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含水量对镁粉最小点火能量的影响：实验和理论模型

摘要

金属燃料作为可再生清洁能源载体，为化石燃料提供了成熟可行的可持续替代方案。然而近年来，潮湿作业工况下的金属粉尘爆炸事故时有发生。为探明潮湿环境中金属粉尘的潜在爆炸风险，本研究选取三种粒径的球形镁粉，制备了含水量 0%~10% 的含湿样品，利用哈特曼管开展了 500~1500 g/m³ 粉尘浓度下的最小点火能量（MIE）实验，同步测定了含湿镁粉的最小点火温度与 120 ms 点火延迟时刻的实时粉尘浓度；基于斯托克斯沉降理论构建了粉尘实时浓度预测模型，并以电火花点火热理论为基础，引入浓度偏离、颗粒团聚、能量损失三项修正，建立了含湿镁粉 MIE 的预测模型。结果表明：镁粉 MIE 随含水量升高呈单调上升趋势，0%~6% 低中含水量区间 MIE 增长相对平缓，8%~10% 高含水量区间出现跃升。含水量主要通过液膜和氧化层隔绝、湿团聚沉降、气化吸热、水蒸气稀释的多重协同机制抑制镁粉点火敏感性；所建立的 MIE 理论模型与实验数据契合度良好。本研究揭示了含水量对镁粉点火敏感性的多尺度影响机理，量化了粒径、浓度与含水量的耦合作用规律，可为工业含湿镁粉的燃爆风险评估与防控提供关键实验支撑和理论依据。

关键词

镁粉；含水量；最小点火能；粉尘爆炸

Abstract

As renewable and clean energy carriers, metal fuels offer a mature and feasible sustainable alternative to fossil fuels. However, metal dust explosion accidents under humid operating conditions have occurred frequently in recent years. To clarify the potential explosion risk of metal dust in humid environments, spherical Mg dust with three particle sizes was selected to prepare moisture-containing samples with moisture contents ranging from 0% to 10% in this study. Minimum ignition energy (MIE) tests were conducted in a Hartmann tube at dust concentrations of 500~1500 g/m³. Meanwhile, the minimum ignition temperature of the moisture-containing Mg dust and the real-time dust concentration at the ignition delay time of 120 ms were synchronously measured. A prediction model for real-time dust concentration was established based on Stokes' settling theory. Furthermore, on the basis of the thermal theory of spark ignition, a prediction model for the MIE of moisture-containing Mg dust was developed by introducing three correction terms, namely concentration deviation, particle agglomeration and energy loss. The results show that the MIE of Mg dust exhibits a monotonically increasing trend with the rise of moisture content. The increase of MIE is relatively gentle in the low and medium moisture content range of 0%~6%, while an abrupt jump occurs in the high moisture content range of 8%~10%. Moisture content inhibits the ignition sensitivity of Mg dust mainly through multiple synergistic mechanisms, including the isolation effect of liquid film and oxide layer, wet agglomeration and settling, gasification heat absorption, and water vapor dilution. The established MIE theoretical model is in good agreement with the experimental data. This study reveals the multi-scale influence mechanism of moisture content on the ignition sensitivity of Mg dust, and quantifies the coupling law of particle size, concentration and moisture content. It can provide critical experimental support and theoretical basis for the combustion and explosion risk assessment, prevention and control of industrial moisture-containing Mg dust.

Keywords

Mg dust; moisture content; minimum ignition energy; dust explosion

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