ULOGA VENTILACIJE U OČUVANJU ZDRAVLJA I SIGURNOSTI RADNIKA U TOKU TUNELOGRADNJE

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Naučni rad

Ekrem Bektašević, Kemal Gutić, Satko Filipović[1]

Sažetak:

Ventilacija u tunelogradnji predstavlja ključni sistem za očuvanje zdravlja i sigurnosti radnika u podzemnim prostorima. Ovaj rad analizira empirijske epidemiološke studije, numeričke CFD simulacije i normativne zahtjeve kako bi se procijenila efikasnost ventilacijskih režima. Rezultati pokazuju da kumulativna izloženost prašini dovodi do prosječnog godišnjeg pada FEV1 od 40 ml kod radnika, u poređenju sa 20 ml u kontrolnim grupama, dok koncentracije CO nakon miniranja često prelaze dopuštene granice. CFD modeli potvrđuju da brzina strujanja od 3 m/s osigurava optimalnu disperziju prašine, ali uz povećanu potrošnju energije, koja može činiti i do 50 % ukupne električne potrošnje gradilišta. Analiza mikroklimatskih faktora ukazuje da povišene temperature i visoka vlažnost dodatno povećavaju fiziološko opterećenje radnika, dok inovativne tehnologije za monitoring omogućavaju pravovremenu kontrolu rizika. Normativni okvir, zasnovan na međunarodnim smjernicama (ITA/AITES, OSHA) i nacionalnim propisima, postavlja minimalne standarde, ali njihova efektivna primjena zahtijeva kontinuiran monitoring i prilagodbu lokalnim geotehničkim uvjetima. Glavni doprinos rada je u integraciji empirijskih podataka i CFD simulacija, čime se osigurava pouzdanija procjena ventilacijskih režima i formuliranje praktičnih preporuka za projektante i izvođače.

Ključne riječi: *tunelogradnja, ventilacija, kvaliteta zraka, zaštita na radu, respiratorni rizici, prašina, ugljični monoksid, azotovi oksidi*

[1] *Faculty of Mining, Geology and Civil Engineering, University of Tuzla, Urfeta Vejzagića No. 2, 75000 Tuzla, Bosnia and Herzegovina; ekrem.bektasevic@untz.ba; kemal.gutic@untz.ba;*[2]*Road Direction of Sarajevo Canton, Ministry of Transport of Sarajevo Canton, Reisa Džemaludina Čauševića 1, Sarajevo 71000, Bosnia & Herzegovina;*

* Correspondence: satko.filipovic.dkps@gmail.com

1. Uvod

Tunelogradnja predstavlja specifičnu granu građevinske industrije u kojoj se radni procesi odvijaju u ograničenim i zatvorenim podzemnim prostorima [1-3], pri čemu su radnici izloženi kombinaciji fizičkih, hemijskih i mikroklimatskih faktora koji mogu nepovoljno uticati na njihovo zdravlje i sigurnost. Glavni izvori zagađenja u takvim uslovima su prašina nastala bušenjem i miniranjem stijenske mase, emisije iz dizelske mehanizacije te prisustvo štetnih plinova, poput azotnih oksida (NO_x) i ugljičnog monoksida (CO), koji nastaju kao nusprodukti rada mehanizacije i primjene eksplozivnih sredstava [4-6].
Brojna istraživanja provedena među radnicima zaposlenim u tunelima ukazuju na izraženije narušavanje respiratornog zdravlja u odnosu na radnike koji nisu izloženi radu u zatvorenim podzemnim prostorima. Dugotrajna profesionalna izloženost prašini i štetnim plinovima povezuje se s češćom pojavom respiratornih tegoba, kao i sa postepenim smanjenjem plućne funkcije, posebno vrijednosti *forced expiratory volume in 1 second* (FEV_1). Longitudinalne studije koje su pratile radnike tokom perioda dužeg od šest godina pokazale su da kumulativna izloženost ima statistički značajan uticaj na pad FEV_1, nezavisno od starosne dobi i pušačkih navika, što potvrđuje direktnu povezanost radnih uslova u tunelogradnji i respiratornih zdravstvenih rizika [5,7,8]. Slični rezultati potvrđeni su i u drugim studijama, koje ukazuju na veću prevalenciju hroničnih respiratornih simptoma i izraženije smanjenje plućne funkcije kod radnika zaposlenih u tunelima u odnosu na kontrolne grupe [4,9].
Kvalitet zraka u radnom prostoru predstavlja ključnu determinantu navedenih zdravstvenih rizika, a zavisi od složenih interakcija između izvora zagađenja, geometrije tunela, intenziteta građevinskih aktivnosti i, presudno, efikasnosti ventilacijskog sistema [10]. Osnovna funkcija ventilacije u tunelima jeste osiguravanje dotoka svježeg zraka na radna mjesta, razrjeđivanje i uklanjanje štetnih plinova i lebdećih čestica te sprječavanje formiranja lokalnih zona s povišenim koncentracijama zagađivača.
U tom smislu, ventilacija se ne može posmatrati isključivo kao tehnički podsistem gradilišta, već kao centralni instrument upravljanja rizicima na radu [11]. Neadekvatno dimenzionirani ili loše optimizirani ventilacijski režimi mogu dovesti do formiranja stabilnih zona sa slabim strujanjem zraka, u kojima se zagađivači zadržavaju tokom dužeg vremenskog perioda, čime se značajno povećava kumulativna izloženost radnika [12].
Savremena tehnička literatura sve češće koristi numeričke simulacije u cilju analize ponašanja ventilacijskih sistema i disperzije zagađivača u tunelima. Rezultati takvih istraživanja pokazuju da raspored ventilacijskih kanala, brzina i smjer strujanja zraka, kao i stepen turbulencije, imaju odlučujući uticaj na prostornu raspodjelu prašine i plinova. U nepovoljnim konfiguracijama moguće je formiranje zona u kojima koncentracije štetnih tvari višestruko premašuju

preporučene granične vrijednosti, čak i u uslovima kada ukupni protok zraka nominalno zadovoljava projektne zahtjeve [13,14].
Pored kontrole zagađenja, ventilacijski sistemi imaju značajnu ulogu u regulaciji mikroklimatskih uslova unutar tunela, uključujući temperaturu i relativnu vlažnost zraka. Povišene temperature i visoka vlažnost, u kombinaciji sa zagađenim zrakom, dodatno povećavaju fiziološko opterećenje radnika, smanjuju radnu efikasnost i povećavaju rizik od termalnog stresa i toplotnih poremećaja [15]. Ovi problemi su posebno izraženi u dubokim tunelima s izraženim geotermalnim uticajima i dugim ventilacijskim sistemima.
Uprkos kontinuiranom razvoju tehnologije i opreme, istraživanja iz različitih zemalja potvrđuju da radnici u tunelogradnji i dalje pokazuju značajne negativne zdravstvene ishode povezane s profesionalnom izloženošću. To se prvenstveno odnosi na povećanu učestalost hroničnih respiratornih simptoma, smanjenje plućne funkcije te veću pojavnost hronične opstruktivne plućne bolesti (HOPB) u poređenju s radnicima u manje zagađenim radnim okruženjima [16-18].
Polazeći od navedenog, istraživački problem ovog rada usmjeren je na analizu uloge ventilacije u smanjenju kumulativne izloženosti radnika štetnim česticama i plinovima u tunelogradnji. Cilj rada je sintetizirati dostupna naučna saznanja, empirijske podatke i rezultate numeričkih simulacija radi razvoja integrirane metodologije za procjenu efikasnosti ventilacijskih sistema. Originalnost istraživanja ogleda se u interdisciplinarnom pristupu koji povezuje geotehniku, inženjerski dizajn ventilacije, medicinu rada i sigurnosni menadžment [19-21], te u pozicioniranju rezultata u okviru međunarodnih smjernica i standarda (WHO, OSHA), s ciljem formuliranja praktičnih preporuka za projektante, izvođače i nadzorne organe.

2. Pregled literature i teorijski okvir

Ventilacija u tunelogradnji predstavlja ključni inženjerski i sigurnosni sustav čija je osnovna funkcija osiguravanje prihvatljive kvalitete zraka u zatvorenim podzemnim prostorima. Njena uloga obuhvata razrjeđivanje i uklanjanje štetnih plinova i prašine, sprječavanje formiranja stagnacijskih zona te regulaciju mikroklimatskih uvjeta. Time ventilacija postaje ne samo tehnički podsistem, već i centralni instrument zaštite zdravlja radnika i upravljanja rizicima na gradilištu.

2.1. Empirijski nalazi o zdravlju radnika

Epidemiološke i longitudinalne studije dosljedno potvrđuju da radnici u tunelima imaju povećan rizik od respiratornih simptoma i smanjenja plućne funkcije u odnosu na kontrolne grupe. Dugotrajna kumulativna izloženost prašini i plinovima povezana je sa statistički značajnim padom FEV1, dok su kratkoročne studije pokazale izražene promjene plućne funkcije već tokom nekoliko mjeseci rada. Empirijska mjerenja koncentracija plinova u realnim tunelima dodatno potvrđuju da ugljični monoksid (CO) često prelazi maksimalno dopuštene koncentracije, osobito nakon miniranja, što predstavlja dominantan rizik za radnike. Radi preglednosti, dosadašnja empirijska istraživanja o respiratornim rizicima u tunelima sistematizirana su u tabeli 1.

