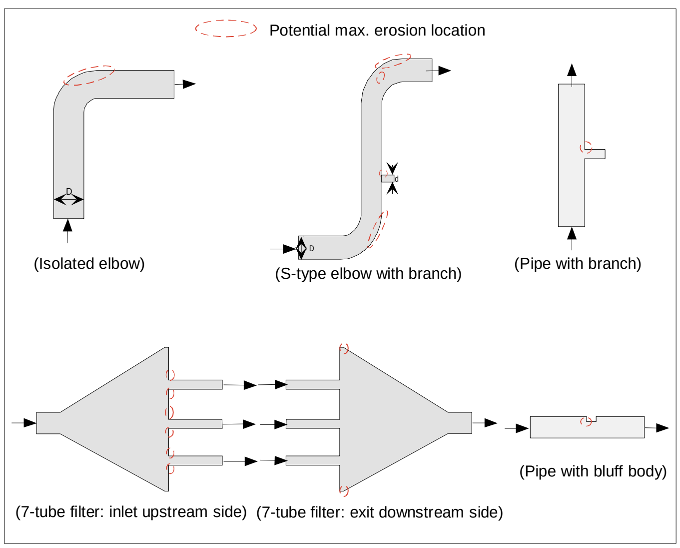
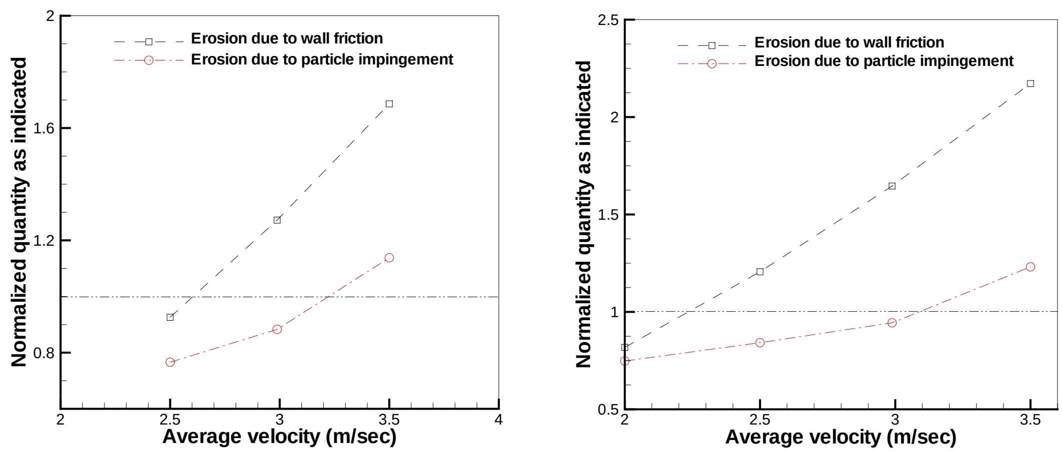


Figure 4. Potential maximum erosion locations at the middle planes of typical key components of the cross-flow filtration facility predicted by the present model

† The relative erosion rate in Tbl. 1 is the predicted maximum erosion rate in a specific piece of pipe geometry normalized by the predicted maximum erosion rate for all the different cases under study, which was at the inlet of the 7-tube filter tube bundle. All predictions in Tbl. 1 are for full-scale pipe.

‡ For brevity, several analyses were left out of the Tbl. 1. The table shows just those parts targeted for inclusion in the scaled test facility. For instance, an analysis was done to determine whether a single or multi-branch pipe arrangement would exhibit the highest erosion rate. Since the single tube was the worst case it is shown in Tbl 1. Other analyses include: the closeness of the two elbows to each other in the S-type section, the closeness of the branch pipe to an elbow, a single filter tube versus a multi-tube bundle, etc.

After making a selection of the flow loop sections to include in the scaled test, through the analyses at full-scale, the CFD models were used to determine scaled operating flow conditions to ensure that the erosion behaviors expected at the full-scale facility are properly captured in the scale-down test facility. In this case, various flow conditions were applied for the scaling considerations under three different size conditions and three different components, including 255-mm prototypic scale, and the 76-mm and 25-mm test scales. The three components are the isolated elbow, the S-type piping, and the straight pipe with bluff body. All physical properties of slurry fluid, particle concentration, and particle size were maintained the same as the prototypic slurry, since the erosion phenomena associated with the scaling of geometrically complicated components have highly non-linear behavior. The typical results for the normalized[†] wall shear stress and erosion rate are shown in terms of slurry velocity through the S-type pipe with a branch in Fig. 5. Note that the nominal average flow velocity for the full-scale facility is about 3 m/sec, corresponding to 0.15 m^3/s flowrate. As expected, the prediction results show that when the slurry velocity increases, the wall shear stress, which is closely related to the abrasive erosion, is more sensitive to the pipe scaling than particle impingement.



