MODELING LIQUID METAL CORROSION IN A FERRITIC STEEL – PbLi SYSTEM WITH AND WITHOUT A MAGNETIC FIELD

SMOLENTSEV Sergey, SAEIDI Sheida, ABDOU Mohamed
Fusion Science and Technology Center, UCLA, USA
E-mail: sergey@fusion.ucla.edu (Sergey Smolentsev)

Abstract: We perform computations of transport processes associated with corrosion of ferritic steel in the flowing eutectic alloy lead-lithium (PbLi). New computer codes have been developed to solve coupled fluid flow, energy and mass transfer equations for several flow geometries, such as a plane channel, rectangular duct or a circular pipe. First, an inverse problem is solved where saturation concentration of iron in PbLi is reconstructed from the experimental data. These reconstructed data are further used as a boundary condition at the solid-liquid interface to perform more analysis and comparisons against available experimental data on corrosion in various flow conditions, including purely hydrodynamic turbulent flows as well as laminar duct flows with and without a magnetic field. A good match with the experimental data is demonstrated.

1. Introduction

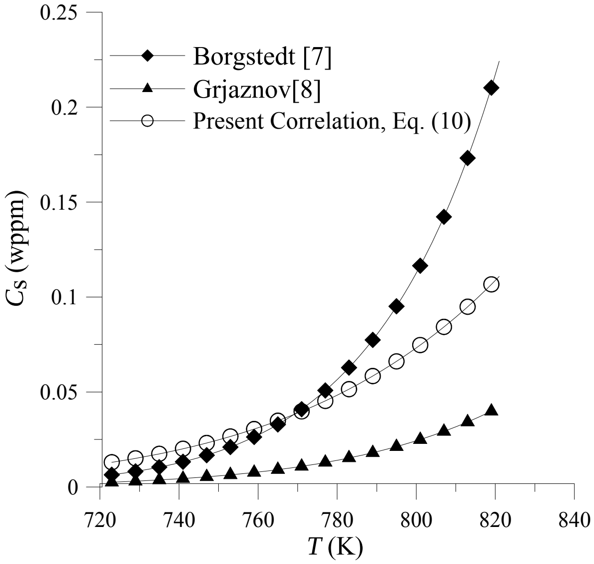


Figure 1: saturation concentration of Fe in PbLi versus temperature from 3 correlations.

Eutectic alloy PbLi and ferritic steel (such as F82H or EUROFER) are attractive candidates for using in breeding blankets of a fusion power reactor as a breeder/coolant and as a structural material respectively. Consequently, implementation of these materials in blanket applications requires further material compatibility studies, including corrosion of ferritic walls in the flowing PbLi at elevated temperatures relevant to the blanket operation conditions. At present, the limit of 20 μm/year associated with precipitation of corrosion products in the cold leg of the liquid metal (LM) loop is accepted [1]. However, this limit was derived in the past based on conservative assumptions and need to be readdressed. This necessitates further development and testing of phenomenological models, boundary conditions as well as further evaluation of material properties associated with corrosion processes in the flowing liquid metal. One of the main goals of this study is to access transport phenomena in the flowing PbLi associated with corrosion of ferritic walls via numerical modeling. As a matter of fact, even in this relatively simple case, where the corrosion mechanism is mostly dissolution of the steel matrix [2], many uncertainties still exist that make the modeling predictions meaningless. For example, the most critical limitation is related to the experimental values of the saturation concentration C_s of iron (Fe) in PbLi versus temperature (fig 1), which sometimes vary by orders of magnitude. In this study, we improve existing correlations for the saturation concentration and predict corrosion rates accurately. First, we develop new computer codes that solve simultaneously the fluid flow, energy and mass transfer equations for either turbulent or laminar flows. The turbulent flow code is then run under the experimental conditions, using experimental data on LM corrosion obtained in the recent past. The goal of these simulations is twofold. Firstly, we benchmark the new code against experimental data. Secondly, we solve an inverse problem where the data on saturation concentration of iron in PbLi is reconstructed by comparing calculated results for the mass loss with the experimental data. The obtained data on the saturation concentration are then approximated with a new correlation, which is further used to perform more analysis and comparisons. Two sets of experimental conditions have been reproduced in the computations: (1) corrosion of ferritic-martensitic steels in purely hydrodynamic turbulent PbLi flows [3] and [5] , and (2) corrosion in laminar rectangular duct flows with and without a magnetic field [4]. The computed and experimental data are in a good agreement, which proofs the adequacy of the suggested modeling approaches and our choice of governing equations and boundary conditions.