Tabela 1. Empirijski nalazi o zdravlju radnika u tunelogradnji

Autor / godina	Fokus istraživanja	Glavni nalazi	Ograničenja	Primjenjivost u praksi
Bakke et al. (2001) [4]	Prašina i plinovi u tunelima	Radnici izloženi prašini i plinovima imaju veći rizik od respiratornih simptoma.	Ograničeno na specifične lokacije.	Epidemiološki dokaz povezanosti izloženosti i zdravlja.
Bakke et al. (2004) [5]	Kumulativna izloženost	Dugotrajna izloženost povezana s padom FEV1, neovisno o dobi i pušenju.	Fokus na jednu regiju.	Potvrđuje dugoročne zdravstvene rizike.
Ulvestad et al. (2015) [9]	Kratkoročna plućna funkcija	Zabilježeni kratkoročni padovi FEV1 kod tunelskih radnika.	Ograničeno na specifične radne uvjete.	Relevantno za monitoring u realnom vremenu.
Klanfar et al. (2015) [22]	Empirijska mjerenja CO i NOx	CO najčešće prelazi MDK u svim fazama gradnje, posebno nakon miniranja.	Fokus na jedan tunel (Mala Kapela).	Naglašava potrebu za kontinuiranim monitoringom.

2.2. CFD simulacije i numerički modeli

Numeričke metode, posebno računalna dinamika fluida (CFD), postale su ključni alat u analizi ventilacijskih sustava u tunelogradnji. One omogućavaju simulaciju distribucije prašine i plinova pod različitim konfiguracijama ventilacijskih parametara, identifikaciju kritičnih zona i optimizaciju rasporeda kanala. Istraživanja pokazuju da CFD simulacije mogu značajno doprinijeti preciznijem projektiranju ventilacijskih sustava, ali se često suočavaju s ograničenjem nedostatka validacije u realnim uvjetima gradnje. Radi preglednosti, dosadašnja istraživanja zasnovana na CFD simulacijama i numeričkim metodama sistematizirana su u tabeli 2.

Tabela 2. CFD simulacije i numerički modeli u tunelogradnji

Autor / godina	Fokus istraživanja	Glavni nalazi	Ograničenja	Primjenjivost u praksi
Yang et al. (2022) [23]	CFD simulacije distribucije prašine	Optimizacija rasporeda kanala smanjuje koncentraciju PM2.5 i CO za 20–30%.	Model zasnovan na simulacijama, bez terenskih podataka.	Pokazuje potencijal CFD-a u projektiranju ventilacije.
Jiang et al. (2021) [24]	CFD kontrola prašine pri bušenju	Numerička simulacija omogućava preciznu kontrolu širenja prašine i identifikaciju kritičnih zona.	Fokusirana na specifične scenarije bušenja.	Primjenjivo u planiranju ventilacije pri bušenju.
Zhang et al. (2024) [14]	Kombinacija mjerenja i CFD	Identifikacija kritičnih zona i optimizacija sustava kroz integraciju empirije i modeliranja.	Zahtijeva validaciju u različitim tunelima.	Integracija empirijskih podataka i simulacija.
Nie et al. (2023) [13]	CFD analiza transporta prašine	Analiza zakona transporta prašine i starosti zraka pod različitim metodama ventilacije.	Ograničeno na modelne uvjete.	Relevantno za optimizaciju metoda ventilacije.
Colella et al. (2009) [25]	Multi-scale CFD model	Vizualizacija strujanja zraka u tunelu, identifikacija near-field i far-field zona.	Stariji model, ograničen na specifične uvjete.	Osnova za kasniji razvoj multi-scale modela.

2.3. Energetska optimizacija i izvedbeni problemi

Pored zdravstvenih i sigurnosnih aspekata, ventilacija u tunelogradnji ima i značajnu tehničku i ekonomsku dimenziju. Energetska potrošnja ventilacijskih sustava predstavlja jedan od najvećih operativnih troškova u podzemnoj gradnji.

Zbog toga se u literaturi sve više naglašava potreba za dinamičkom kontrolom protoka zraka, kako bi se istovremeno smanjili profesionalni rizici i optimizirala potrošnja energije. Međutim, brojna istraživanja ukazuju da stvarna izvedba ventilacijskih kanala često ne postiže projektirane performanse, zbog problema poput zrakonepropusnosti i povećanog otpora zraka. Ovi faktori mogu rezultirati smanjenim protokom i akumulacijom zagađivača u radnom prostoru, čime se direktno ugrožava sigurnost radnika. U nastavku su prikazani odabrani radovi koji se bave energetskom optimizacijom i izvedbenim problemima ventilacijskih sustava u tunelogradnji.

Tabela 3.Energetska optimizacija i izvedbeni problemi ventilacijskih sustava

Autor / godina	Fokus istraživanja	Glavni nalazi	Ograničenja	Primjenjivost u praksi
Si, Cao & Chen (2020) [26]	Dinamička kontrola protoka zraka	Optimizacija protoka smanjuje profesionalne rizike i potrošnju energije.	Primjena ograničena na longitudinalne sustave ventilacije.	Relevantno za održive projekte i smanjenje troškova.
Chang et al. (2024) [27]	Zrakonepropusnost i otpor zraka	Neadekvatna izvedba kanala dovodi do curenja zraka i povećanog otpora.	Numerička simulacija, bez validacije u realnim uvjetima.	Naglašava razliku između projektnih parametara i izvedbenih performansi.

2.4. Mikroklimatski faktori

Ventilacija u tunelogradnji ne utječe samo na koncentraciju prašine i plinova, već i na mikroklimatske uvjete unutar podzemnog prostora. Povišene temperature, visoka relativna vlažnost i ograničen protok zraka dodatno povećavaju fiziološko opterećenje radnika, smanjuju radnu efikasnost i povećavaju rizik od termalnog stresa. Ovi problemi su posebno izraženi u dubokim tunelima s izraženim geotermalnim utjecajem, gdje ventilacija mora istovremeno osigurati razrjeđivanje zagađivača i regulaciju toplinskih uvjeta. Pored topline i vlage, prašina i plinovi se također smatraju mikroklimatskim faktorima jer direktno utiču na kvalitet zraka i zdravstvene ishode radnika. Savremena istraživanja dodatno naglašavaju važnost kontinuiranog monitoringa mikroklime i primjene inovativnih tehnologija koje omogućavaju pravovremeno praćenje parametara i smanjenje rizika od toplotnog stresa i respiratornih oboljenja. Radi sistematizacije, u nastavku se izdvajaju relevantni radovi koji analiziraju mikroklimatske faktore u tunelogradnji, s naglaskom na njihove ključne nalaze i praktičnu primjenjivost.

Tabela 4.Mikroklimatski faktori u tunelogradnji

Autor / godina	**Fokus istraživanja**	**Glavni nalazi**	**Ograničenja**	**Primjenjivost u praksi**
Nath, Sahu & Lee (2026) [15]	Globalna izloženost toplini	Kombinacija topline, vlage i zagađenja povećava rizik od termalnog stresa i smanjenja produktivnosti.	Pregledni rad, globalni fokus, bez specifičnih tunelskih podataka.	Relevantno za duboke tunele s geotermalnim utjecajem.
Sharma (2020) [12]	Ventilacija i mikroklima u tunelima	Ventilacija doprinosi regulaciji temperature i vlažnosti, čime se smanjuje fiziološko opterećenje radnika.	Ograničeno na tehnički opis, bez epidemioloških podataka.	Primjenjivo u projektiranju ventilacijskih režima.
Wei, Jiang & Di (2024) [28]	Generacija i distribucija prašine	Visoke koncentracije prašine u zonama slabog strujanja uzrokuju respiratorne rizike, uključujući pneumokoniozu.	Fokus na prašinu, bez analize temperature i vlage.	Primjenjivo za procjenu zdravstvenih rizika i mjere zaštite.
Wang et al. (2024) [29]	Predikcija temperaturnog polja	Geotermalni utjecaj stijenske mase značajno povećava temperaturu u dubokim tunelima.	Fokus na termalne uvjete, bez analize prašine.	Primjenjivo za duboke tunele s visokim geotermalnim utjecajem.

Sorlini et al. (2023) [30]	Inovativne tehnologije za monitoring	Tehnologije za praćenje mikroklime smanjuju rizik od toplotnog stresa i zagađenja.	Fokus na tehnologije, manje na empirijske podatke.	Primjenjivo za modernizaciju tunelskih projekata.
Rojas-Alva et al. (2016) [31]	TBM tunelska gradnja – mikroklima	Poljski testovi pokazali varijacije temperature, vlažnosti i brzine zraka tokom TBM rada; predložene kontrolne vrijednosti.	Stariji rad, fokus na TBM, bez šire primjene.	Relevantno za mehanizovane projekte tunela.
Chang et al. (2025) [32]	Ventilacija i difuzija zagađivača	Distribucija prašine i plinova zavisi od protoka zraka i geometrije tunela.	Fokus na zagađivače, manje na termalne uvjete.	Primjenjivo za projektiranje ventilacijskih režima.

2.5. Normativni i međunarodni okvir

Pored empirijskih nalaza i numeričkih modela, značajnu ulogu u oblikovanju ventilacijskih sustava imaju međunarodne smjernice i nacionalna regulativa. One postavljaju minimalne standarde za kvalitet zraka, sigurnost radnika i tehničke zahtjeve ventilacijskih instalacija. Smjernice međunarodnih organizacija poput ITA/AITES osiguravaju globalnu standardizaciju, dok OSHA regulativa definira obavezne parametre u američkoj praksi. U Bosni i Hercegovini, „Smjernice za projektovanje, građenje, održavanje i nadzor na putevima – Knjiga II: Građenje, Dio 3: Posebni tehnički uslovi za tunele“ (2005) propisuju konkretne vrijednosti za minimalnu količinu zraka i brzinu strujanja u tunelima, čime se osigurava usklađenost projektnih rješenja s lokalnim normativnim zahtjevima. Tabela 5 daje sažet prikaz ključnih smjernica i standarda koji definiraju tehničke zahtjeve ventilacije u tunelima, ističući njihovu primjenjivost i ograničenja.

