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Physics-Informed Reduced-Order Modeling for Temperature Prediction in Industrial Reheating Furnaces

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Industrial steel reheating furnaces operate at temperatures between 800℃ and 1300℃ and consume a significant fraction of energy for the heating process. These units are significantly energy-intensive, and accurate prediction of furnace gas and slab temperature distributions is essential. This can help to maintain slab quality, support operational decision-making, improve thermal efficiency and enable decarbonization strategies (fuel switching, electrification). However, high-fidelity computational fluid dynamics (CFD) simulations are computationally expensive, which makes systematic design optimization impractical. In contrast, purely data-driven surrogate models can alleviate the computational cost. These methods often extrapolate poorly and can violate physics when applied outside their training envelope.

This study proposes a hybrid Reduced-Order Model with Physics-Informed Neural Network (ROM-PINN) framework for fast and physically consistent prediction of furnace and slab temperature distributions in an industrial reheating furnace. Detailed CFD simulations have been carried out and validated with real observations. These simulations are carried out for multiple syngas–natural gas blends and representative operating conditions for the industrial reheating furnace. The resulting high-dimensional CFD fields are reduced using Proper Orthogonal Decomposition (POD), yielding a compact set of dominant modes. A fully connected feed-forward neural network learns the mapping from operating parameters to the corresponding POD modal coefficients, which are used to reconstruct the full temperature field.

Radiation and conduction equations, as well as physical boundary conditions, are embedded directly into the neural network training through a multi-term loss function. The physics loss penalizes violations of Fourier heat conduction in the steel slab and radiative transfer equation (RTE) for the participating furnace gas, together with the Stefan–Boltzmann law governing the exchanges between the gas and solid surfaces and global energy conservation over the furnace control volume. An adaptive weighting strategy tracks the relative magnitudes of data and physics residuals during training.

The proposed framework can achieve speedups of several orders of magnitude compared with full CFD simulations. In addition, this model can remain robust in extrapolation which means even when applied outside the training envelope, it can avoid non-physical temperature overshooting or violating physical constraints.

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