Numerical simulation of the attenuation of hydrogen explosion by spraying water

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Abstract

High-pressure blast waves are critical in many industrial and environmental processes involving hydrogen energy. Accidental shock waves from hydrogen explosions pose significant risks to structural integrity and human safety, making water spray systems a vital strategy for mitigating such hazards, particularly in nuclear reactor containment scenarios. This manuscript investigates shock-spray interactions to mitigate hydrogen explosions through advanced multiphase modeling. The study examines the coupled effects of momentum, heat, and mass transfer during shock-wave interactions with water sprays, a proven strategy for explosion attenuation. Initial numerical simulations in one- and two - dimensional configurations focus on momentum transfer, analyzing drag forces on polydisperse particles in air and hydrogen-air mixtures. A reduced-order theoretical model is developed to study dispersion topology, validated against direct numerical simulations. Results show that polydisperse particle clouds significantly enhance shock attenuation compared to monodisperse ones, with smaller diameters and higher standard deviation exhibiting stronger effects. Greater particle volume fractions further amplify attenuation. A critical incident Mach number (Ms < 2.8) is identified, where the transmitted shock transitions from supersonic to subsonic states. Expanding upon the initial investigation of momentum transfer during shock-droplet interactions, the subsequent phase of the study introduces heat transfer and evaporation mechanisms to comprehensively analyze multiphase shock wave attenuation. The results reveal that incorporating heat transfer and evaporation significantly enhances shock attenuation, with smaller droplets in highly polydisperse and dense configurations promoting faster evaporation due to their larger cumulative surface area, leading to efficient energy dissipation and improved mitigation. The analysis reveals a linear relationship between the saturated transmitted shock Mach number, ((M{st}){sat}), and the incident Mach number, (Ms). An empirical correlation was developed to predict ((M{st}){sat}\) as a function of incident Mach number (Ms) and droplet diameter. This work provides a detailed understanding of multiphase interactions in droplet-laden environments and highlights the potential of water sprays as a robust mitigation strategy for hydrogen explosion risks in industrial and nuclear safety contexts.