2. Mathematical model

In liquid metal blankets, corrosion always occurs in the presence of a flowing liquid metal. Along with the temperature, the flow is one of the most important conditions that might increase the corrosion rate compared to static liquids. The mathematical model thus includes the fluid flow equations, the energy equation and the mass transfer equation. The latter is written here in the dilution approximation assuming all corrosion products are fully dissolved in the liquid metal. We also assume that the main corrosion process that eventually determines the wall mass loss is uniform dissolution of iron and compute only iron concentration C in the PbLi. Transport of other metallic components (Cr, Ni, Mn, W, V, Ta) is not considered due to their lower concentration. The key issue in solving the mass transfer problem for corrosion and transport of corrosion products in the flowing liquid is the boundary condition at the solid-liquid interface. Most of the studies performed in LMs have shown that a corrosion process is controlled by mass transfer [5]. In such a case, the global dissolution at the interface is at equilibrium and the corrosion rate is limited by the diffusion/convection of the dissolved species through the boundary layer at the material interface to the bulk of the flow. Given the above observation, the boundary condition at the interface can be written as a Dirichlet boundary condition [6]:

$$C\big|_w = C_s, \tag{1}$$

where C_s is the saturation concentration of Fe in PbLi at the wall temperature.

2.1. Turbulent hydrodynamic flows. The experimental data for corrosion of ferritic-martensitic steels in turbulent PbLi flows without a magnetic field are presented in [3]. These results had been approximated with a simple correlation known as the *Sannier's equation*:

$$ML = 8\times 10^8 \times Exp[-\frac{25690}{1.98T}]\times V^{0.875} \times D_h^{-0.125},\ \text{µm/year}. \qquad (2)$$

Here, *ML* is the material loss, *T* is the absolute temperature of the flowing PbLi (613-753 K), and *V* is the flow velocity (up to 0.3 m/s). To describe this kind of corrosion processes, the transport model is written here in the boundary-layer approximation in terms of the velocity components U and V, temperature T, pressure P and concentration C as follows:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{1}{y^m}\frac{\partial}{\partial y}[y^m(\nu+\nu_t)\frac{\partial U}{\partial y}], \qquad (3)$$

$$\frac{\partial U}{\partial x} + \frac{1}{y^m}\frac{\partial}{\partial y}(y^m V) = 0 \ , \qquad (4)$$

$$\rho C_p(\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y}) = \frac{1}{y^m}\frac{\partial}{\partial y}[y^m(k+k_t)\frac{\partial T}{\partial y}], \qquad (5)$$

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial y} = \frac{1}{y^m}\frac{\partial}{\partial y}[y^m(D+D_t)\frac{\partial C}{\partial y}] \ . \qquad (6)$$

The integer parameter *m* is either 1 (plane channel) or 2 (circular pipe) and ν_t, k_t and D_t are the turbulent transport properties: viscosity, thermal conductivity and diffusion coefficient of iron in PbLi, which are calculated using a well-known $k-\varepsilon$ model of turbulence.

2.2. Laminar flow in a rectangular duct with and without a magnetic field. The experimental data for this case are presented in [4] for a laminar PbLi flow in a rectangular duct 2.7x1 cm^2 with inserts made of EUROFER at 550°C for two cases with (B_0=1.7 T) and without (B_0=0) a magnetic field and for two velocities 2.5 and 5.0 cm/s. To simulate corrosion processes, a fully developed MHD flow model written in terms of the axial induced magnetic field component B_x, axial velocity *U* and iron concentration *C* is used as follows:

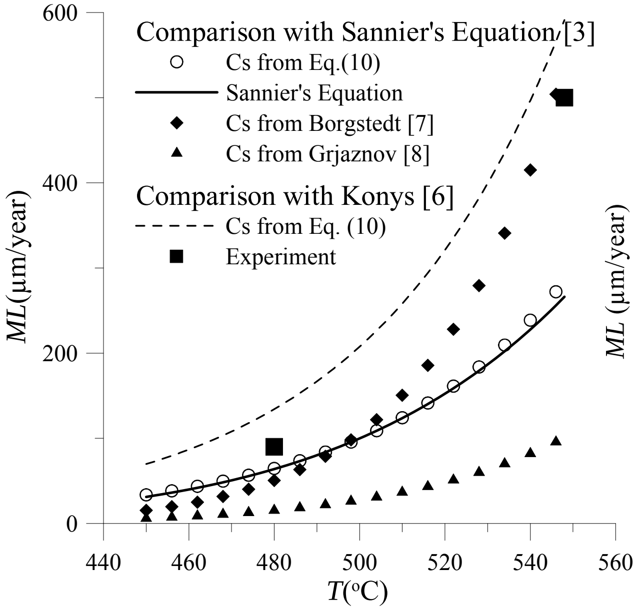
$$\frac{\partial^2 U}{\partial z^2} + \frac{\partial^2 U}{\partial y^2} + \frac{B_0}{\mu\mu_0}\frac{\partial B_x}{\partial z} - \frac{1}{\nu\rho}\frac{dP}{dx} = 0, \qquad (7)$$

$$U\frac{\partial C}{\partial x} = D(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}), \qquad (8)$$

$$\frac{\partial^2 B_x}{\partial z^2} + \frac{\partial^2 B_x}{\partial y^2} + \sigma\mu_0 B_0\frac{\partial U}{\partial z} = 0. \qquad (9)$$

3. Results

Two computer codes, one for turbulent hydrodynamic flows [Eqs. (3-6)] and the other for MHD laminar flows [Eqs. (7-9)] have been developed and tested and then applied to the analysis of corrosion processes under experimental conditions described in Section 1.



