

# Multiphysics Simulation of Flow-Assisted Erosion in the Secondary System Piping of i-SMR

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## 1. Introduction

Flow-Accelerated Corrosion (FAC) and Flow-Assisted Erosion (FAE) represent major degradation mechanisms in secondary system piping of pressurized water reactor (PWR). FAE involves mechanical thinning of pipe walls by high-speed particle-laden flow, distinct from FAC as it emphasizes physical erosion over chemical reactions.

FAE poses significant risks to pipe integrity, potentially leading to wall thinning, leakage, and structural failure, thereby compromising reactor safety and elevating maintenance costs. FAC exhibits pronounced temperature dependence peaking around 150°C, prompting expectation that FAE may exhibit similar temperature-dependent behavior in wet steam environments, which forms the basis for this investigation [1].

This study investigates FAE in a pipe elbow using COMSOL Multiphysics simulations, replicating innovative small modular reactor (i-SMR) secondary pipeline flow conditions to quantify erosion rates and temperature sensitivities.

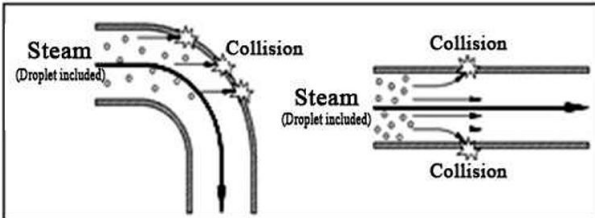


Fig. 1. Mimetic diagram of FAE [2].

## 2. Methods and Results

FAE analysis employs a two-stage process using COMSOL Multiphysics. The stationary solver applies the k- $\omega$  turbulence model from the CFD module to compute turbulent flow fields. The transient solver utilizes the particle tracing module for fluid flow to simulate particle trajectories and erosion impacts. This coupled approach enables comprehensive FAE prediction in pipe elbows under i-SMR secondary steam line conditions.

### 2.1 Fluid Flow Model

COMSOL Multiphysics CFD module computes turbulent flow fields in i-SMR main steam line elbows under high-velocity wet steam conditions. Analysis employs Reynolds-Averaged Navier-Stokes (RANS) equations with the Wilcox revised k- $\omega$  turbulence model, selected for accurate near-wall treatment and adverse pressure gradient prediction in pipe geometries.

The model solves turbulent kinetic energy (k) and specific turbulent dissipation rate ( $\omega$ ) through the governing equations:

$$\rho \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = P_k - \rho \beta^* k \omega + \nabla \cdot ((\mu + \sigma^* \mu_T) \nabla k) \quad (1)$$

$$\rho \frac{\partial \omega}{\partial t} + \rho u \cdot \nabla \omega = \alpha \frac{\omega}{k} P_k - \rho \beta \omega^2 + \nabla \cdot ((\mu + \sigma^* \mu_T) \nabla \omega) \quad (2)$$

where  $P_k$  represents production of turbulent kinetic energy, and  $\mu$  is molecular viscosity. Other relations appear in Fig. 2. below.

$$\mu_T = \rho \frac{k}{\omega} \quad \beta = \beta_0 f_\beta \quad \beta^* = \beta_0^* f_\beta^* \quad \sigma = \frac{1}{2} \quad \sigma^* = \frac{1}{2} \quad \beta_0 = \frac{13}{125} \quad \beta_0^* = \frac{9}{100}$$

$$f_\beta = \frac{1+70\chi\omega}{1+80\chi\omega} \quad \chi\omega = \frac{|\Omega_{ij}\Omega_{jk}S_{ki}|}{(\beta_0^*\omega)^3} \quad f_\beta^* = \begin{cases} 1 & \chi_k \leq 0 \\ \frac{1+680\chi_k^2}{1+400\chi_k^2} & \chi_k > 0 \end{cases} \quad \chi_k = \frac{1}{\omega^3} (\nabla k \cdot \nabla \omega)$$

$$\Omega_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} - \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad S_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)$$

$$P_k = \mu_T \left( \nabla u : (\nabla u + (\nabla u)^T) - \frac{2}{3} (\nabla \cdot u)^2 \right) - \frac{2}{3} \rho k \nabla \cdot u$$

$\Omega_{ij}$ : Mean rotation-rate tensor  
 $S_{ij}$ : Mean strain-rate tensor  
 $P_k$ : Production term  
 $I_T$ : Turbulent intensity

Fig. 2. Wilcox revised k- $\omega$  model relations and coefficients.

