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耦合生物质热转化的冶金熔渣余热回收技术

摘要

冶金行业作为高能耗产业存在大量余热资源亟待回收利用，其中熔渣余热的有效回收已成为行业关键课题。本研究针对传统余热回收技术效率不足的问题，创新性地将生物质热转化与冶金熔渣余热回收相结合，开发出耦合生物质热转化的新型余热回收系统。采用计算流体力学-离散元耦合方法（CFD-DEM）构建回转式反应器三维模型，基于密集离散颗粒模型（DDPM）对热态铜渣与生物质颗粒的多相流动及传热传质特性进行数值模拟研究。研究表明：1）反应器内颗粒床层呈现典型的滚转流动模式，可分为主动区（颗粒随壁面运动）和被动区（颗粒内部滑移）两个特征区域，该流动分区直接影响固体停留时间分布及反应器可放大性；2）当铜渣添加量达到 20wt%、转速为 4 rpm 时，生物质颗粒升温至目标温度所需时间较无铜渣工况缩短约 188 秒，且颗粒粒径比（dp,slag/dp,biomass）降低至 0.5 时升温速率提升显著；3）反应器转速对混合特性影响显著，混合指数随转速增加呈线性增长，而粒径比增大导致偏析效应增强，混合指数下降；4）数值模拟结果与实验数据对比显示最大相对偏差为 4.7%，验证了模型的可靠性。本工作建立的 CFD-DEM 多尺度模型成功揭示了回转式反应器中颗粒体系的传热机制与混合特性，为生物质热解气化反应器的优化设计提供了理论依据，对实现冶金余热高效回收与生物质能源化利用具有重要指导意义。

关键词

冶金熔渣；余热回收；生物质；热化学转换；回转窑；CFD-DEM 方法；颗粒运动和传热

Abstract

The metallurgical industry, characterized by high energy consumption, generates substantial waste heat resources requiring efficient utilization, particularly the critical challenge of recovering thermal energy from molten slag. This study addresses the limitations of conventional waste heat recovery technologies through the innovative integration of biomass thermochemical conversion with metallurgical slag heat recovery, developing a novel hybrid thermal energy recovery system. A three-dimensional rotary reactor model was established using coupled Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) simulations, with the dense discrete particle model (DDPM) employed to investigate multiphase flow dynamics and heat-mass transfer characteristics between copper slag and biomass particles. Key findings reveal: 1) Particulate bed behavior exhibits distinct rolling flow patterns, partitioned into active (wall-adherent particle motion) and passive (internal particle slippage) regions, fundamentally governing solid residence time distribution and reactor scalability. 2) Under optimized conditions (20 wt% slag addition, 4 rpm rotation), biomass particle heating duration to target temperature reduced by 188 seconds compared to slag-free operation, with particle size ratio (dp,slag/dp,biomass=0.5) demonstrating 23.7% thermal enhancement. 3) Rotational velocity linearly regulates mixing efficiency, while increased particle size disparity amplifies segregation effects, reducing mixing index. 4) Model validation shows maximum 4.7% deviation between simulated and experimental data. The developed multiscale CFD-DEM framework elucidates particle-scale heat transfer mechanisms and mixing behavior in rotary reactors, providing theoretical foundations for biomass gasification reactor optimization and advancing synergistic utilization of metallurgical waste heat with renewable biomass resources.

Keywords

Metallurgical slag; Waste heat recovery; Biomass; Thermochemical conversion; Rotary kiln; CFD-DEM method; Particle motion and heat transfer

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