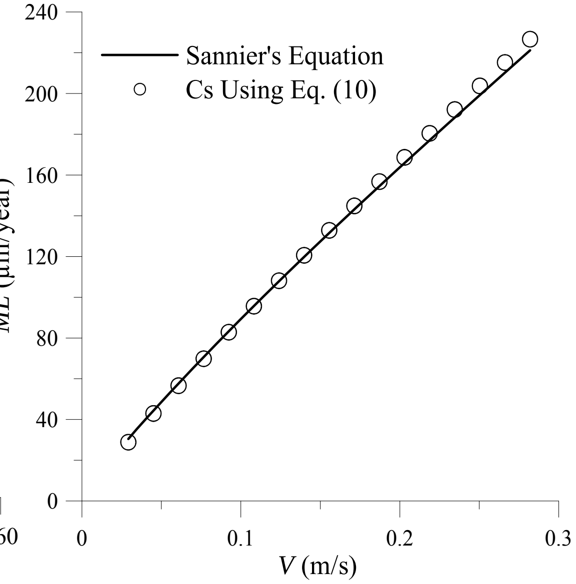
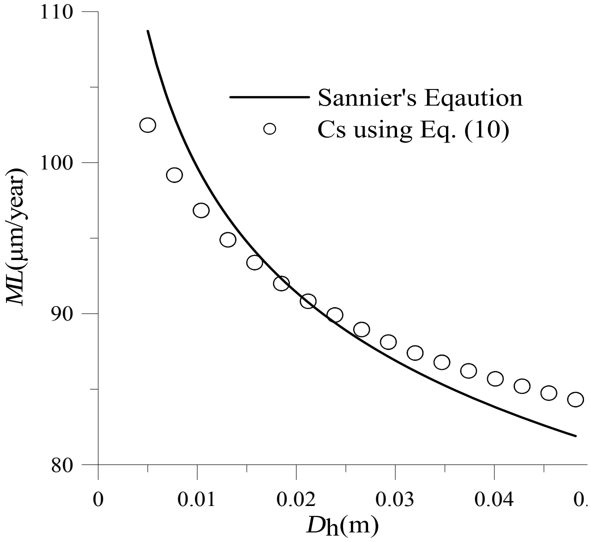


Figure 2: mass loss in a turbulent flow computed with the present code against Sannier's equation (V=0.11m/s, D_h=0.02) and experimental data [6] (V= 0.22 m/s, D_h=0.008)

Figure 3: mass loss in a turbulent flow as a function of velocity at T= 500^o C and D_h= 0.02 m.



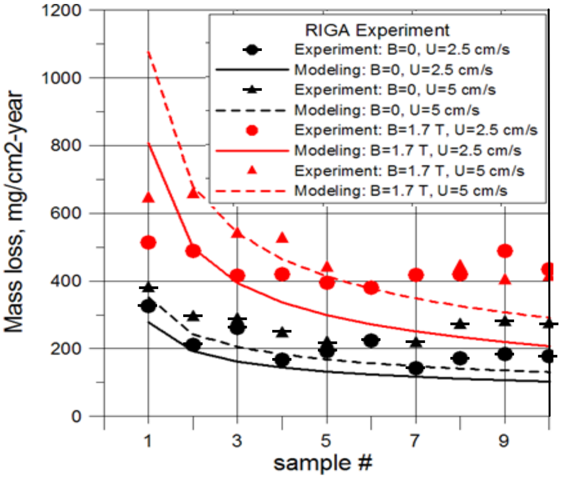


Figure 4: mass loss as a function of hydraulic diameter in a turbulent flow at T= 500^{o}C and V=0.11 m/s.

Figure 5: computed mass loss against experimental data [4] for laminar flows with and without a magnetic field.

3.1. Turbulent flows. Using empirical correlations for saturation concentration by Borgstedt [7] and Grjaznov [8] in computations of the mass loss as a function of the wall temperature doesn't lead to a good fit with the Sannier's equation as seen in fig 2. A new improved correlation has been obtained by matching calculated and experimental data in the following form:

$$C_s = 2.0 \times Exp(0.0218T). \tag{10}$$

This correlation is then used to compute the mass loss as a function of the velocity (fig 3) and hydraulic diameter (fig 4). In all these cases there is a good match between computed and experimental values. The same correlation is also used in comparisons with more recent corrosion data obtained in the PICOLO loop [5] resulting in maximum discrepancy of 30% (fig 2).

3.2. Laminar flows. The velocity profile is computed first using the thin-wall boundary conditions and then the velocity data are used to solve the mass transfer equation (9) by applying the same correlation (10). The results are compared with the experimental data for the mass loss from the Hartmann wall in fig 5, showing again a reasonably good match.

4. Conclusions

The main result of the present study is the new improved correlation for saturation concentration of iron in PbLi Eq. (10). Using this correlation in computations of corrosion processes in either turbulent or laminar flows with or without a magnetic field along with the Dirihlet boundary condition (1), results in satisfactory predictions of the wall mass loss in a wide range of flow velocities, temperatures and duct dimensions.

5. References

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