Boundary conditions specify pressure inlet and fully developed outlet flow with average velocity,  $V_{avg}$  5.5 m/s. Stationary solver achieves convergence at residual tolerance of 0.01, providing velocity and turbulence fields for subsequent particle tracing.

### 2.2 Erosion Model

COMSOL Multiphysics Particle Tracing module computes particle trajectories and erosion rates [kg/(m<sup>2</sup>·s)] in elbows. Time-dependent solver integrates particle motion over 0-2 seconds with 10<sup>-4</sup> second time intervals and 0.01 tolerance.

Finnie model predicts erosion through ductile material removal proportional to particle kinetic energy and impact angle. The core equation expresses erosion rate as:

$$V = \frac{cMU^2}{4p(1+\frac{mr^2}{I})} f(\alpha) \quad (3)$$

$$f(\alpha) = \begin{cases} \cos^2 \alpha & \tan \alpha > \frac{p}{2} \\ \left[ \sin(2\alpha) - \frac{2}{p} \sin^2 \alpha \right] & \tan \alpha \leq \frac{p}{2} \end{cases} \quad (4)$$

where  $c$  represents fraction of particles cutting in idealized manner,  $M$  denotes total mass of eroding particles,  $U$  indicates magnitude of incident particle velocity,  $p$  signifies Vickers hardness of material,  $m$  is mass of individual particle hitting surface,  $r$  denotes average particle radius,  $I$  represents moment of inertia of individual particle about center of mass,  $\alpha$  is angle of incidence ( $\alpha = \pi/2$  means normal to surface), and  $P = K / (1 + mr^2 / I)$ , where  $K$  is ratio of vertical and horizontal forces acting on particle.

DNV Model employs empirical erosion for offshore applications, emphasizing velocity exponent and angle effects:

$$E = K \left( \frac{v}{1 + \frac{m}{s}} \right)^{-n} F(\alpha) \quad (5)$$

$$F(\alpha) = 9.370\alpha - 42.295\alpha^2 + 110.864\alpha^3 - 175.804\alpha^4 + 170.137\alpha^5 - 98.398\alpha^6 + 31.211\alpha^7 - 4.170\alpha^8 \quad (6)$$

where  $K_{DNV}$ ,  $n_{DNV}$  represent dimensionless constants depending on surface material from experimental investigations [3].

Das et al. model (2015) incorporates wall temperature effects into erosion correlations, enhancing micro-scale cutting predictions for high-velocity particle-laden flows:

$$\dot{E} = \frac{1}{A\rho_{elb}} \sum_{i(A)} \dot{m}_i e_{r,i} \quad (7)$$

$$E(t) = \int_0^t \dot{E} dt \quad (8)$$

$$e_r = Kg(\theta) \left( \frac{v}{v_r} \right)^n f(d_p) h(T_w) \quad (9)$$

$$g(\theta) = 5.703 \times 10^{-9} \theta^5 - 1.519 \times 10^{-6} \theta^4 + 1.537 \times 10^{-4} \theta^3 - 7.49 \times 10^{-3} \theta^2 + 0.1735\theta \quad (10)$$

$$h(T_w) = 0.003798 \left( \frac{T_w}{T_r} \right)^2 - 0.01270 \left( \frac{T_w}{T_r} \right) + 1.009 \quad (11)$$

$$f(d_p) = 1 - e^{-\frac{3(d_p - d_{min})}{d_e}} \quad (12)$$

where  $\rho_{elb}$  represents density of elbow pipe material,  $A$  denotes impact face area equal to grid cell area in numerical calculations,  $m_i$  indicates mass of each particle colliding with face in unit time,  $e_{r,i}$  signifies erosion ratio of particle,  $K$  is erosion constant,  $g(\theta)$  describes function of impact angle  $\theta$ ,  $v$  represents impact velocity,  $f(d_p)$  captures function of particle size, and  $h(T_w)$  accounts for function of impact wall temperature [4].

Each model couples with CFD velocity fields for comprehensive FAE prediction.