Tabela 5.Normativni i međunarodni okvir ventilacije u tunelogradnji

Izvor	**Fokus**	**Glavni nalazi / zahtjevi**	**Ograničenja**	**Primjenjivost u praksi**

ITA/AITES (2011) [33]	Međunarodne smjernice	Sigurna upotreba privremenih ventilacijskih sistema u tunelima; preporuke za projektiranje i održavanje.	Opće smjernice, bez lokalnih specifičnosti.	Standardizacija u globalnoj praksi; referentni okvir za projektante.
OSHA (2003) [34]	Regulativa	Minimalni standardi za kvalitet zraka, sigurnost radnika i ventilacijske parametre u tunelima.	Fokus na američku praksu; zahtijeva prilagodbu lokalnim uvjetima.	Normativni okvir za sigurnost i zaštitu zdravlja radnika.
Smjernice, Knjiga II, Dio 3: Posebni tehnički uslovi za tunele (2005) [35]	Nacionalni tehnički standard	Propisuju minimalnu količinu zraka i brzinu strujanja u tunelima, ovisno o vrsti radova.	Primjenjivo samo u lokalnom/regionalnom kontekstu.	Obavezni normativni dokument u projektiranju i izvođenju tunela.

3. Analiza i diskusija dosadašnjih istraživanja

Pregled literature pokazuje da se istraživanja ventilacije u tunelogradnji mogu podijeliti u nekoliko komplementarnih kategorija: empirijski nalazi, numerički modeli, energetska optimizacija, mikroklimatski faktori i normativni okvir. Svaka od ovih kategorija daje specifičan doprinos razumijevanju problema, ali tek njihova integracija omogućava cjelovitu sliku. Empirijske studije (Bakke et al., Ulvestad et al., Klanfar et al.) jasno potvrđuju povećan rizik od respiratornih oboljenja kod radnika, dok CFD simulacije (Yang, Jiang, Zhang, Nie, Colella) nude mogućnost predviđanja distribucije zagađivača i optimizacije ventilacijskih sistema. Međutim, nedostatak validacije simulacija u realnim uvjetima ostaje ključni izazov. Energetska istraživanja (Si, Cao & Chen; Chang) ukazuju na potrebu balansiranja između sigurnosti i ekonomičnosti, dok mikroklimatski radovi (Nath, Sharma, Wei, Wang, Sorlini, Rojas-Alva, Chang) dodatno pokazuju da kombinacija topline, vlage, prašine i plinova povećava rizik od termalnog stresa i respiratornih oboljenja, pri čemu su predložene kontrolne vrijednosti i monitoring tehnologije ključne za smanjenje opterećenja radnika. Normativni dokumenti (ITA/AITES, OSHA, Smjernice Knjiga II, Dio 3) osiguravaju minimalne standarde, ali se u praksi često javljaju razlike između projektnih zahtjeva i izvedbenih mogućnosti.

3.1 Diskusija empirijskih nalaza

Empirijska istraživanja provedena među tunelskim radnicima dosljedno potvrđuju povećan rizik od respiratornih oboljenja, što se kvantitativno očituje kroz pad plućne funkcije i učestalost respiratornih simptoma. Longitudinalna studija pokazala je da se vrijednost FEV1 kod radnika s visokom kumulativnom izloženošću prašini smanjuje znatno brže u odnosu na kontrolne grupe, pri čemu je zabilježen prosječan godišnji pad od oko 40 ml naspram 20 ml kod radnika koji nisu bili izloženi [4]. Ovi rezultati potvrđuju da je radno okruženje ključan faktor u ubrzanom smanjenju plućne funkcije. Dodatna istraživanja pokazala su da se smanjenje FEV1 javlja neovisno o dobi i pušenju, što naglašava direktan utjecaj izloženosti prašini i plinovima [5]. Slične rezultate o utjecaju bušenja i sidrenja na sigurnost radnika donosi i Filipović et al. [36], gdje se pokazuje da tehnološki postupci direktno utiču na stabilnost i sigurnost radnog prostora.

Analize prevalencije respiratornih simptoma također ukazuju na značajne razlike između tunelskih radnika i kontrolnih grupa. Utvrđeno je da kronični kašalj pogađa više od trećine radnika, dok je u kontrolnim populacijama taj udio gotovo dvostruko manji [9]. Ovi podaci jasno ukazuju na povezanost između intenziteta izloženosti i učestalosti respiratornih tegoba. Dodatno, mjerenja provedena u hrvatskim tunelima pokazala su da koncentracije respirabilne prašine prelaze graničnu vrijednost od 3 mg/m³, što je direktno povezano s povećanom učestalošću respiratornih simptoma [22]. Ye et al. [37] kroz analizu defekata u kineskim tunelima dodatno potvrđuju da strukturni nedostaci i neadekvatna ventilacija povećavaju rizik od kumulativne izloženosti radnika.

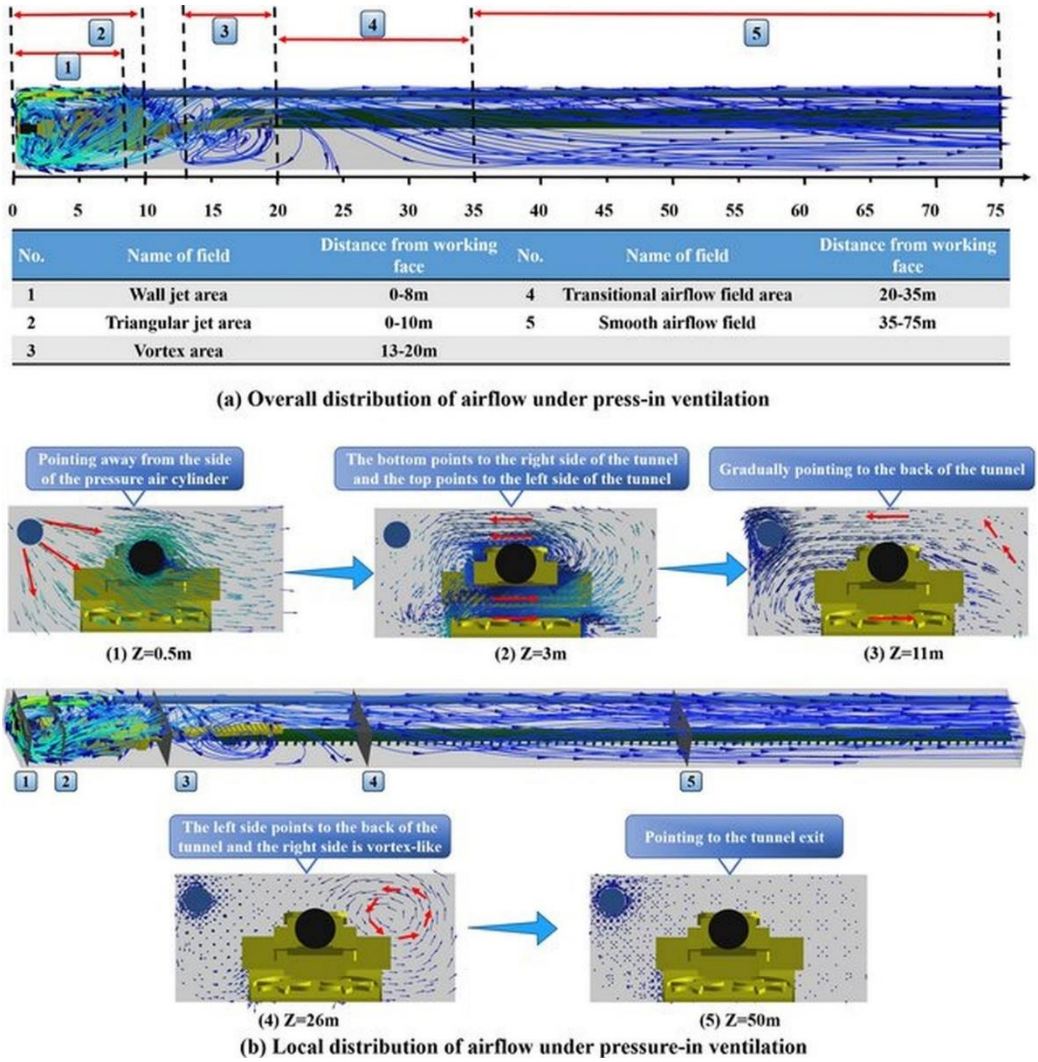
Sveukupno, empirijski nalazi ukazuju na kumulativni efekt izloženosti prašini i plinovima, s mjerljivim smanjenjem plućne funkcije i povećanom prevalencijom respiratornih simptoma. Ovi rezultati predstavljaju čvrstu osnovu za dalju analizu u kontekstu numeričkih modela i normativnih zahtjeva, jer jasno pokazuju da se zdravstveni rizici ne mogu sagledati samo kroz teorijske proračune, već zahtijevaju kontinuirano praćenje i validaciju u realnim uvjetima.

