Numerical Simulation of Carbon Steel Corrosion Exposed to Flowing Solutions Vhrough an Annular Duct

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Introduction: Generally changes in the fluid velocity and the concentration of aggressive species on the metallic surface, are decisive parameters in the corrosion rate determination. In this work, the corrosion phenomenon is studied in terms of interactions at the solid-liquid interface, using a 3D-model to cylindrical specimens.
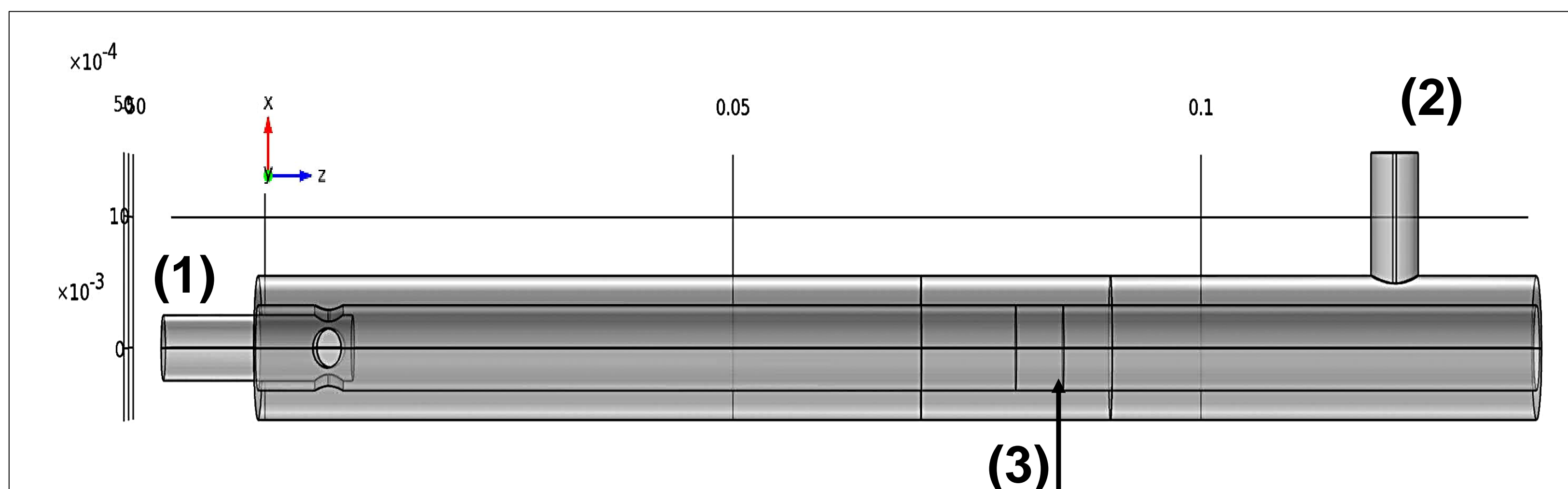

Figure 1. Model geometry of the corrosion cell. (1) Flow inlet, (2) flow outlet, (3) Carbon steel specimen

Computational Methods: The PDE's are solved for an incompressible and Newtonian fluid under stationary conditions, considering:

1) Navier-Stokes and the continuity equation:
$$\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = \nabla\cdot\left[-p\boldsymbol{I} + \mu\left(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T\right)\right] + F$$
$$\rho\nabla\cdot\boldsymbol{u} = 0$$
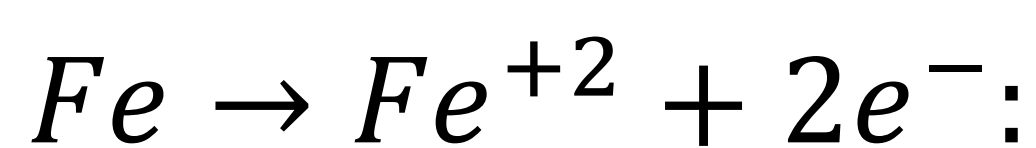
2) Nernst-Planck and the electroneutrality equation:
$$\nabla\left(-D_j\nabla c_j - z_j u_{m,j}F c_j\nabla V\right) + \boldsymbol{u}\nabla c_j + R_j = 0$$
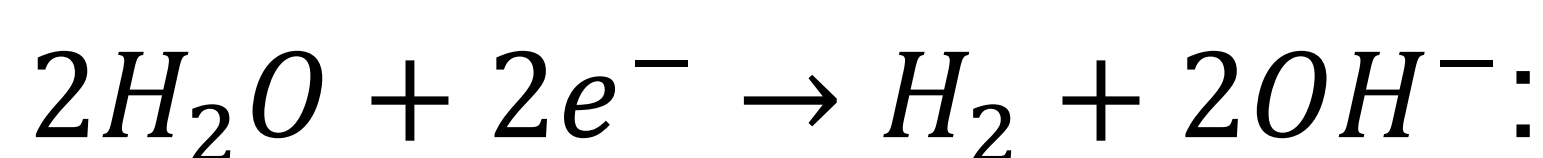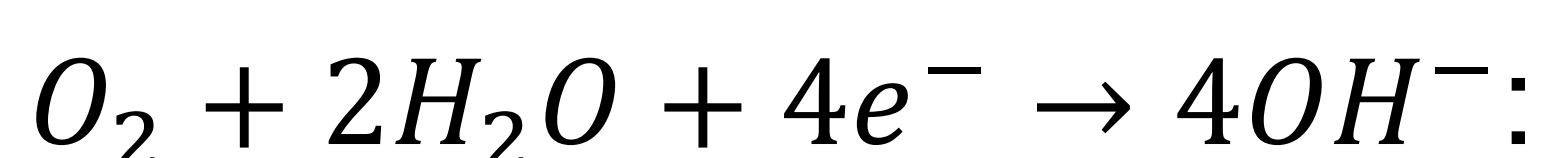$$\sum_j z_j c_j = 0$$

