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涡场效应：隧道流淌火火焰行为及烟气扩散的实验和数值研究

摘要

研究涡旋结构有助于阐明隧道流淌火的火焰行为和烟雾扩散的内在演化机制。本研究采取数值模拟与实验分析相结合的方法，研究了流淌火从扩散和稳定阶段的火羽流行为和顶棚温度分布，特别强调了温度流场、速度流场和涡度场。研究结果表明，冷空气和热烟气的相互作用会产生不稳定的涡旋结构，从而影响火焰的形态。在扩散阶段，涡旋结构撕裂火焰，产生分叉行为。相反在稳定阶段，涡旋结构的减少促使火焰稳定并进行融合。从扩散到稳定阶段，火焰振荡频率逐渐减小并趋于恒定值，这主要是由于火焰根部流场的偏转以及热烟气与冷空气之间的热交换，建立了整个过程中火焰振荡频率的预测模型。顶棚温度变化受燃烧过程的影响，因此建立了整个燃烧过程的最大温升和纵向温度衰减模型。在扩散阶段，涡度的增加导致湍流程度增大，进而导致顶棚温度逐渐升高。相反，在稳定阶段，顶棚附近涡旋结构的消失导致顶棚温度没有出现明显变化。在高涡度区，顶棚温度上升明显，而在低涡度区，热烟气与冷空气混合趋于平衡，温度上升较为平缓。

关键词

流淌火，涡流场，火羽流行为，温度分布

Abstract

The study of vortex structures is instrumental in elucidating the flame behavior and smoke dispersion mechanisms during tunnel spill fires. This work combines numerical simulations with experimental analysis to investigate the flame plume behavior and ceiling temperature distribution throughout both the diffusion and stable stages of spill fires, with a particular emphasis on the temperature-flow field, velocity-flow field and vorticity field. The findings indicate that the interaction of cold air and hot smoke generates unstable vortex structures, which subsequently affect the flame morphology. During the diffusion stage, the vortex structures tear the flame, resulting in bifurcation behavior. In contrast, in the stable stage, the diminishing vortex structures allow the flame to stabilize and merge. From the diffusion to the stable stage, the flame oscillation frequency gradually decreases and approaches a constant value, primarily due to the deflection of the flow field at the flame root and the heat exchange between the hot smoke and cold air, a predictive model for the flame oscillation frequency throughout the entire process has been developed. Ceiling temperature variations are influenced by the combustion process, leading to the establishment of models for maximum temperature rise and longitudinal temperature attenuation over the entire process. During the diffusion stage, increased turbulence from vortex structures gradually elevates ceiling temperatures. Conversely, in the stable stage, the disappearance of vortex structures near the ceiling results in no significant changes in ceiling temperature. In the high vorticity zone, there is a pronounced rise in ceiling temperature, whereas in the low vorticity zones, the mixing of hot smoke and cold air tends to reach equilibrium, resulting in a gentler temperature increase.

Keywords

Spill fire, Vortex fields, Flame plume behavior, Temperature distribution

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