3.2 Diskusija CFD simulacija

Numerički modeli ventilacije u tunelima, posebno oni zasnovani na CFD metodama, omogućavaju detaljno predviđanje distribucije zagađivača i dinamike strujanja zraka. Jiang i saradnici su pokazali da koncentracija ugljičnog

monoksida u tunelu može dostići vrijednosti iznad 50 ppm u zonama slabog strujanja, dok se primjenom optimiziranog ventilacijskog režima koncentracija smanjuje ispod 20 ppm, što je u skladu s preporučenim sigurnosnim granicama [24]. Yang et al. su simulacijama dokazali da brzina strujanja zraka od 3 m/s osigurava efikasnu disperziju prašine i plinova, dok niže brzine dovode do lokalne akumulacije i povećanog rizika za radnike [23].
CFD modeli također ukazuju na značaj geometrije tunela. Zhang et al. su pokazali da u tunelima s kompleksnim raskrsnicama dolazi do formiranja turbulencija koje povećavaju lokalne koncentracije zagađivača za više od 30 % u odnosu na linearne dionice [14]. Ovi rezultati potvrđuju da projektiranje ventilacijskih sistema mora uzeti u obzir specifičnu geometriju i dinamičke karakteristike gradilišta.
Dodatno, Nie et al. su simulacijama potvrdili da maksimalne koncentracije prašine u blizini radne fronte pri klasičnoj potisnoj ventilaciji prelaze 1200 mg/m³, dok se primjenom kombinovanih režima vrijednosti smanjuju na 400–600 mg/m³. Uveli su i pokazatelj „air age“, pri čemu je u zonama slabog strujanja starost zraka prelazila 300 s, dok je optimizacijom ventilacije smanjena ispod 100 s, što ukazuje na bržu izmjenu i bolju kvalitetu zraka [13]. Yin et al. [38] dodatno potvrđuju da parametri ventilacije, poput brzine i smjera strujanja, mogu optimizirati učinak zračnih zavjesa u uklanjanju prašine.

Dodatno, Zhang et al. [39] analizirali su obrasce distribucije prašine i optimizaciju ventilacijskog sistema, potvrđujući da kombinacija empirijskih mjerenja i CFD modela daje najpreciznije rezultate. Xu et al. [40] proširuju primjenu CFD modela na scenarije požara, potvrđujući da prirodna ventilacija može biti validirana eksperimentalnim podacima. Ovi rezultati potvrđuju da CFD simulacije ne samo da omogućavaju predviđanje distribucije zagađivača, već i kvantitativnu procjenu ventilacijske efikasnosti.
U istom radu, Nie et al. su prikazali i segmentaciju strujnih zona u tunelu pod režimom potisne ventilacije, uključujući mlazne, vrtložne i prijelazne tokove. U nastavku je prikazana slika 1, koja dokumentira raspodjelu strujanja zraka u tunelskom profilu i lokalne obrasce strujanja na karakterističnim presjecima.



No.	Name of field	Distance from working face	No.	Name of field	Distance from working face
1	Wall jet area	0-8m	4	Transitional airflow field area	20-35m
2	Triangular jet area	0-10m	5	Smooth airflow field	35-75m
3	Vortex area	13-20m			

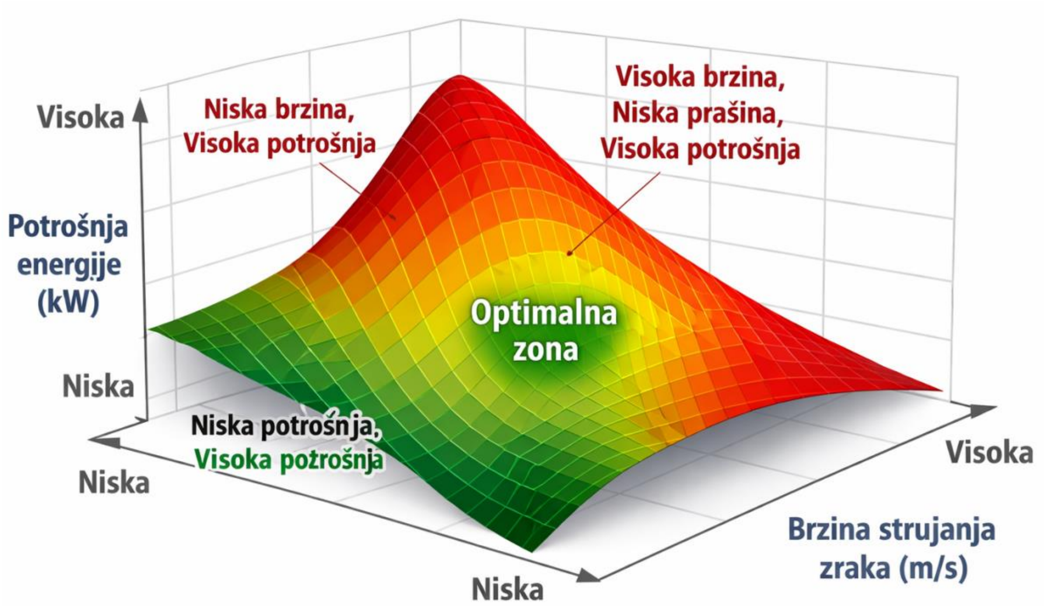
Slika 1.Raspodjela strujanja zraka u tunelu pod režimom potisne ventilacije, sa prikazom pet karakterističnih strujnih zona i lokalnih presjeka [13].

3.3 Energetska optimizacija ventilacije

Ventilacija u tunelima nije samo pitanje sigurnosti, već i jedan od najvećih potrošača energije u podzemnim radovima. Prema dostupnim studijama, energetski troškovi ventilacije mogu činiti i do 40–50 % ukupne potrošnje električne energije na gradilištu, što naglašava potrebu za optimizacijom sistema. CFD simulacije imaju ključnu ulogu u pronalaženju balansa između sigurnosti radnika i energetske efikasnosti. Yang i saradnici su pokazali da brzina strujanja zraka od 3 m/s osigurava efikasnu disperziju prašine i plinova, ali istovremeno zahtijeva značajnu potrošnju energije. Smanjenje brzine na 2 m/s može smanjiti potrošnju energije za više od 20 %, ali dovodi do povećane akumulacije zagađivača i lokalnih rizika [23]. Liu et al. [41] predlažu primjenu neuronskih mreža za frekvencijsku kontrolu ventilacije, čime se postiže dodatna optimizacija potrošnje energije uz očuvanje sigurnosnih standarda. Zhang et al. [42] dodatno pokazuju da optimizacija ventilacije u ekstra dugim tunelima kroz racionalan raspored kanala može značajno smanjiti potrošnju energije, bez kompromisa po pitanju sigurnosti.

Nie i saradnici su dodatno istakli da kombinovani režimi ventilacije (potisna + izvlaka) ne samo da smanjuju koncentraciju prašine za više od 50 % u odnosu na jednostranu potisnu ventilaciju, već i optimiziraju potrošnju energije kroz ravnomjerniju raspodjelu strujanja [13]. Ovi rezultati ukazuju da projektiranje ventilacijskih sistema mora biti zasnovano na integrisanom pristupu, gdje se sigurnosni zahtjevi i energetska održivost razmatraju istovremeno.

U nastavku je prikazana slika 2, koja sintetizira podatke iz Jiang et al. [24], Yang et al. [23] i Nie et al. [13], te prikazuje kompromis između brzine strujanja zraka, koncentracije prašine i potrošnje energije. Optimalna zona se nalazi oko 3 m/s, gdje je koncentracija prašine ispod sigurnosne granice, a potrošnja energije još uvijek prihvatljiva.



Slika 2.Vizualizacija odnosa između brzine strujanja zraka, koncentracije prašine i potrošnje energije u tunelu. Slika autora, na osnovu podataka iz Jiang et al. (2021), Yang et al. (2022) i Nie et al. (2023).

3.4 Diskusija mikroklimatskih faktora

Radovi koji se bave mikroklimom u tunelima dosljedno ukazuju na to da povišene temperature i visoka relativna vlažnost značajno povećavaju fiziološko opterećenje radnika. Nath, Sahu i Lee kroz globalnu analizu pokazuju da kombinacija topline, vlage i zagađenja dovodi do povećanog rizika od termalnog stresa i smanjenja produktivnosti, što je naročito izraženo u dubokim tunelima s geotermalnim utjecajem [15]. Ovi nalazi potvrđuju da mikroklimatski faktori moraju biti integralni dio projektiranja ventilacijskih sistema, a ne samo sporedni parametar.

Sharma naglašava da ventilacija ima dvostruku funkciju: osim razrjeđivanja prašine i plinova, ona osigurava regulaciju temperature i vlažnosti. Time se smanjuje fiziološko opterećenje radnika i povećava radna efikasnost [12]. Chen et al. [43] dodatno naglašavaju važnost raspodjele brzine zraka i koeficijenta prijenosa topline u ventilacijskim kanalima, što direktno utiče na mikroklimatske uvjete. Rojas-Alva kroz poljske testove u TBM tunelima potvrđuje da temperatura, vlažnost i brzina zraka variraju tokom rada mehanizacije, te predlaže kontrolne vrijednosti za optimalne uvjete [31]. Njegovi rezultati ukazuju da mikroklimatski faktori nisu statični, već se mijenjaju u zavisnosti od intenziteta radova i korištene tehnologije.

Prašina i plinovi se također moraju posmatrati kao mikroklimatski faktori. Wei, Jiang i Di ističu da visoke koncentracije prašine u zonama slabog strujanja povećavaju rizik od respiratornih oboljenja, uključujući pneumokoniozu. Njihova analiza prostorno-vremenske distribucije prašine pokazuje da čestice mogu ostati suspendovane u zraku duže vrijeme u suhim uslovima, što direktno utiče na kvalitet mikroklime [28].