3) Electrochemical kinetic:

Mixed potential theory: $i_T = i_{Fe} + i_{O_2} + i_{H_2O}$

$Fe \rightarrow Fe^{+2} + 2e^-$:
$$i_{Fe} = i_{0,Fe}\,exp\left(\frac{2.303(E-V-E_{eq,Fe})}{b_{Fe}}\right)$$

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$:
$$i_{H_2O} = i_{0,H_2O}\,exp\left(\frac{2.303(E-V-E_{eq,H_2O})}{b_{H_2O}}\right)$$

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$:
$$i_{O_2} = i_{0,O_2}\,exp\left(\frac{2.303(E-V-E_{eq,O_2})}{b_{O_2}}\right)\left(\frac{c_{s,O_2}}{c_{b,O_2}}\right)$$

Table. 1. Parameters used in the study

Variable	Value	Variable	Value
$C_{b,O2}$, mol/m³	0.21	C_{NaCl}, mol/m³	1000
Solution pH	6.7	d_{eq}, m	0.0045
$\bar{u}$ (inlet port), m/s	0.32	Re (annular section)	1446

Results: Uniform velocity profile, low turbulence and different concentration distribution were observed close to the specimen surface.
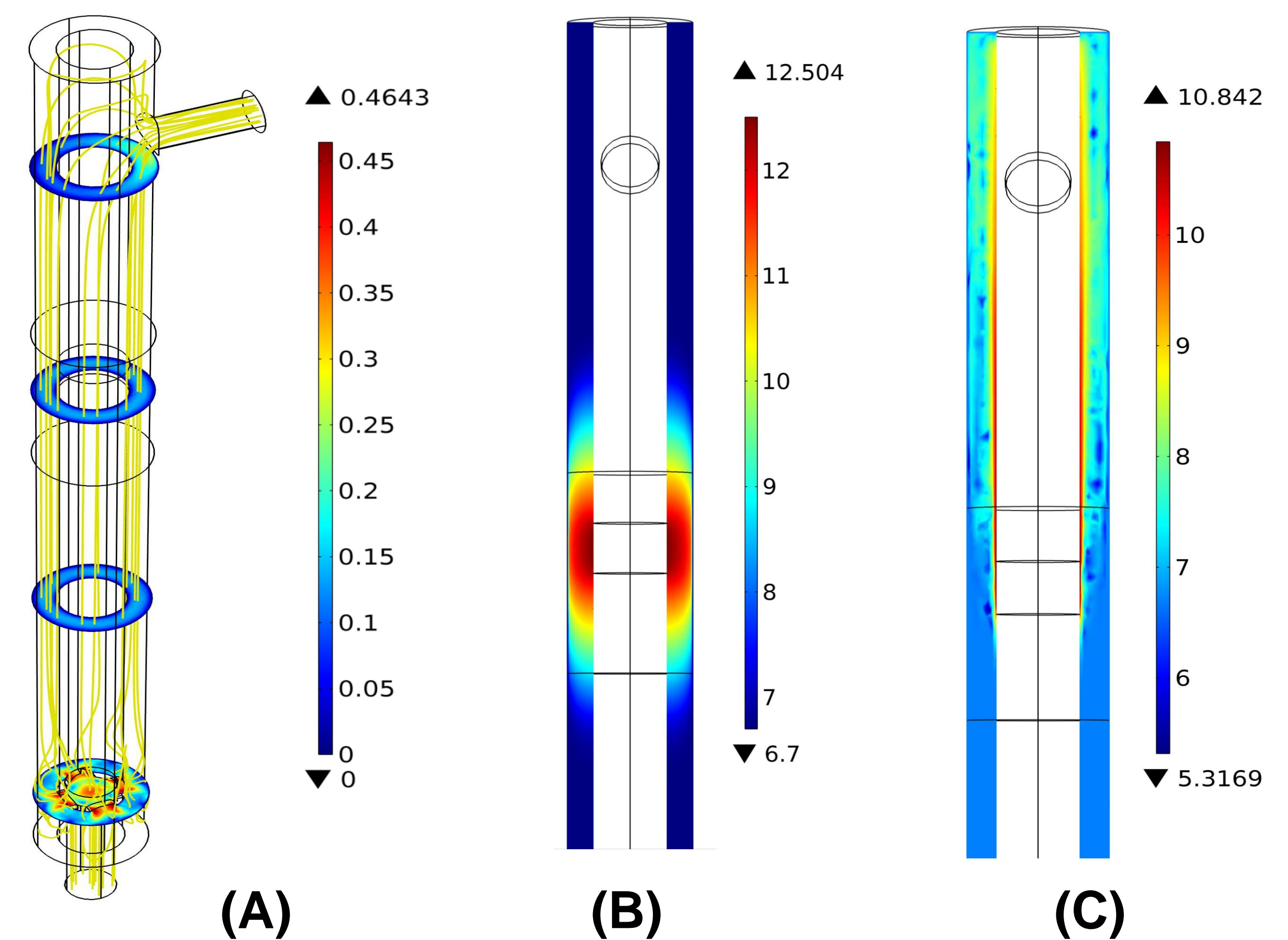

