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A Hybrid Physical–Machine Learning Framework for Real-Time Bath Oxygen and Carbon Soft Sensing in DRI-Based Electric Arc Furnaces

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Reliable real-time knowledge of bath oxygen and carbon is a long-standing challenge in DRI-based Electric Arc Furnace (EAF) operation, directly impacting energy efficiency, decarburization control, and endpoint stability. This paper presents a novel hybrid physics-guided machine learning framework for continuous bath oxygen and carbon prediction, explicitly coupling metallurgical first principles with high-frequency operational data. The physical layer embeds oxygen and carbon mass balances, decarburization kinetics, carbon–oxygen equilibrium, and bath thermal evolution. A key innovation is the integration of time-series stack emission data—including CO, CO_2, O_2 concentrations and post-combustion rate—as dynamic indicators of in-furnace reaction intensity and oxygen utilization. Multiple machine-learning algorithms (Gaussian Process Regression, Artificial Neural Networks, and Long Short-Term Memory networks) were developed and benchmarked within the hybrid architecture. The selected model achieved R^2 values exceeding 0.9 for both oxygen and carbon across varying operating regimes, outperforming standalone physical and purely data-driven approaches. The proposed framework establishes a robust soft-sensing foundation for digital twin deployment, advanced EAF process control, and real-time energy optimization in industrial DRI-EAF steelmaking.

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