DESIGN ANALYSIS FOR A SCALED EROSION TEST

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SAVANNAH RIVER TECHNOLOGY CENTER

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April 2002

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Nomenclature

A = area (ft$^2$ or m$^2$)
C = solid volume concentrations in slurry (\text{--})
d = branch diameter or solid particle size in slurry (ft or m)
D = main pipe diameter (ft or m)
f = empirical factor
F = Force (N)
g = gravity (m/sec$^2$)
I = turbulence intensity (\text{--})
k = constant in eq. (2) (\text{--})
m = particle mass flowrate (kg/sec)
P = pressure (Pa)
Pr = Prandtl number, $\mu C_p/k$, (\text{--})
R = curvature radius of elbow (ft or m)
Re = Reynolds number, $d \rho u/\mu$
t = time (second)
U = slurry velocity (ft/sec or m/sec)
u = component velocity in x-direction (ft/sec or m/sec)
u' = local turbulent velocity fluctuation in x-direction (ft/sec or m/sec)
v = local flow velocity or component velocity in y-direction (ft/sec or m/sec)
v' = local turbulent velocity fluctuation in y-direction (ft/sec or m/sec)
V = average velocity magnitude (ft/sec or m/sec)
W = weight fraction of solids in slurry (\text{--})
w = component velocity in z-direction (ft/sec or m/sec)
w' = local turbulent velocity fluctuation in z-direction (ft/sec or m/sec)
x = local position along the x-direction under Cartesian coordinate system (ft or m)
y = local position along the y-direction under Cartesian coordinate system (ft or m)
z = local position along the y-direction under Cartesian coordinate system (ft or m)
Greek
ρ = density (kg/m³)
β = impingement angle of particle against wall surface
κ = turbulent kinetic energy (\( = \frac{1}{2} (v'^2 + w'^2 + u'^2)_{avg} \))
ε = rate of dissipation of turbulent kinetic energy
Δ = difference
∇ = gradient operator
μ = dynamic viscosity (N sec/m²)
ν = kinematic viscosity (m²/sec)
ζ = empirical facto for erosion rate

Subscript
avg = average
c = critical
d = incident particle
f = fluid
in = incidence
p = particle
s = solid particle
t = turbulent
wall = wall surface
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<table>
<thead>
<tr>
<th>Elbow Curvature (C/R)</th>
<th>2.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate</td>
<td>2400 gpm</td>
<td>2400 gpm</td>
</tr>
<tr>
<td>Elbow Diameter</td>
<td>10 in</td>
<td>10 in</td>
</tr>
<tr>
<td>Max. Wall Shear</td>
<td>67.2 Pa</td>
<td>31.6 Pa</td>
</tr>
<tr>
<td>Relative scale for erosion rate</td>
<td>1.0</td>
<td>~0.65</td>
</tr>
</tbody>
</table>
Table 7. Maximum wall shear stresses for the cases considered in the analysis associated with erosion (D = 10 in and d= 3 in)

<table>
<thead>
<tr>
<th>Cases (Fig. 4)</th>
<th>Case-b</th>
<th>Case-c</th>
<th>Case-d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presence (?) of elbows at the downstream and upstream regions of the 10&quot; pipe</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of legs</td>
<td>2</td>
<td>1(leg 1)</td>
<td>1(leg 2)</td>
</tr>
<tr>
<td>Total length between elbows</td>
<td>36in</td>
<td>36in</td>
<td>36in</td>
</tr>
<tr>
<td>a</td>
<td>12in</td>
<td>12in</td>
<td>12in</td>
</tr>
<tr>
<td>b</td>
<td>12in</td>
<td>12in</td>
<td>12in</td>
</tr>
<tr>
<td>c</td>
<td>12in</td>
<td>12in</td>
<td>12in</td>
</tr>
<tr>
<td>Max. wall shear (Pa)</td>
<td>62.6</td>
<td>63.7</td>
<td>63.2</td>
</tr>
</tbody>
</table>
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Figure 21. Wall shear stress and turbulence intensity distributions for the 36 in long and 10 in diameter pipe with 3in leg (case g) associated with wall erosion.
Table 8. Maximum wall shear stresses for the models of the filter component associated with erosion (filter tube diameter = 0.5 in)