(A) (B) (C)

Figure 2. (A) Velocity profile (m/s), (B) pH profile at ū=0 m/s, and (C) pH profile at ū=0.32 m/s, at E=-0.85 mV/SHE
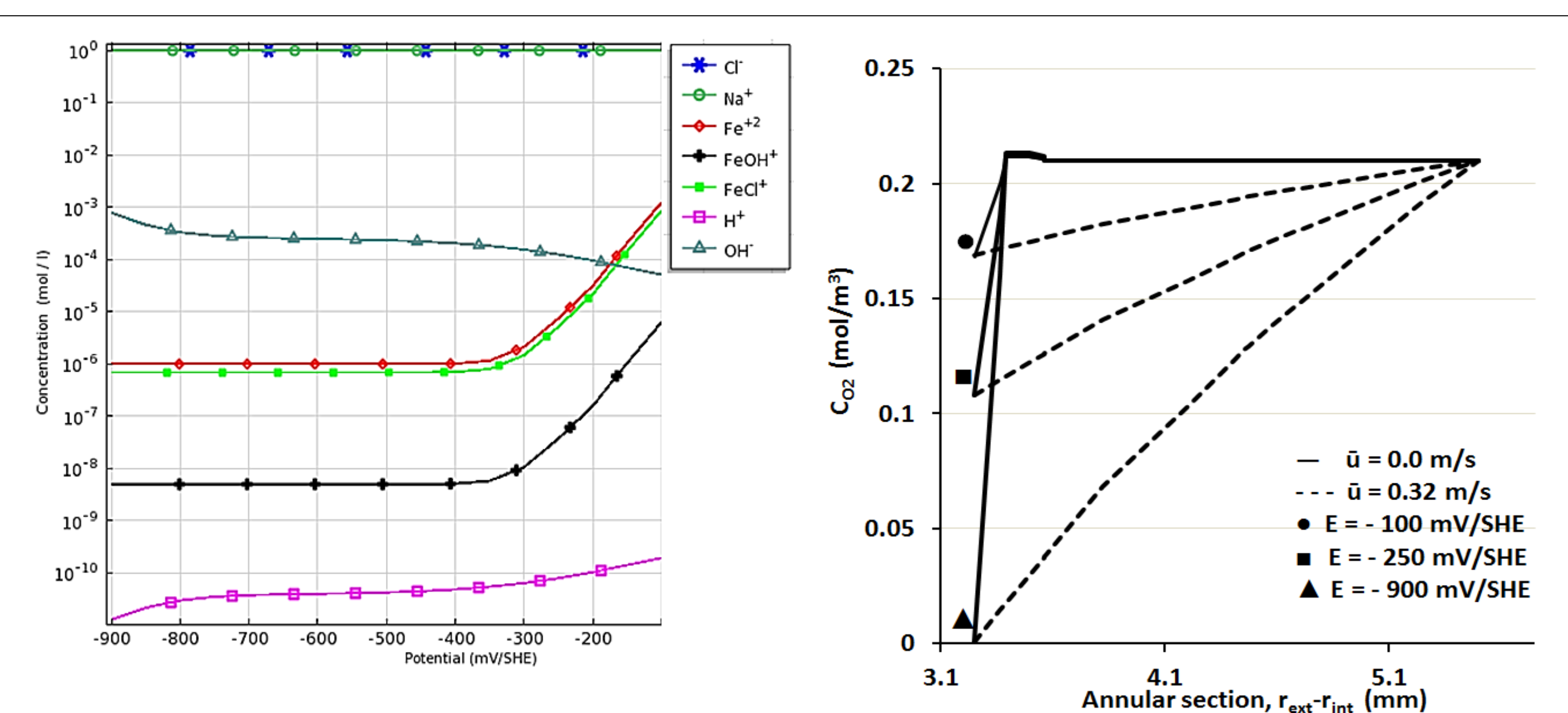