Wang dodatno naglašava da geotermalni utjecaj stijenske mase u dubokim tunelima značajno podiže temperaturu, što zahtijeva posebne mjere hlađenja i prilagođene ventilacijske režime [29]. Sorlini ukazuje na važnost inovativnih tehnologija za monitoring mikroklime, koje omogućavaju pravovremeno praćenje parametara i smanjenje rizika od toplotnog stresa i zagađenja [30]. Bektašević et al. [44] dodatno naglašavaju važnost multidisciplinarnog pristupa preventivnim mjerama sigurnosti u tunelogradnji, potvrđujući da kontrola mikroklime mora biti povezana sa širim sistemom zaštite na radu.

Sveukupno, nalazi pokazuju da mikroklimatski faktori u tunelima imaju dinamičan karakter i da njihova kontrola predstavlja ključni element sigurnosti, zaštite zdravlja i održivosti u podzemnim radovima. Integracija empirijskih mjerenja, tehnološkog monitoringa i prilagođenih ventilacijskih režima jedini je način da se osigura stabilna i sigurna mikroklima u složenim uslovima tunelogradnje.

3.5 Normativni okvir - diskusija

Normativni okvir ventilacije u tunelogradnji zasniva se na međunarodnim smjernicama, nacionalnim propisima i tehničkim standardima koji definiraju minimalne zahtjeve za kvalitet zraka, sigurnost radnika i projektiranje ventilacijskih sistema [33-35]. Pregled stručne literature ukazuje da se ovi dokumenti u praksi često koriste kao polazna tačka, dok stvarna sigurnost zavisi od dosljedne primjene i prilagođavanja specifičnim uvjetima gradilišta [27].

Nepodudarnosti između projektnih parametara i izvedbenih performansi mogu dovesti do formiranja stagnacijskih zona, povećane kumulativne izloženosti radnika i odstupanja od propisanih granica koncentracija plinova i prašine [27].
Savremeni radovi naglašavaju da normativni zahtjevi moraju biti dopunjeni kontinuiranim monitoringom mikroklimatskih faktora i integracijom inovativnih tehnologija za mjerenje u realnom vremenu [30]. BS 6164:2019 - Code of practice for health and safety in tunnelling ističe da ventilacija mora biti praćena stalnim mjerenjem koncentracija prašine i plinova, uz kontrolu temperature i vlažnosti. Slično tome, ITA/AITES Guidelines for good occupational health and safety practice in tunnel construction naglašavaju da međunarodne smjernice treba dopuniti lokalnim monitoringom te da se osnovni principi zaštite moraju potvrditi empirijskim mjerenjima na gradilištu [33].
U američkom kontekstu, OSHA standardi za podzemnu gradnju (29 CFR 1926.800) propisuju minimalne vrijednosti za ventilaciju i kvalitet zraka, ali njihova efektivnost zavisi od stalne validacije u realnim uvjetima, jer odstupanja u izvedbi mogu povećati izloženost radnika [34]. U kineskom kontekstu, JTG-2005 [45] tehničke specifikacije za gradnju tunela propisuju detaljne zahtjeve za ventilaciju, što pokazuje da lokalni standardi imaju ključnu ulogu u oblikovanju sigurnosnih režima. Shokofe et al. [46] dodatno ukazuju da nesigurnost u emisiji plinova može značajno uticati na distribuciju zraka, što potvrđuje da normativni zahtjevi moraju biti dopunjeni analizom nesigurnosti modela. Bektašević et al. [47] kroz studiju o tunelskoj podršci u urbanim zonama s malim nadvišenjem dodatno potvrđuju da normativni zahtjevi moraju biti prilagođeni lokalnim geotehničkim uvjetima kako bi se osigurala sigurnost i stabilnost konstrukcije.

Zaključak

Ventilacija u tunelogradnji predstavlja ključni faktor očuvanja zdravlja i sigurnosti radnika, ali i jedan od najvećih tehničkih i ekonomskih izazova podzemne gradnje. Analiza dostupnih empirijskih studija pokazuje da kumulativna izloženost prašini i plinovima dovodi do mjerljivog smanjenja plućne funkcije i povećane prevalencije respiratornih simptoma, što potvrđuje da se zdravstveni rizici ne mogu sagledati samo kroz teorijske proračune, već zahtijevaju kontinuirano praćenje u realnim uvjetima. Numerički modeli zasnovani na CFD simulacijama omogućavaju preciznu identifikaciju kritičnih zona i optimizaciju ventilacijskih režima, ali njihova pouzdanost zavisi od validacije empirijskim mjerenjima. Energetska istraživanja ukazuju da ventilacija može činiti i do 50 % ukupne potrošnje električne energije na gradilištu, što naglašava potrebu za integrisanim pristupom koji istovremeno uzima u obzir sigurnost radnika i održivost sistema. Mikroklimatski faktori, poput povišene temperature i vlažnosti, dodatno povećavaju fiziološko opterećenje radnika, dok inovativne tehnologije za monitoring omogućavaju pravovremenu kontrolu rizika. Normativni okvir, zasnovan na međunarodnim smjernicama i nacionalnim propisima, postavlja minimalne standarde, ali njihova efektivna primjena zahtijeva prilagodbu lokalnim geotehničkim uvjetima i stalnu validaciju u praksi. Glavni doprinos ovog rada ogleda se u integraciji empirijskih nalaza, numeričkih simulacija i normativnih zahtjeva, čime se osigurava cjelovitija procjena ventilacijskih sistema u tunelogradnji. Time se potvrđuje da interdisciplinarni pristup – koji povezuje geotehniku, inženjerski dizajn, medicinu rada i sigurnosni menadžment – predstavlja jedini način da se dugoročno osigura sigurnost, zdravlje i produktivnost radnika u složenim uslovima podzemne gradnje.

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Popis slika

Popis tabela

THE ROLE OF VENTILATION IN PRESERVING WORKER HEALTH AND SAFETY DURING TUNNEL CONSTRUCTION

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Scientific paper

Ekrem Bektašević, Kemal Gutić, Satko Filipović[2]

Abstract

Ventilation in tunnel construction represents a key system for preserving the health and safety of workers in underground environments. This paper analyses empirical epidemiological studies, numerical CFD simulations, and regulatory requirements in order to assess the effectiveness of ventilation regimes. The results show that cumulative dust exposure leads to an average annual decline in FEV_1 of 40 ml among workers, compared to 20 ml in control groups, while carbon monoxide (CO) concentrations after blasting frequently exceed permissible limits. CFD models confirm that an airflow velocity of 3 m/s ensures optimal dust dispersion, but at the cost of increased energy consumption, which can account for up to 50% of the total electrical energy consumption of the construction site. Analysis of microclimatic factors indicates that elevated temperatures and high humidity further increase the physiological workload of workers, while innovative monitoring technologies enable timely risk control. The regulatory framework, based on international guidelines (ITA/AITES, OSHA) and national regulations, establishes minimum standards; however, their effective implementation requires continuous monitoring and adaptation to local geotechnical conditions. The main contribution of this paper lies in the integration of empirical data and CFD simulations, providing a more reliable assessment of ventilation regimes and the formulation of practical recommendations for designers and contractors.

Keywords: *tunnel construction, ventilation, air quality, occupational safety, respiratory risks, dust, carbon monoxide, nitrogen oxides*

[2] *Faculty of Mining, Geology and Civil Engineering, University of Tuzla, Urfeta Vejzagića No. 2, 75000 Tuzla, Bosnia and Herzegovina; ekrem.bektasevic@untz.ba; kemal.gutic@untz.baRoad Directorate of Sarajevo Canton, Ministry of Transport of Sarajevo Canton, Reisa Džemaludina Čauševića 1, 71000 Sarajevo, Bosnia and Herzegovina*Correspondence: satko.filipovic.dkps@gmail.com*

1. Introduction

Tunnel construction represents a specific branch of the construction industry in which work processes take place in confined and enclosed underground spaces [1–3], exposing workers to a combination of physical, chemical, and microclimatic factors that may adversely affect their health and safety. The main sources of pollution in such conditions include dust generated during drilling and blasting of rock masses, emissions from diesel-powered machinery, and the presence of harmful gases such as nitrogen oxides (NO_x) and carbon monoxide (CO), produced as by-products of machinery operation and the use of explosives [4–6].

Numerous studies conducted among tunnel workers indicate more pronounced impairment of respiratory health compared to workers not exposed to enclosed underground environments. Long-term occupational exposure to dust and harmful gases is associated with a higher prevalence of respiratory symptoms and a gradual decline in lung function, particularly in forced expiratory volume in one second (FEV_1). Longitudinal studies monitoring workers over periods exceeding six years have shown that cumulative exposure has a statistically significant effect on FEV_1 decline, independent of age and smoking habits, confirming a direct link between working conditions in tunnel construction and respiratory health risks [5,7,8]. Similar results have been confirmed by other studies, reporting a higher prevalence of chronic respiratory symptoms and a more pronounced reduction in lung function among tunnel workers compared to control groups [4,9].

Air quality in the working environment is a key determinant of these health risks and depends on complex interactions between pollution sources, tunnel geometry, construction activity intensity, and, critically, the efficiency of the ventilation system [10]. The primary function of tunnel ventilation is to ensure the supply of fresh air to workplaces, dilute and remove harmful gases and airborne particles, and prevent the formation of localized zones with elevated pollutant concentrations.

In this context, ventilation cannot be viewed merely as a technical subsystem of the construction site, but rather as a central instrument of occupational risk management [11]. Inadequately designed or poorly optimized ventilation regimes may lead to the formation of stable low-airflow zones where pollutants persist for extended periods, significantly increasing cumulative worker exposure [12].

Contemporary technical literature increasingly employs numerical simulations to analyse ventilation system behaviour and pollutant dispersion in tunnels. Such studies demonstrate that the arrangement of ventilation ducts, airflow velocity and direction, and the degree of turbulence have a decisive influence on the spatial distribution of dust and gases. In unfavourable configurations, zones may form in which pollutant concentrations exceed recommended limit values several times, even when the overall airflow nominally meets design requirements [13,14].