<table>
<thead>
<tr>
<th>Cases</th>
<th>One-tube equivalent model (case-e in Fig. 4)</th>
<th>Seven-tube equivalent model (case-g in Fig. 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter geometry</td>
<td>One tube</td>
<td>7 tube</td>
</tr>
<tr>
<td>Filter tube diameter</td>
<td>0.5in</td>
<td>0.50in</td>
</tr>
<tr>
<td>Filter boundary diameter</td>
<td>7/8in</td>
<td>4in</td>
</tr>
<tr>
<td>Max. wall shear</td>
<td>185.2 Pa</td>
<td>171.5 Pa</td>
</tr>
<tr>
<td>Max. erosion location due to impingement</td>
<td>Upstream tube sheet (see Fig. 25)</td>
<td>Upstream tube sheet (see Fig. 25)</td>
</tr>
<tr>
<td>Relative scale for erosion</td>
<td>1.0</td>
<td>~0.7</td>
</tr>
</tbody>
</table>
Figure 22. Comparison of velocity distributions at the center planes of the one-tube models with smooth and welded tubes (case-e and case-f in Fig. 4).
Figure 23. Comparison of velocity distributions at the center plane of the one-tube and seven-tube filter models to simulate the cross-flow filtration component.
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Figure 32. Potential maximum erosion locations at the middle planes of key components of the cross-flow filtration facility selected by the present model.

Table 9. Maximum wall shears for the models of the key components considered in the analysis associated with erosion (filter tube diameter = 0.5 in)

<table>
<thead>
<tr>
<th>Cases</th>
<th>Isolated elbow (case-a*)</th>
<th>Two elbows with branch (case-c*)</th>
<th>7-tube filter</th>
<th>Pipe with bluff body (case-i*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inlet (case-g*)</td>
<td>Exit (case-h*)</td>
</tr>
<tr>
<td>Max. wall shear (Pa)</td>
<td>72.0</td>
<td>66.2</td>
<td>171.5</td>
<td>115.8</td>
</tr>
<tr>
<td>Max. erosion location due to impingement (see Fig. 31)</td>
<td>Outer elbow</td>
<td>Outer elbow</td>
<td>Upstream tube sheet</td>
<td>Downstream tube sheet</td>
</tr>
<tr>
<td>Relative** scale for max. erosion rate</td>
<td>~0.4</td>
<td>~0.9</td>
<td>1.0</td>
<td>~0.1</td>
</tr>
</tbody>
</table>

Note: * Each case is identified in Fig. 4.
** The scale is relative to the maximum erosion rate of case-g.
Figure 33. Comparison of the erosion distributions due to particle impingement under three different scaled elbow components.
Figure 34. Nondimensional erosion ratio of scale-down (3 in and 1 in) to 10 in prototypic elbow for various slurry velocities.
Figure 35. Nondimensional erosion ratio of scale-down (3 in and 1 in) to 10 in prototypic S-type pipings for various slurry velocities.
Figure 36. Nondimensional erosion ratio of scale-down (3 in and 1 in) to 10 in prototypic bluff body for various slurry velocities
5. Conclusions

This report presents 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. 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 abraded surface can cause wear. The other is that some particles impinged on the wall surface are able to cut 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-impinged erosions. For typical operating conditions of the facility, Reynolds number is about $10^5$ corresponding to fully-turbulent flow regime. 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 work. 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 taking into account the complex nature of fluid-solid two-phase phenomena.

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 system. 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. To be conservative, the highest velocity over full-scale value (9.8 ft/sec) will be used, that is, 3.4 m/sec (11.2 ft/sec) for the 3 in test loop (14% over full-scale) and 3.7 m/sec (12.1 ft/sec) for the 1 in test loop (24% over full-scale). The results are also shown in Fig. 34.

From the present analysis results, main conclusions are drawn as follows:

- The prediction results show that when the slurry velocity increases, wall shear stress closely related to the abrasive erosion is more sensitive to the scaling of pipe size, compared to that of particle impingement behavior.

- The analysis results show that erosion decreases with increasing turbulence intensity, leading to the increased radial dispersion of slurry. This is consistent with the literature information.

- All the main loop components of the cross-flow filtration facility were studied to simplify the components without losing key erosion phenomena and slurry flow characteristics expected in the full-scale facility. Key components selected by the present analysis are isolated elbow, two-elbow connected closely with single branch, seven-tube filter arrangement, and bluff body attached to the inner wall of horizontal pipe.

- The present computational models determined operating flow conditions for the scaled test facility to ensure that the erosion behaviors expected at the full-scale
facility are properly captured in the scale-down test facility. In this case, three different component configurations were applied for the scaling considerations under three different size conditions, including 10 in prototypic scale, 3 in and 1 in test scales.

- The locations of high erosion, which were predicted by the particle impingement model for each of the selected components, provided the guidance for erosion measurement under scaled test facility.

- From the benchmarking of the present CFD models against the literature data, the model predictions agree with the test data within about 15%.

When the test results from the scaled experiment facility at SRTC are available, the present models will be benchmarked in more detail. This results in a validation of those calculations, and will allow the test results to be applied to a quantitative estimation of erosion over the entire plant lifetime of the full-scale filtration facility.
6. References


