CFD Modeling Of Ventilation In Large Underground Mines - Impact Of Booster Fan Placement

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Abstract

Large underground mines (LUMs), which constitute over 60% of metal and nonmetal mining operations in the United States, are critical to national infrastructure and materials supply (Bhattacharyya et al., 2023; Gendrue et al., 2021). These mines are characterized by vast entries exceeding 100 m2, with relatively shallow depths and minimal flow resistance. Ventilation in LUMs is not only essential for supplying oxygen and removing heat, dust, and diesel particulate matter (DPM), but also incurs significant operational costs - often accounting for up to 30-40% of total mine operating expenses (Carter, 2018). Historically, the ventilation techniques used in large-opening stone mines have often been the result of trial-and-error methodology or based on experience. This study utilizes high-fidelity Multiphysics simulation to evaluate the impact of booster fans on airflow distribution in a complex LUM, focusing on air exchange and residence time in operationally significant zones.

A detailed 3D model of the Thomasville limestone mine (Figure 1) was developed in CAD software, consisted over 500 interconnected entries spanning around 730 m × 880 m. This geometry was then imported into COMSOL Multiphysics®, where the simulation framework was built. The Turbulent Flow, Heat Transfer in Moist Air, and Moisture Transport in Air interfaces were coupled in COMSOL Multiphysics®. A weakly compressible formulation was adopted to account for variable density due to temperature and humidity gradients, particularly in zones adjacent to inlets, fans, and localized heat sources. Gravity was included, and the realizable k-ε turbulence model was used to resolve recirculation zones. Mesh refinement was selectively applied near the booster fan outlet and at fan boundaries. Fan boundary conditions were imposed at the outlet (main exhaust) and interior booster fan (only active in Case 2), while open boundary conditions were utilized for a boundary which was open to the atmosphere. The turbulent model was solved using a stationary, segregated solver with algebraic multigrid (AMG) and a relative tolerance of 0.001.

Two scenarios were compared: Case 1 (No Booster Fan) and Case 2 (With Booster Fan). Velocity distribution results (Figure 2) show enhanced airflow penetration in the southern domain with booster assistance. Four analysis zones (Figure 3) were selected based on projected future mining regions. Zone 1, located upstream near the booster, showed a dramatic increase in flow rate from 0.28 m3/s (Case 1) to 32.18 m3/s (Case 2), resulting in a Volumetric Air Exchange Index (VAEI) improvement from 0.019/h to 2.32/h and a reduction in air residence time from 50.1 to 0.43 hours (Figure 4). VAEI quantifies how frequently fresh air replaces the air in a zone, while residence time reflects how long air lingers—together they indicate the effectiveness of ventilation in maintaining safe working conditions. By contrast, changes in Zones 2 - 4 were more moderate or negligible, indicating localized control effectiveness of booster fans. This work utilizing COMSOL Multiphysics software contributes to improving ventilation design strategies in deep and expansive underground mines, where empirical methods alone are insufficient for predicting airflow behavior under variable thermal and humidity conditions.

Reference

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R.A. Carter, Focusing the Flow: Engineering, Geology, Mineralogy, Metallurgy, Chemistry, etc. Engineering and Mining Journal, 219(6), 50–55 (2018)

N. Gendrue et al (2021), Field survey of mine ventilation system for large opening underground mines: Pressure, relative humidity, and temperature, Mine Ventilation, 489–497 (2021)