In addition to pollution control, ventilation systems play a significant role in regulating microclimatic conditions within tunnels, including air temperature and relative humidity. Elevated temperatures and high humidity, combined with polluted air, further increase the physiological workload of workers, reduce work efficiency, and raise the risk of thermal stress and heat-related disorders [15]. These issues are particularly pronounced in deep tunnels with strong geothermal influences and long ventilation systems.

Despite continuous technological development, studies from various countries confirm that tunnel workers continue to experience significant adverse health outcomes associated with occupational exposure. These primarily include an increased prevalence of chronic respiratory symptoms, reduced lung function, and a higher incidence of chronic obstructive pulmonary disease (COPD) compared to workers in less polluted working environments [16–18].

Based on the above, the research problem addressed in this paper focuses on analysing the role of ventilation in reducing cumulative worker exposure to harmful particles and gases in tunnel construction. The aim of the study is to synthesise available scientific knowledge, empirical data, and numerical simulation results to develop an integrated methodology for assessing ventilation system effectiveness. The originality of the research lies in its interdisciplinary approach, linking geotechnical engineering, ventilation design, occupational medicine, and safety management [19–21], and in positioning the results within international guidelines and standards (WHO, OSHA) to formulate practical recommendations for designers, contractors, and supervisory authorities.

2. Literature review and theoretical framework

Ventilation in tunnel construction represents a key engineering and safety system whose primary function is to ensure acceptable air quality in enclosed underground spaces. Its role includes the dilution and removal of harmful gases and dust, prevention of stagnation zones, and regulation of microclimatic conditions. Consequently, ventilation becomes not merely a technical subsystem but a central instrument for protecting worker health and managing risks on construction sites.

2.1. Empirical findings on worker health

Epidemiological and longitudinal studies consistently confirm that tunnel workers face an increased risk of respiratory symptoms and reduced lung function compared to control groups. Long-term cumulative exposure to dust and gases is associated with a statistically significant decline in FEV_1, while short-term studies have demonstrated noticeable changes in lung function within just a few months of work. Empirical measurements of gas concentrations in operational tunnels further confirm that carbon monoxide (CO) frequently exceeds maximum permissible concentrations, particularly after blasting, representing a dominant risk for workers. For clarity, previous empirical studies on respiratory risks in tunnel construction are systematised in Table 1.

Table 1. Empirical findings on worker health in tunnel construction

Author / Year	Research focus	Key findings	Limitations	Practical implications
Bakke et al. (2001) [4]	Dust and gases in tunnels	Workers exposed to dust and gases have a higher risk of respiratory symptoms.	Limited to specific locations.	Provides epidemiological evidence of the association between occupational exposure and health outcomes.
Bakke et al. (2004) [5]	Cumulative exposure	Long-term exposure is associated with a decline in FEV_1, independent of age and smoking status.	Focused on a single region.	Confirms long-term health risks associated with tunnel work.
Ulvestad et al. (2015) [9]	Short-term lung function	Short-term declines in FEV_1 were recorded among tunnel workers.	Limited to specific working conditions.	Relevant for real-time health and exposure monitoring.
Klanfar et al. (2015) [22]	Empirical measurements of CO and NO_x	CO most frequently exceeds permissible exposure limits in all construction phases, especially after blasting.	Focused on a single tunnel (Mala Kapela).	Highlights the need for continuous air quality monitoring.

2.2. CFD simulations and numerical models

Numerical methods, particularly Computational Fluid Dynamics (CFD), have become a key tool in the analysis of ventilation systems in tunnel construction. They enable the simulation of dust and gas distribution under various configurations of ventilation parameters, the identification of critical zones, and the optimization of duct layouts. Studies indicate that CFD simulations can significantly contribute to more accurate design of ventilation systems; however, they often face limitations due to a lack of validation under real construction conditions. For clarity, previous studies based on CFD simulations and numerical methods are systematized in Table 2.

Table 2. CFD Simulations and numerical models in tunnel construction

Author / Year	Research focus	Key findings	Limitations	Practical implications
Yang et al. (2022) [23]	CFD simulations of dust distribution	Optimization of duct layout reduces PM2.5 and CO concentrations by 20–30%.	Simulation-based model without field data.	Demonstrates the potential of CFD in ventilation system design.
Jiang et al. (2021) [24]	CFD-based dust control during drilling	Numerical simulation enables precise control of dust dispersion and identification of critical zones.	Focused on specific drilling scenarios	Applicable to ventilation planning during drilling operations.
Zhang et al. (2024) [14]	Combination of measurements and CFD	Identification of critical zones and system optimization through integration of empirical data and modeling.	Requires validation in different tunnels.	Integration of empirical measurements and simulations.
Nie et al. (2023) [13]	CFD analysis of dust transport	Analysis of dust transport mechanisms and air age under different ventilation methods.	Limited to model conditions.	Relevant for optimization of ventilation methods.
Colella et al. (2009) [25]	Multi-scale CFD model	Visualization of airflow patterns in tunnels and identification of	Older model, limited to specific conditions.	Foundation for subsequent development of multi-scale models.

		near-field and far-field zones.		

2.3. Energy optimization and implementation issues

In addition to health and safety aspects, ventilation in tunnel construction also has a significant technical and economic dimension. The energy consumption of ventilation systems represents one of the largest operational costs in underground construction. Therefore, the literature increasingly emphasizes the need for dynamic control of airflow in order to simultaneously reduce occupational risks and optimize energy consumption. However, numerous studies indicate that the actual performance of ventilation ducts often fails to achieve the designed performance due to issues such as air leakage and increased airflow resistance. These factors can result in reduced airflow rates and the accumulation of pollutants in the working area, thereby directly compromising worker safety. The following section presents selected studies addressing energy optimization and implementation issues of ventilation systems in tunnel construction.

Table 3. Energy optimization and implementation issues of ventilation systems

Author / Year	Research focus	Key findings	Limitations	Practical implications
Si, Cao & Chen (2020) [26]	Dynamic airflow control	Flow optimization reduces occupational risks and energy consumption.	Application limited to longitudinal ventilation systems.	Relevant for sustainable projects and cost reduction.
Chang et al. (2024) [27]	Air leakage and airflow resistance	Inadequate duct installation leads to air leakage and increased airflow resistance.	Numerical simulation without validation under real conditions.	Highlights the discrepancy between design parameters and actual performance.

2.4. Microclimatic factors

Ventilation in tunnel construction affects not only dust and gas concentrations but also the microclimatic conditions within the underground environment. Elevated temperatures, high relative humidity, and limited airflow further increase the physiological workload of workers, reduce work efficiency, and raise the risk of thermal stress. These issues are particularly pronounced in deep tunnels with significant geothermal influence, where ventilation must simultaneously ensure pollutant dilution and thermal regulation. In addition to heat and humidity, dust and gases are also considered microclimatic factors, as they directly impact air quality and workers' health outcomes. Recent studies further emphasize the importance of continuous microclimate monitoring and the application of innovative technologies that allow timely parameter tracking and reduce the risk of heat stress and respiratory diseases. For the sake of systematization, the following section highlights relevant studies analyzing microclimatic factors in tunnel construction, focusing on their key findings and practical applicability.

Table 4. Microclimatic factors in tunnel construction

Author / Year	**Research focus**	**Key findings**	**Limitations**	**Practical implications**
Nath, Sahu & Lee (2026) [15]	Global heat exposure	Combination of heat, humidity, and pollution increases the risk of thermal stress and reduced productivity.	Review paper, global focus, without specific tunnel data.	Relevant for deep tunnels with geothermal influence.
Sharma (2020) [12]	Tunnel ventilation and microclimate	Ventilation contributes to regulating temperature and humidity, thereby reducing workers' physiological workload.	Limited to technical description, without epidemiological data.	Applicable for designing ventilation regimes.
Wei, Jiang & Di (2024) [28]	Dust generation and distribution	High dust concentrations in low-flow zones cause respiratory risks, including pneumoconiosis.	Focus on dust, without analysis of temperature and humidity.	Applicable for health risk assessment and protective measures.
Wang et al. (2024) [29]	Prediction of temperature fields	Geothermal influence of rock mass significantly increases temperature in deep tunnels.	Focus on thermal conditions, without dust analysis.	Applicable for deep tunnels with high geothermal influence.

Sorlini et al. (2023) [30]	Innovative monitoring technologies	Microclimate monitoring technologies reduce the risk of heat stress and pollution.	Focus on technologies, less on empirical data.	Applicable for modernizatio n of tunnel projects.
Rojas-Alva et al. (2016) [31]	TBM tunnel construction – microclimate	Field tests showed variations in temperature, humidity, and airflow during TBM operations; recommended control values provided.	Older study, focus on TBM, without broader applicability.	Relevant for mechanized tunnel projects.
Chang et al. (2025) [32]	Ventilation and pollutant diffusion	Dust and gas distribution depends on airflow and tunnel geometry.	Focus on pollutants, less on thermal conditions.	Applicable for designing ventilation regimes.

2.5. Regulatory and international framework

In addition to empirical findings and numerical models, international guidelines and national regulations play a significant role in shaping tunnel ventilation systems. They establish minimum standards for air quality, worker safety, and technical requirements for ventilation installations. Guidelines from international organizations such as ITA/AITES ensure global standardization, while OSHA regulations define mandatory parameters in U.S. practice. In Bosnia and Herzegovina, the "Guidelines for Design, Construction, Maintenance, and Supervision of Roads – Book II: Construction, Part 3: Special Technical Conditions for Tunnels" (2005) specify concrete values for minimum airflow and air velocity in tunnels, ensuring that design solutions comply with local regulatory requirements. Table 5. provides a concise overview of key guidelines and standards defining technical requirements for tunnel ventilation, highlighting their applicability and limitations.

