



Ph.D. DISSERTATION DEFENSE

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Degree: Doctor of Philosophy
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Department: Mechanical Engineering
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Title: Predicting Thermal Radiative Transport in Porous Media Using Data- Driven Modeling and Experiment

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ABSTRACT

The precise measurement and prediction of thermal radiative properties are central to advancing technologies that rely on light-matter interaction, including solar energy conversion, photonics, and thermal management. These properties - absorption, reflection, transmission, and scattering become increasingly sensitive to the topology of geometry, porosity, and surface morphology at the micro and nanoscale. This creates a critical need for computationally efficient, and experimentally validated frameworks capable of characterizing radiative transport in highly nonlinear porous media.

The objective of this dissertation is to develop a unified computational-experimental framework for studying radiative transport in micro- and nano-scale porous media. The computational components include physics-based radiative transport modeling, Monte Carlo Ray Tracing (MCRT) for stochastic microscale analysis, Finite Difference Time Domain (FDTD) methods for wavelength-resolved nanoscale electromagnetic simulations and reduced-order data-driven machine learning (ML) based surrogate models to mitigate the high computational cost of full-order solvers. Surrogate model is trained on high-fidelity datasets to enable rapid prediction of

effective radiative properties across varying geometries, porosities, and spectral regimes. To ensure physical credibility and practical applicability, the framework is experimentally verified through micro-scale additive manufacturing using Two-Photon Polymerization (TPP) to fabricate deterministic true-scale porous structures, followed by micro-spectrophotometric measurements for validation. This closed-loop integration of simulation, surrogate learning, and microfabrication establishes a scalable methodology that bridges theory and experiment. The developed framework is further applied to nanoscale porous systems and nanoporous thin-film solar cells, incorporating spectral radiative characterization and analytical optical transfer matrix modeling to study carrier recombination phenomena. Collectively, this dissertation advances a physics-informed, data-enabled pipeline for radiative property characterization and accelerated design of porous media. The resulting methodology significantly reduces computational and experimental cost while enabling systematic optimization of micro- and nano-engineered structures for next-generation photonic, energy, and semiconductor thermal applications.