Figures used in the abstract

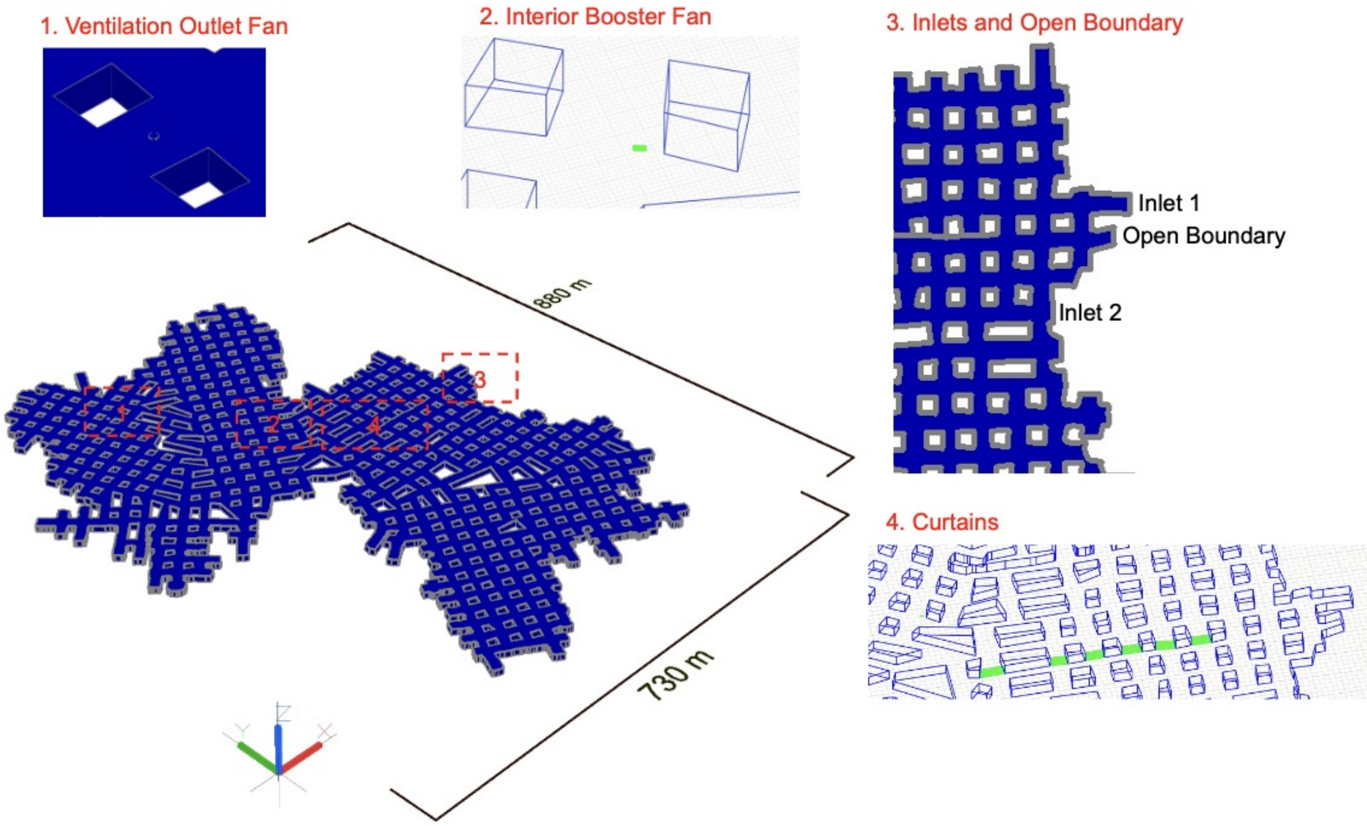

Figure 1 : Detailed 3D model of Thomasville Large opening underground Limestone mine. Key modeling components are two inlets (1 and 2) an open boundary, interior curtains, an outlet fan and a booster fan in the Case 2 where impact of booster fan on overall ventilati