Table 5. Regulatory and international framework for tunnel ventilation

Source	**Focus**	**Key findings/Requireme nts**	**Limitation s**	**Practical Applicability**

ITA/AITES (2011) [33]	International guidelines	Safe use of temporary ventilation systems in tunnels; recommendations for design and maintenance.	General guidelines, without local specifics.	Standardization in global practice; reference framework for designers.
OSHA (2003) [34]	Regulations	Minimum standards for air quality, worker safety, and ventilation parameters in tunnels.	Focus on U.S. practice; requires adaptation to local conditions.	Regulatory framework for worker safety and health protection.
Guidelines, Book II, Part 3: Special Technical Conditions for Tunnels (2005) [35]	National technical standard	Specify minimum airflow and air velocity in tunnels, depending on the type of work.	Applicable only in local/regional context.	Mandatory regulatory document for tunnel design and construction.

3. Analysis and discussion of previous research

The literature review indicates that research on ventilation in tunnel construction can be classified into several complementary categories: empirical findings, numerical models, energy optimization, microclimatic factors, and regulatory frameworks. Each of these categories contributes specific insights into the problem; however, only their integration provides a comprehensive understanding. Empirical studies (Bakke et al., Ulvestad et al., Klanfar et al.) clearly confirm an increased risk of respiratory diseases among tunnel workers, while CFD simulations (Yang, Jiang, Zhang, Nie, Colella) offer the ability to predict pollutant distribution and optimize ventilation systems. Nevertheless, the lack of validation of simulations under real construction conditions remains a key challenge. Energy-related studies (Si, Cao & Chen; Chang) highlight the need to balance safety and economic efficiency, whereas microclimatic studies (Nath, Sharma, Wei, Wang, Sorlini, Rojas-Alva, Chang) further demonstrate that the combined effects of heat, humidity, dust, and gases increase the risk of thermal stress and respiratory diseases. In this context, proposed control values and monitoring technologies are essential for reducing workers' physiological burden. Regulatory documents (ITA/AITES, OSHA, Guidelines Book II, Part 3) ensure minimum standards; however, discrepancies between design requirements and actual implementation frequently occur in practice.

3.1. Discussion of empirical findings

Empirical studies conducted among tunnel workers consistently confirm an increased risk of respiratory diseases, which is quantitatively reflected in reduced lung function and a higher prevalence of respiratory symptoms. A longitudinal study showed that forced expiratory volume in one second (FEV_1) among workers with high cumulative dust exposure decreases significantly faster compared to control groups, with an average annual decline of approximately 40 ml versus 20 ml in non-exposed workers [4]. These results confirm that the working environment is a key factor in the accelerated decline of lung function. Additional studies have demonstrated that reductions in FEV_1 occur independently of age and smoking status, emphasizing the direct impact of exposure to dust and gases [5]. Similar findings regarding the effects of drilling and rock bolting on worker safety were reported by Filipović et al. [36], showing that technological procedures directly influence the stability and safety of the working environment. Analyses of the prevalence of respiratory symptoms also reveal significant differences between tunnel workers and control groups. Chronic cough was found to affect more than one-third of tunnel workers, whereas the proportion in control populations was almost twice as low [9]. These data clearly indicate a relationship between exposure intensity and the frequency of respiratory symptoms. Furthermore, measurements conducted in Croatian tunnels showed that concentrations of respirable dust exceed the limit value of 3 mg/m^3, which is directly associated with an increased prevalence of respiratory symptoms [22]. Ye et al. [37], through an analysis of defects in Chinese tunnels, further confirmed that structural deficiencies and inadequate ventilation increase the risk of cumulative exposure among workers.

Overall, empirical findings indicate a cumulative effect of exposure to dust and gases, resulting in measurable reductions in lung function and an increased prevalence of respiratory symptoms. These results provide a solid basis for further analysis in the context of numerical models and regulatory requirements, as they clearly demonstrate that health risks cannot be assessed solely through theoretical calculations but require continuous monitoring and validation under real working conditions.

3.2. Discussion of CFD simulations

Numerical models of tunnel ventilation, particularly those based on CFD methods, enable detailed prediction of pollutant distribution and airflow dynamics. Jiang et al. demonstrated that carbon monoxide concentrations in tunnels can reach values exceeding 50 ppm in low-airflow zones, whereas the application of optimized ventilation regimes reduces concentrations below 20 ppm, in accordance with recommended safety limits [24]. Yang et al. showed through simulations that an airflow velocity of 3 m/s ensures efficient dispersion of dust and gases, while lower velocities lead to local accumulation and increased risk to workers [23].

CFD models also highlight the importance of tunnel geometry. Zhang et al. demonstrated that tunnels with complex intersections generate turbulence that increases local pollutant concentrations by more than 30% compared to linear tunnel sections [14]. These findings confirm that ventilation system design must account for site-specific geometry and dynamic construction characteristics.

Furthermore, Nie et al. confirmed through simulations that maximum dust concentrations near the working face under conventional forcing ventilation exceed 1200 mg/m³, whereas the application of combined ventilation regimes reduces these values to 400–600 mg/m³. They also introduced the indicator "air age", showing that in low-airflow zones air age exceeded 300 s, while ventilation optimization reduced it below 100 s, indicating faster air exchange and improved air quality [13]. Yin et al. [38] further confirmed that ventilation parameters, such as airflow velocity and direction, can optimize the performance of air curtains in dust removal.

Additionally, Zhang et al. [39] analyzed dust distribution patterns and ventilation system optimization, confirming that the integration of empirical measurements and CFD models yields the most accurate results. Xu et al. [40] extended the application of CFD models to fire scenarios, demonstrating that natural ventilation can be validated using experimental data. These results confirm that CFD simulations not only enable prediction of pollutant distribution but also provide a quantitative assessment of ventilation efficiency.

In the same study, Nie et al. also presented segmentation of airflow zones within tunnels under forcing ventilation regimes, including jet flow, vortex flow, and transitional flow regions. Figure 1 presents the airflow distribution within the tunnel profile and local airflow patterns at characteristic cross-sections.

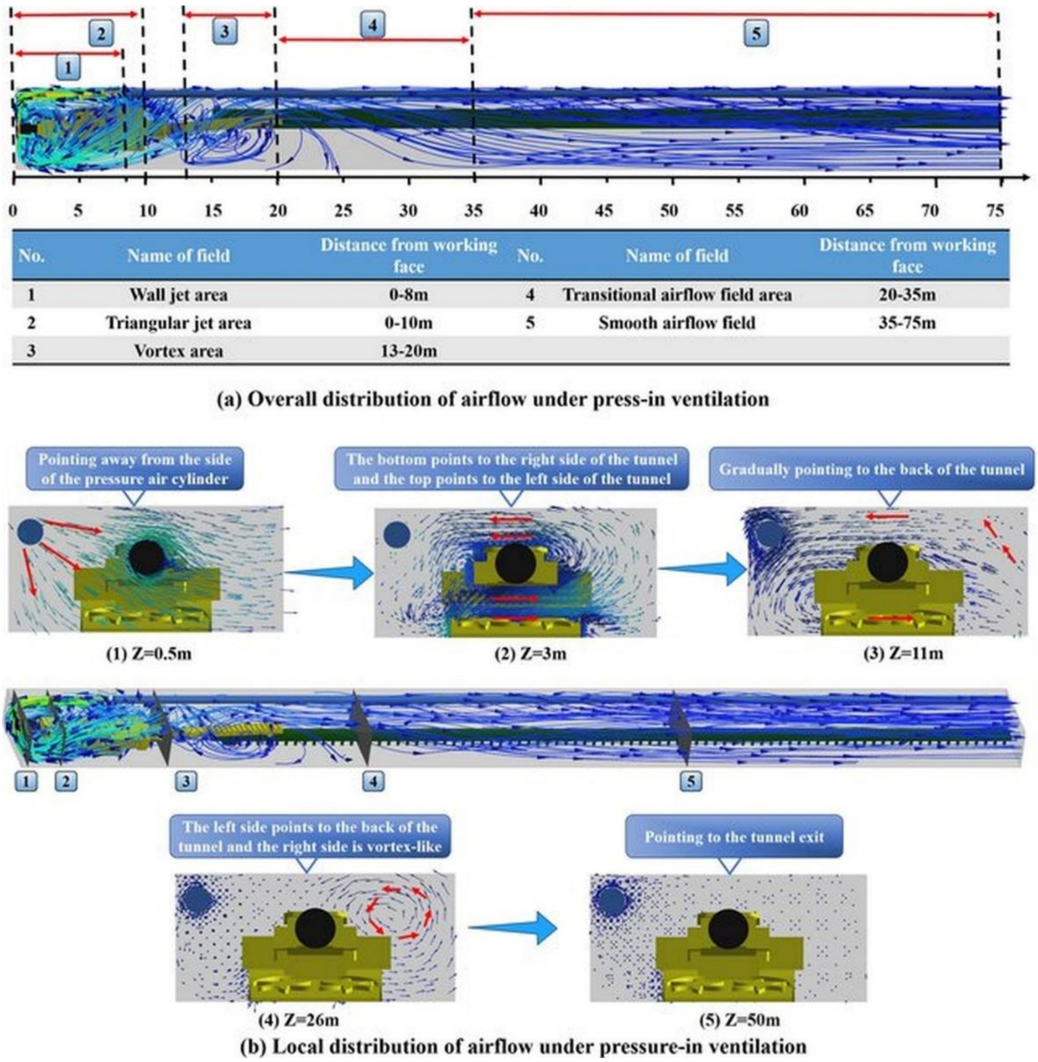

Figure 1. Airflow distribution in a tunnel under a forcing ventilation regime, showing five characteristic flow zones and local cross-sections [13].

