Corrosion Behavior and Mass Transport of SS316L in a NaCl-KCl-$MgCl_2$ Molten Salt Natural Circulation Micro Loop

Taeho Kim [a,b*], Seok Min Yoon [a,b], Seol Kim [a,b], Suhyeon Lee [a,b], Eun-Young Choi [a,b], Chang Hwa Lee [a,b]
[a] *Advanced Nuclear Fuel Cycle Technology Development Division, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*
[b] *Quantum Energy Chemical Engineering, University of Science & Technology, Daejeon, 34113, South Korea*
[*] *Corresponding author: tkim@kaeri.re.kr*

Keywords : Molten chloride salt; SS316L; Natural circulation; Thermal-gradient mass transport

1. Introduction

Molten chloride salts are considered for use as coolants and fuel-solvent media in molten salt reactors (MSRs) because of their high boiling points, low vapor pressures, and suitable thermophysical properties. A major materials issue is corrosion of structural alloys. In stainless steels, Cr is preferentially dissolved because of its relatively high electrochemical activity, particularly in the presence of residual moisture-derived impurities such as $MgOH^+$ and HCl [1]. Most corrosion studies of chloride salts have been conducted under static and isothermal conditions. These conditions do not account for mass transport caused by a temperature gradient, in which alloying elements dissolve preferentially in hotter regions and may precipitate or deposit in colder regions as the salt circulates through the system [2]. In a loop, removal of dissolved species from the hot section can delay local saturation and maintain further dissolution. Deposits formed in the cold section may also be important in small-diameter tubing because they can reduce the effective flow area.

To examine corrosion under simultaneous flow and temperature-gradient conditions, a natural circulation micro-loop made of 1/4-inch SS316L tubing was constructed and operated at the Korea Atomic Energy Research Institute (KAERI) using a NaCl-KCl-$MgCl_2$ eutectic salt. This study evaluates the loop operating behavior, estimates the natural-circulation flow rate from temperature and electrical data, and compares the post-test corrosion features of the hot and cold legs. The observed differences are discussed in relation to thermal-gradient-driven mass transport.

2. Experimnental

The loop consisted of a parallelogram-shaped closed circuit fabricated from 1/4-inch OD × 0.035-inch-wall 316L tubing (ID 4.57 mm). The vertical leg height was 0.34 m, and the total flow path length was approximately 1.38 m. An expansion tank was connected at the top of the loop and a drain tank at the bottom. Heating was supplied by Kanthal A-1 resistance wire (0.9 mm diameter) wound directly around the tubing in five independently controlled zones and powered at 27 V DC. The loop was insulated with ceramic paper. 15 K-type thermocouples were welded to the outer tube wall, and the temperatures and three heater currents were recorded at 20-s intervals. No mechanical pump was used; the flow was generated by natural circulation.

The NaCl-KCl-$MgCl_2$ eutectic salt was vacuum-dried in the expansion tank at approximately from 160 to 200 °C for about 70 h before melting and introduction into the loop. In the reference run, the hot-leg heater was operated at 189 W. The loop was then maintained at steady state for 26 h, with a heated-path inlet temperature of 521 °C, an outlet temperature of 625 °C (ΔT = 104.3 °C), and a maximum heater wall temperature of approximately 670 °C. After the test, tube sections were taken from the hot and cold legs, and the inner-wall cross sections were examined by SEM and EDS elemental mapping.

Because a conventional flowmeter was not used in the small-bore high-temperature salt loop, the circulating flow rate was estimated from the measured temperature and current data using two independent approaches. The first was an energy balance over the heated path, for which parasitic heat loss was calibrated in situ using the pre-melting period with stagnant, frozen salt in the same run. The second was a momentum balance in which the buoyancy head calculated from the measured leg temperature distributions was equated to the laminar friction loss ($f = 64/Re$). Uncertainties associated with thermophysical properties, form losses, and heat-loss scaling were evaluated by Monte Carlo analysis (N = 20,000).

3. Results and Discussion

The flow rates estimated by the two methods agreed within their uncertainty ranges. The energy balance gave 0.41 g/s [0.25–0.55], whereas the momentum balance gave 0.60 g/s [0.52–0.71]. Combining the two estimates gave a flow rate of 0.49 g/s [0.39–0.58], corresponding to a mean velocity of approximately 1.8 cm/s and $Re \approx 100$. A separate run with modified cold-side heater settings gave a comparable value of 0.56 g/s [0.40–0.70]. At a flow rate of 0.49 g/s, one loop transit required approximately 75 s, corresponding to more than 1,000 circulations during the 26-h steady-state period. The Reynolds number indicates laminar flow; under these conditions, wall mass transfer is expected to be governed mainly by molecular diffusion rather than

turbulent mixing, and mechanical erosion is unlikely to make a major contribution to the observed degradation.

Cross-sectional analyses showed different corrosion features in the hot and cold legs. The hot-leg inner wall had a thin, porous oxide layer, and EDS showed Cr as the dominant metallic element in the scale. The cold-leg inner wall, in contrast, had a denser Cr–O layer. Mn and Fe were depleted beneath this layer, whereas Ni was enriched in the subsurface region.

The difference between the hot and cold legs is consistent with thermal-gradient-driven mass transport. Cr-containing species generated in the hotter section can be transported by the circulating salt and, as the temperature decreases, become less soluble and contribute to deposition in the colder section. Continuous circulation also limits the accumulation of dissolved Cr in the hot leg and can therefore maintain a concentration gradient for further dissolution. During the 26-h steady-state period, the salt passed repeatedly through both temperature regions more than 1,000 times. Although the present observations do not quantify the Cr transport flux, the hot/cold asymmetry shows a corrosion feature that is not represented by static isothermal tests. In small-bore loops, continued deposition in the cold leg could gradually reduce the flow area. Changes in the estimated flow rate and loop ΔT may therefore provide useful indicators of flow-path restriction during long-term operation. Quantitative comparison of the deposit thickness with the wall temperature distribution, together with a mass balance between dissolution and deposition, is currently in progress.

3. Conclusion

A 316L stainless steel natural circulation micro-loop containing NaCl-KCl-$MgCl_2$ eutectic salt was operated for 26 h at steady state with a temperature difference of 104 °C across the heated path. The circulating flow rate estimated by two independent balance methods was 0.49 g/s (Re $\approx$ 100), and a comparable value was obtained in a separate run. The hot and cold sections showed different corrosion morphologies: a thin porous oxide layer was observed in the hot leg, whereas a dense Cr–O layer with Mn/Fe depletion and subsurface Ni enrichment formed in the cold leg. These results are consistent with thermal-gradient-driven transport of Cr-containing species by the circulating salt. The results also show the value of non-isothermal loop experiments for evaluating corrosion behavior that is not represented in static tests. Longer-duration (>1,000 h) loop experiments with different structural materials are planned to quantify mass transport rates and assess their effect on small-bore flow paths.

REFERENCES

[1] S. Guo et al., “Corrosion in the Molten Fluoride and Chloride Salts and Materials Development for Nuclear Applications,” Progress in Materials Science 97 (2018)

[2] J. W. Koger, “ Corrosion Product Deposition in Molten Fluoride Salt Systems,” Corrosion 30 (1974)

[3] S. Yoon et al., “Effect of Various Impurity Additives on the Corrosion Behavior of Structural Materials in NaCl-$MgCl_2$ Salt,” Progress in Nuclear Energy 200 (2026)