Figure 3. Partial polarization curves from mixed potential theory (left), radial oxygen dissolved profile (right)
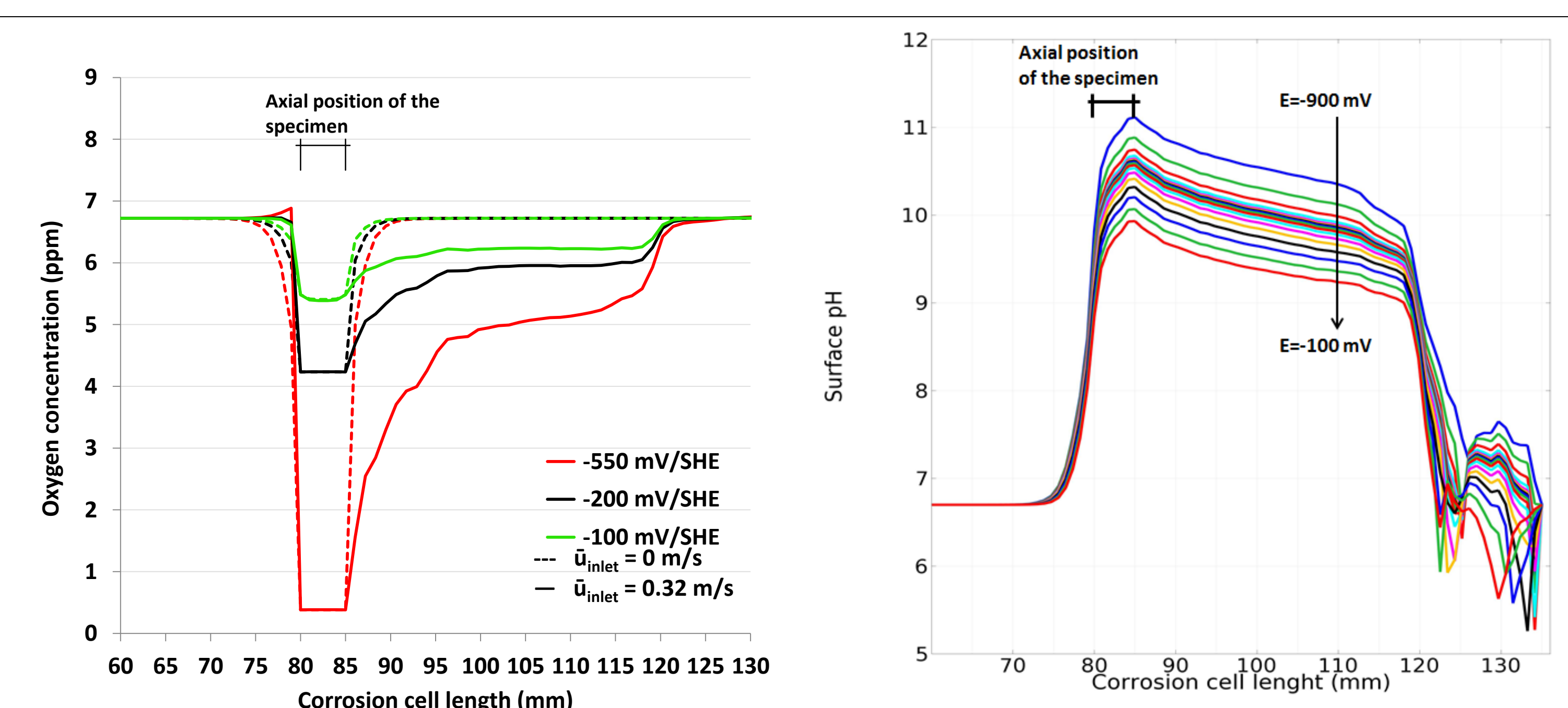

Figure 4. Oxygen and pH distribution in axial direction

Conclusions: The high oxygen concentration in the solid-liquid interface leads to obtain high corrosion rates. More corrosion products would be deposited at the top end of the specimen, limiting the oxygen diffusion at the surface.

References:
1. Caceres et al., Electrochim. Acta, 54, 7435 (2009)
2. Katsounaros et al., Electrochem. Commun., 13, 643 (2011)