3.3. Energy optimization of ventilation

Ventilation in tunnels is not only a safety issue but also one of the largest energy consumers in underground construction. According to available studies, energy costs associated with ventilation can account for up to 40–50% of the total electricity consumption on construction sites, highlighting the need for system optimization. CFD simulations play a key role in identifying the balance between worker safety and energy efficiency. Yang et al. demonstrated that an airflow velocity of 3 m/s ensures efficient dispersion of dust and gases but simultaneously requires significant energy consumption. Reducing the airflow velocity to 2 m/s can decrease energy consumption by more than 20%; however, it leads to increased pollutant accumulation and localized risks [23]. Liu et al. [41] proposed the application of neural networks for frequency-based ventilation control, achieving additional energy optimization while maintaining safety standards. Zhang et al. [42] further showed that ventilation optimization in extra-long tunnels through rational duct layout can significantly reduce energy consumption without compromising safety.

Nie et al. further emphasized that combined ventilation regimes (forcing + exhaust) not only reduce dust concentrations by more than 50% compared to single forcing ventilation but also optimize energy consumption through more uniform airflow distribution [13]. These findings indicate that ventilation system design must be based on an integrated approach in which safety requirements and energy sustainability are considered simultaneously.

Figure 2 presents a synthesis of data from Jiang et al. [24], Yang et al. [23], and Nie et al. [13], illustrating the trade-off between airflow velocity, dust concentration, and energy consumption. The optimal zone is located around 3 m/s, where dust concentrations remain below safety limits while energy consumption remains acceptable.

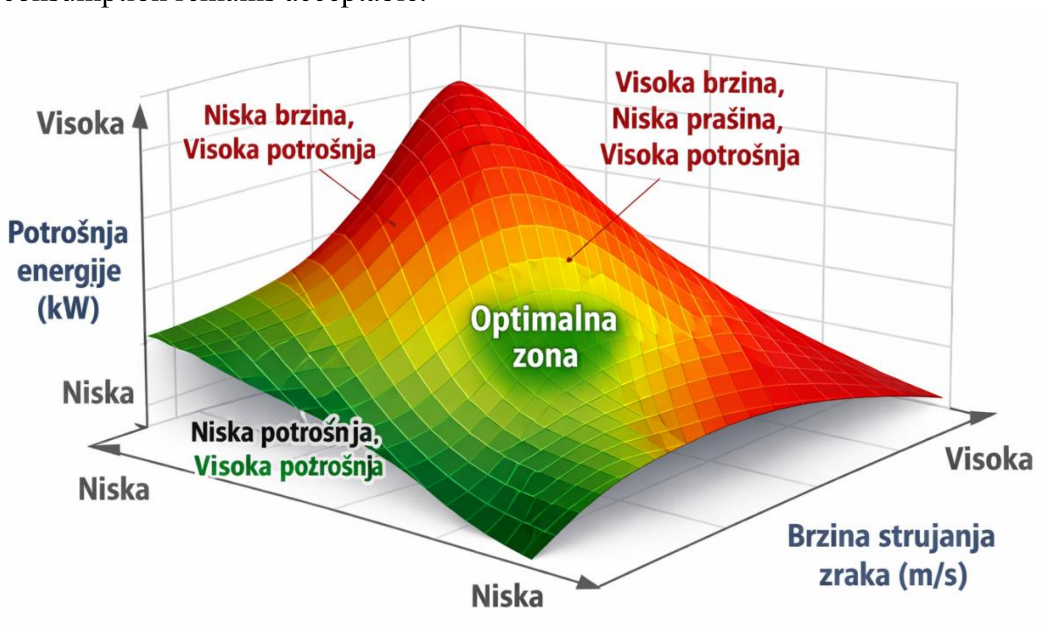

Figure 2. Visualization of the relationship between airflow velocity, dust concentration, and energy consumption in a tunnel. Author's illustration based on data from Jiang et al. (2021), Yang et al. (2022), and Nie et al. (2023).

3.4. Discussion of microclimatic factors

Studies addressing tunnel microclimate consistently indicate that elevated temperatures and high relative humidity significantly increase workers' physiological workload. Nath, Sahu, and Lee, through a global analysis, demonstrate that the combined effects of heat, humidity, and pollution lead to an increased risk of thermal stress and reduced productivity, which is particularly pronounced in deep tunnels with geothermal influence [15]. These findings confirm that microclimatic factors must be an integral part of ventilation system design rather than secondary parameters.

Sharma emphasizes that ventilation has a dual function: in addition to diluting dust and gases, it regulates temperature and humidity. This reduces workers' physiological strain and increases work efficiency [12]. Chen et al. [43] further highlight the importance of airflow velocity distribution and heat transfer coefficients within ventilation ducts, which directly affect microclimatic conditions. Rojas-Alva, through field tests conducted in TBM tunnels, confirms that temperature, humidity, and airflow velocity vary during mechanized operations and proposes control values for optimal conditions [31]. These results indicate that microclimatic factors are not static but vary depending on construction intensity and applied technologies.

Dust and gases must also be considered as microclimatic factors. Wei, Jiang, and Di emphasize that high dust concentrations in low-airflow zones increase the risk of respiratory diseases, including pneumoconiosis. Their analysis of the spatiotemporal distribution of dust shows that particles can remain suspended in the air for extended periods under dry conditions, directly affecting microclimate quality [28].

Wang further highlights that the geothermal influence of the surrounding rock mass in deep tunnels significantly increases temperature, necessitating special cooling measures and adapted ventilation regimes [29]. Sorlini points to the importance of innovative microclimate monitoring technologies, which enable timely parameter tracking and reduce the risks of heat stress and pollution [30]. Bektašević et al. [44] additionally emphasize the importance of a multidisciplinary approach to preventive safety measures in tunnel construction, confirming that microclimate control must be integrated into a broader occupational safety framework.

Overall, the findings indicate that microclimatic factors in tunnels exhibit a dynamic character and that their control represents a key element of safety, health protection, and sustainability in underground works. The integration of empirical measurements, technological monitoring, and adaptive ventilation regimes is the only effective approach to ensuring a stable and safe microclimate under the complex conditions of tunnel construction.

3.5. Regulatory framework – Discussion

The regulatory framework for tunnel ventilation is based on international guidelines, national regulations, and technical standards that define minimum requirements for air quality, worker safety, and ventilation system design [33–35]. A review of the professional literature indicates that these documents are often used in practice as a starting point, while actual safety depends on consistent implementation and adaptation to site-specific conditions [27]. Discrepancies between design parameters and as-built performance can lead to the formation of stagnation zones, increased cumulative worker exposure, and deviations from prescribed limits for gas and dust concentrations [27].

Recent studies emphasize that regulatory requirements must be supplemented by continuous monitoring of microclimatic factors and the integration of innovative real-time measurement technologies [30]. BS 6164:2019 – *Code of Practice for Health and Safety in Tunnelling* states that ventilation must be accompanied by continuous measurement of dust and gas concentrations, along with temperature and humidity control. Similarly, the *ITA/AITES Guidelines for Good Occupational Health and Safety Practice in Tunnel Construction* emphasize that international guidelines should be complemented by local monitoring and that fundamental protection principles must be verified through empirical measurements at construction sites [33].

In the U.S. context, OSHA standards for underground construction (29 CFR 1926.800) prescribe minimum requirements for ventilation and air quality; however, their effectiveness depends on continuous validation under real working conditions, as deviations in implementation may increase worker exposure [34]. In the Chinese context, the JTG-2005 [45] technical specifications for tunnel construction prescribe detailed ventilation requirements, demonstrating that local standards play a crucial role in shaping safety regimes. Shokofe et al. [46] further indicate that uncertainty in gas emissions can significantly affect airflow distribution, confirming that regulatory requirements must be supplemented by uncertainty analysis in modeling approaches. Bektašević et al. [47], through a study on tunnel support in urban areas with shallow overburden, further confirm that regulatory requirements must be adapted to local geotechnical conditions to ensure structural safety and stability.

Conclusion

Ventilation in tunnel construction represents a key factor in preserving workers' health and safety, as well as one of the major technical and economic challenges of underground construction. The analysis of available empirical studies shows that cumulative exposure to dust and gases leads to measurable reductions in lung function and an increased prevalence of respiratory symptoms, confirming that health risks cannot be assessed solely through theoretical calculations but require continuous monitoring under real working conditions. Numerical models based on CFD simulations enable precise identification of critical zones and optimization of ventilation regimes; however, their reliability depends on validation through empirical measurements. Energy-related studies indicate that ventilation can account for up to 50% of total electricity consumption at construction sites, emphasizing the need for an integrated approach that simultaneously considers worker safety and system sustainability. Microclimatic factors, such as elevated temperature and humidity, further increase workers' physiological burden, while innovative monitoring technologies enable timely risk control. The regulatory framework, based on international guidelines and national regulations, establishes minimum standards, but their effective application requires adaptation to local geotechnical conditions and continuous validation in practice.

The main contribution of this paper lies in the integration of empirical findings, numerical simulations, and regulatory requirements, providing a more comprehensive assessment of ventilation systems in tunnel construction. This confirms that an interdisciplinary approach - linking geotechnical engineering, engineering design, occupational medicine, and safety management-is the only way to ensure long-term safety, health, and productivity of workers under the complex conditions of underground construction.

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