### 2.3 Simulation Procedure

CFD module simulates steady-state turbulent flow conditions in i-SMR secondary pipeline elbows using the stationary  $k-\omega$  solver. Particle Tracing module

subsequently tracks lagrangian particle trajectories within the computed flow field over transient time steps. Erosion magnitude depends on cumulative wall impact intensity from particle collisions, determined by number of colliding particles and impact angle distribution. Sequential coupling transfers CFD velocity fields to initialize particle motion, enabling accurate prediction of local erosion rates across pipe geometries. This procedure integrates fluid dynamics with particle-wall interaction physics for comprehensive FAE assessment.

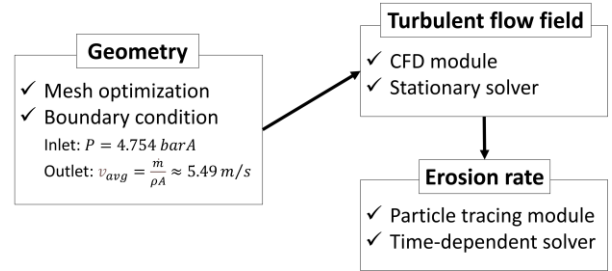


Fig. 3. FAE three-stage simulation procedure flowchart.

### 2.4 Simulation Results

Finnie and DNV models compute elbow inner wall erosion rate distributions using average flow fields and particle trajectories, without direct temperature incorporation. Both models apply identical flow and particle conditions; differences arise from erosion formulas and material constants. Finnie model yields maximum erosion rate of  $4.57 \times 10^{-5}$  kg/(m<sup>2</sup>·s), with peaks at particle trajectory deflection zones due to flow turning. DNV model produces lower maximum of  $8.4 \times 10^{-6}$  kg/(m<sup>2</sup>·s), yet similar distribution patterns concentrating at elbow inlet, outer curvature, and diminishing downstream.

Das et al. model directly evaluates temperature dependence across 75, 125, 150, 175, and 225°C, implemented in COMSOL for i-SMR secondary system elbow under uniform flow/particle conditions. For 10 μm droplets, maximum erosion rises from  $3.56 \times 10^{-5}$  kg/(m<sup>2</sup>·s) at 75°C to  $4.22 \times 10^{-5}$  kg/(m<sup>2</sup>·s) at 225°C, exhibiting linear increase consistent with material softening and damage accumulation. For 300 μm droplets, rates elevate further:  $3.99 \times 10^{-5}$  to  $4.81 \times 10^{-5}$  kg/(m<sup>2</sup>·s), amplified by higher momentum at concentration zones like outer curvature.

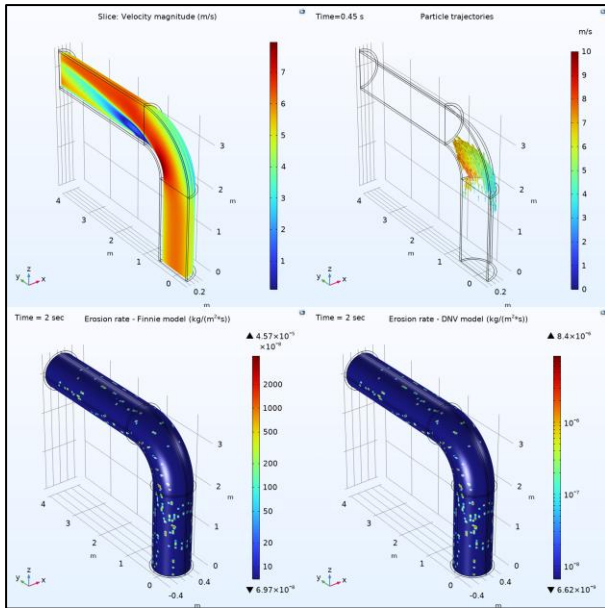


Fig. 4. Simulated velocity fields and erosion rate contours on elbow inner walls using COMSOL Multiphysics.

### 3. Conclusions

COMSOL Multiphysics CFD and Particle Tracing modules enable FAE analysis for i-SMR secondary system elbows under 150°C high-pressure wet steam conditions. RANS-based turbulence modeling couples with Finnie, DNV, and Das et al. erosion models. Das et al. application quantitatively confirms linear erosion rate increase with rising temperature, contrasting FAC's peak at 150°C [1].

Finnie and DNV models predict comparable elbow erosion distributions, with maximum rates at curvature regions. Temperature effects manifest as elevated erosion at higher wall temperatures via Das et al. correlations. L-shaped pipes exhibit highest erosion at elbows. Future work requires experimental validation and comparisons for i-SMR piping applications.

### ACKNOWLEDGEMENT

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