Abstract

Overexposure to the surface mining-generated PM has been linked to several irreversible respiratory diseases among mine workers as well as adjoining communities. Therefore, real-time quantification of PM and understanding its dispersion is of paramount interest. Current regulatory-approved PM monitoring devices used in the mining industry are heavy, bulky, and expensive, and mostly employed for the purpose of regulatory compliance or personal monitoring. These standard instruments are usually fixed or ground-based and are incapable of spatially reaching different working locations for simultaneous measurement of PM concentrations along the vertical extent of the surface mine. Consequently, vertical profile measurements that provide information about the accumulation, dispersion, and vertical transport of emitted PM inside a surface mine atmosphere remain unevaluated or poorly evaluated, leading to incorrect exposure estimates of mine workers and mining-impacted communities. Recent advancements in low-cost sensors have enabled affordable, portable, and scalable solutions for dense spatial and temporal monitoring, particularly in environments where deploying multiple standard instruments is impractical due to cost or logistical constraints. Integrating a low-cost PM sensor with an unmanned aerial vehicle (UAV), this study introduces an advanced approach for real-time quantification of the different-sized airborne PM mass concentrations (PM_1, $PM_{2.5}$, and PM_{10}) in vertical and horizontal directions in and around the surface mine. Further, for providing an extended understanding of the fate and behavior of mining-generated PM, interactions with key meteorological and operational factors of a highly mechanized large-scale surface mine are investigated.

To identify the suitability of several commercially available low-cost PM sensors for real-time and continuous monitoring in surface mines, the sensor performance was evaluated by conducting a calibration experiment following the testing protocol and metrics recommended by the US EPA. Out of the three sensors (OPC N3, SPS 30, and NOVA SDS011), OPC N3 and SPS 30 sensors demonstrated high linearity ($R^2 \geq 90$), precision ($CV < 6\%$), and error values ($NRMSE < 30\%$) against the research-grade reference instrument in most of the tested conditions for all the PM sizes. Considering the uncontrolled calibration conditions in the mining environment, OPC N3 was found to be the most suitable sensor for real-time monitoring of a wide range of PM concentrations in surface mines. Therefore, the OPC N3 sensor, along with a portable

weather station, was integrated to a customized UAV to obtain vertical and horizontal profiles of PM mass concentrations and meteorological parameters.

Firstly, 30 UAV vertical flights were conducted from the pit bottom (100 mRL) to the pit top (228 mRL), and 10 UAV flights in a horizontal direction in a surface coal mine. Results for the vertical flights indicate that mean PM_1, $PM_{2.5}$, and PM_{10} mass concentrations at higher altitudes (65, 120, 180 μg m^{-3}) are less compared to the corresponding pit bottom PM levels (69, 165, 300 μg m^{-3}). For all three particle sizes, the majority of the cases of higher PM concentration at higher altitudes happened during the evening as compared to the morning and afternoon flights. Poor vertical movement of pollutants due to low mixing height and emissions from continuous mining operations in the evening is suggested to be the reason for this. Overall, a vertical fall of 8 - 40% fall was observed in PM mass levels along the ~130 m deep surface coal mine. Physical characterization of airborne PM revealed the presence of fly ash particles originating from surface fires of rejected coal, alongside mineral particles from mechanical excavation activities. No clear pattern of variation in PM concentration was observed for the horizontal profiles away from the pit top up to a 150 m distance.

A second field-based measurement study was carried out in a 130 m deep surface chromite mine by conducting 23 UAV flights close to the active mining operations (loading and hauling) across the spatial extent of the mine. Irrespective of the depth of the working locations, UAV flights were conducted up to 130 m above the source. It was found that mean in-pit PM (PM_1, $PM_{2.5}$, PM_{10}) concentrations in the surface chromite mine (54, 67, 128 μg m^{-3}) are significantly higher than the corresponding out-pit concentrations (48, 57, 83 μg m^{-3}) due to direct contribution from the active in-pit mining operations. Based on ground and UAV measurements, PM concentrations near hauling activities are approximately 1.6 to 2.8 times the PM emitted from loading operations. Vertical PM profiles above the pit top revealed significantly higher concentrations in the downwind profiles, with surface mining operations contributing 17-25% of PM to the surrounding ambient atmosphere. PM concentrations generally decreased with increasing distance from the pit center in both vertical and horizontal directions, with a sharp decline at the mine boundary.

Comparison of vertical PM profiles between coal and chromite mines has shown higher PM concentration along the vertical extent of the surface coal mine due to the increased material handled or the production intensity. Percentage of fall in PM concentration with respect to the pit bottom is higher in the case of the chromite mine (50-22%) than in the coal mine (40-11%), as the dust generated in coal mines is often finer and has the potential to remain suspended compared to harder chromite ore. The results of this research highlight the significance of spatiotemporal variability in PM and the role of diurnal variations, key production activities, and vertical depth on PM dispersion within surface mines. The integration of UAV-mounted low-cost sensors not only advances the methodology for real-time PM monitoring in complex mining environments but also provides essential insights for refining exposure assessment and developing effective dust mitigation strategies in surface mining operations.

Keywords: Low-cost air sensors; Unmanned aerial vehicle; Particulate matter exposure; Vertical measurements; Horizontal measurements; occupational mining environment.