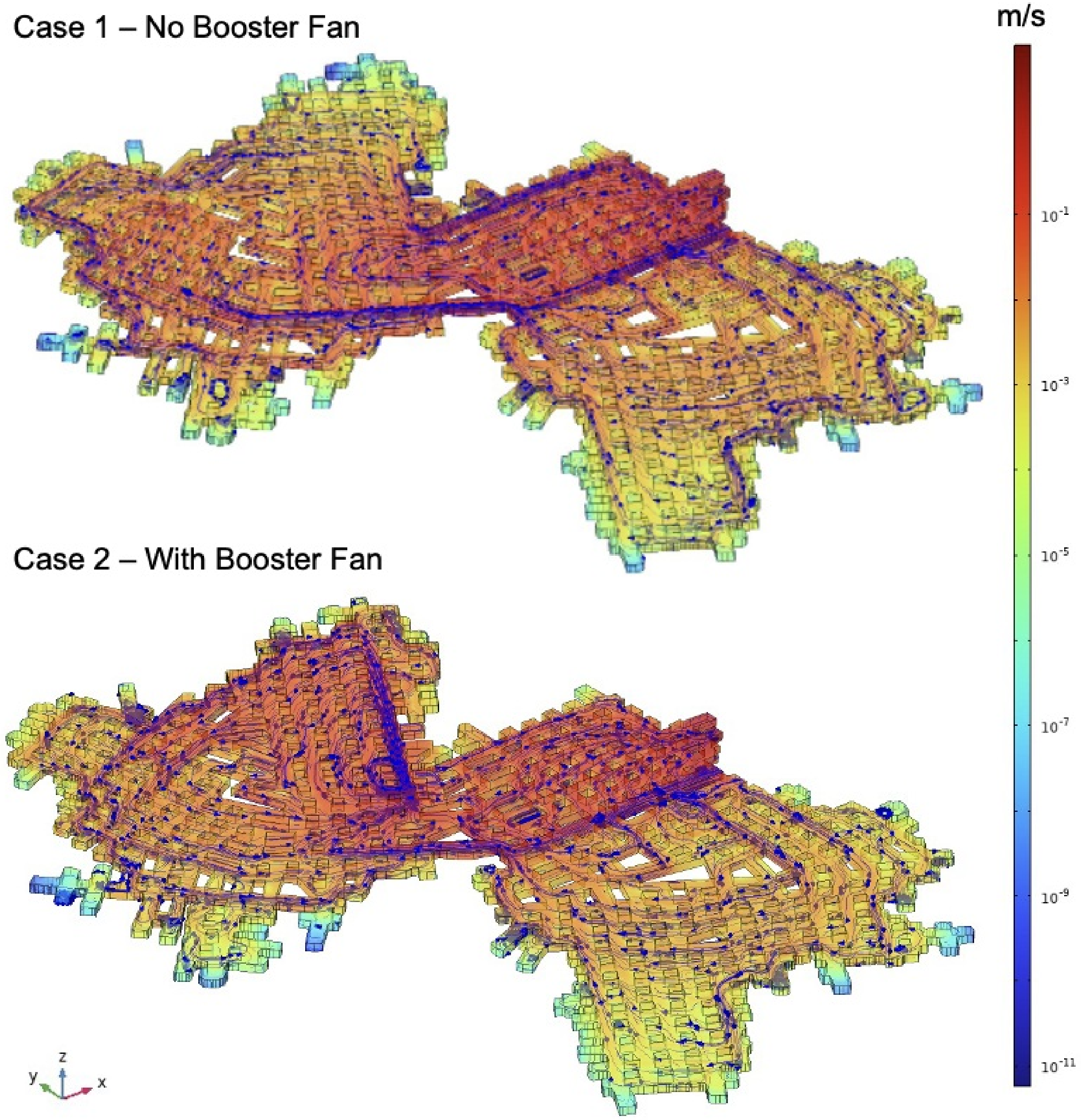

Figure 2 : Ventilation air velocity distribution (m/s) in the mine for Case 1 (No Booster Fan) and Case 2 (With booster fan).

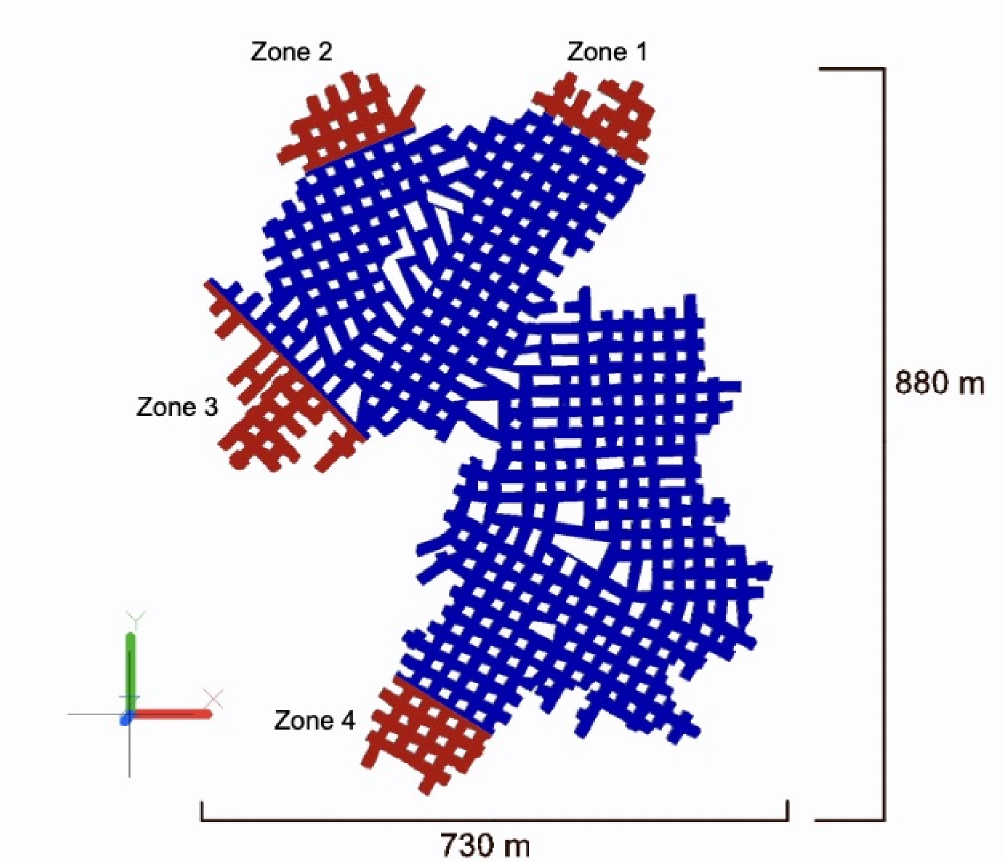

Figure 3 : Plan view of the mine layout showing four designated analysis zones for localized airflow evaluation and performance comparison across ventilation scenarios

	Zone	Flow Rate (m^3/s)	Volume of Zone (m^3)	VAEI (1/hours)	Air Residence Time (Hours)
Case 1 - No Booster Fan	1	0.27729	50008.7132	0.0199614	50.09668298
	2	11.486	65596.11615	0.63036659	1.586378493
	3	33.463	89791.48395	1.34162834	0.745362905
	4	1.1109	67351.70145	0.05937846	16.84112518
Case 2 - Booster Fan	1	32.181	50008.7132	2.31662829	0.431661826
	2	10.285	65596.11615	0.56445415	1.77162308
	3	19.185	89791.48395	0.76918208	1.300082297
	4	1.039	67351.70145	0.05553535	18.00655049

Figure 4 : Comparison of ventilation metrics across four mine zones for Case 1 and 2