(76-mm pipe size) (25-mm pipe size)

Figure 5. Normalized CFD results of maximum wall shear stresses and erosion rates of scaled components by the maximum values of the prototypic (255 mm) S-type pipe, with a branch, for various slurry velocities

CONCLUSIONS

This paper discusses the application of CFD methods to ensure that the design of a scaled test will capture the erosion phenomena expected in the full-scale cross-flow ultrafiltration facility. The present models assume that there are two manners in which a wall surface is worn. The first is based on the homogeneous solid-fluid model, and its basic mechanism is that wall friction of the mixed slurry on the abrasive surface can cause wear. The other is of solid particles that impinge a pipe wall causing the removal of chips out of the impacted surface. For the present work, Eulerian continuous transport equations and Lagrangian momentum balance for the solid phase dispersed in the slurry flow were used to estimate wall shear and particle-impingement erosions, respectively. For typical operating conditions of the facility, Reynolds number is about 10^5, corresponding to a fully-turbulent flow regime. A two-equation turbulence model was used to consider the dispersion effect of particles due to turbulent eddies. In the present calculations, solids content of the working fluid, the regions of high wall shear, and particle impingement with the walls were considered as major mechanisms associated with the erosion.

Three sets of representative experiments were chosen to test the CFD models presented in this paper. All these tests were performed using sand-water slurry. The benchmarking results against the literature data for hydraulic transport and erosion tests are reasonably good.

[†] In Fig. 5 the predicted wall shear stresses and erosion rates for the scaled equipment (i.e., 76 mm and 25 mm pipe) were normalized by the maximum values obtained in the predicted full-size pipe (i.e., 255 mm).

The CFD analyses were then designed to characterize slurry-flow profiles, wall shear, and particle impingement distributions in key pipe bends and fittings representative of the filtration facility. Pipe diameters, lengths, the locations of pipe fittings, and slurry velocities were scaled with the CFD calculations to ensure that the erosion drivers in the test facility were representative of the full-scale facility. The models will be benchmarked against the data obtained from the scaled test facility. This results in a validation of the theoretical determination of those drivers, and will allow the test results to be applied to a quantitative prediction of erosion in the full-scale filtration facility.

REFERENCES

Burstein, G.T. and Sasaki, K., 2000. Effect of impact angle on the slurry erosion-corrosion of 304L stainless steel. Wear **240**, 80-94.

Eibling, R.E. and Nash, C.A., 2000. Hanford waste simulants created to support the research and development on the River Protection Project – Waste Treatment Plant. Westinghouse Savannah River Company Report No. WSRC-TR-2000-00338.

Elmore, M.R., 2000. Simulant Erosion Testing. Battelle Pacific Northwest National Laboratory Report No. WTP-RPT-001.

Finnie, I., 1995. Some reflections on the past and future of erosion. Wear **186-187**, 1-10.

FLUENT, 1998. Fluent, Inc., Lebanon, New Hampshire.

Foley, T. and Levy, A., 1983. The erosion of heat-treated steels. Wear **91**, 45-64

Gandhi, B.K., Singh, S.N., and Seshadri, V., 1999. Study of the parametric dependence of erosion wear for the parallel flow of solid-liquid mixtures. Tribology International **32**, 275-282.

Golcar, G.R., Brooks, K.P., Darab, J.G., Davis, J.M., and Jagoda, L.K., 2000. Development of inactive high-level waste envelope D Simulant for scaled crossflow filtration testing. Battelle Pacific Northwest National Laboratory Report No. PNWD-3042.

Hisamitsu, N., Iseh, T., and Takeishi, Y., 1981. An experimental study on pipe erosion by sand slurry. Proc. 6th Conference on Slurry Transportation, Slurry Transport Association, 319-332.

Iwai, Y. and Nambu, K., 1997. Slurry wear properties of pump lining materials. Wear **210**, 211-219.

Mills, D. and Mason, J.S., 1981. Conveying velocity effects in bend erosion. J. Pipelines **1**, 69-81.

Mishra, A. and Finnie, I., 1981. On the size effect in abrasive and erosive wear. Wear **65**, 359-373.

Neilson, J. H. and Gilchrist, A., 1968. An analytical and experimental investigation of the velocities of particles entrained by the gas flow in nozzles. J. of Fluid Mech. **33**, 131-149.

Roco, M.C. and Cader, T., 1990, Energy approach for wear distribution in slurry pipelines", Jap. Journal of Multiphase Flow **4**, 2-20.

Roco, M.C and Minani, L.K., 1989. Effect of particle size distribution and gravitation on wear in centrifugal pump castings", American Society of Mechanical Engineers, Paper No. 89-FE8.

Shook, C.A. and Roco, M.C., 1991. Slurry Flow. Publ. Butterworth-Heinemann (ISBN 0-7506-9110-7).

Singh, T., Tiwari, N., and Sundararajan, G., 1991. Room temperature erosion behaviour of 304, 316, and 410 stainless steels. Wear **145**, 77-100.

Smith H.D. and Elmore, M.R., 1992. Corrosion studies of carbon steel under impinging jets of simulated slurries of neutralized current acid waste (NCAW) and neutralized cladding removal waste (NCRW). Battelle Pacific Northwest National Laboratory Report No. PNL-7816 (also UC-721), (January).

Toda, M., Komori, N., Saito, S., and Maeda, S., "Hydraulic Conveying of Solids thruough Pipe Bends", J. of Chemical Engineering of Japan, Vol. 5, No. 1, pp. 4-13, 1972.

Zhong, Y. and Minemura, K., 1996. Measurement of erosion due to particle impingement and numerical prediction of wear in pump casing. Wear **199**, 36-44.