





Review

From Dust to Disease: A Review of Respirable Coal Mine Dust Lung Deposition and Advances in CFD Modeling

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Abstract: The United States has witnessed a concerning surge in the incidence of diseases like Coal Workers' Pneumoconiosis (CWP), despite numerous efforts aimed at prevention. This study delves into the realm of respiratory health by investigating the deposition of dust particles within the respiratory tract and lungs. By analyzing particles of varying sizes, shapes, velocities, and aerodynamic diameters, we aim to gain a comprehensive understanding of their impact on deposition patterns. This insight could potentially drive changes in dust exposure protocols within mining environments and improve monitoring practices. The interplay of several critical factors, including particle characteristics and an individual's breathing patterns, plays a pivotal role in determining whether particles settle in the lungs or are exhaled. This paper provides a comprehensive literature review on Respirable Coal Mine Dust (RCMD), with a specific focus on examining particle deposition across different regions of the airway system and lungs. Additionally, we explore the utility of Computational Fluid Dynamics (CFD) in simulating particle behavior within the respiratory system. Predicting the precise behavior of dust particles within the respiratory airway poses a significant challenge. However, through numerical simulations, we aspire to enhance our understanding of strategies to mitigate total lung deposition by comprehensively modeling particle interactions within the respiratory system.

Keywords: respirable coal mine dust; lung deposition; coal dust; dust exposure; respiratory diseases; exposure limits; computational fluid dynamics; aerosol; airflow



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1. Introduction

The human body engages with its environment in diverse ways, one of which is the interaction between the lungs and the external environment through the act of breathing. The extensive surface area of the lungs, coupled with an incredibly thin air–blood barrier, exposes this vital organ to particles suspended in the inhaled air. The repercussions of this particle–lung interaction can be detrimental to health when inhaled aerosols contain toxic pollutants. Conversely, when inhaled particles consist of therapeutic aerosolized drugs, this interaction can be beneficial for disease treatment. In both scenarios, accurately estimating the dose and pinpointing deposition sites within the respiratory tract stand as fundamental prerequisites for understanding subsequent biological responses. To comprehend these aspects fully, a grasp of the basic physics governing particle motion and engineering principles is essential [1].

The inhalation of dust particles in underground coal mines poses a series of complications, primarily affecting the small airways in miners' lungs exposed to such environments [2]. These complications collectively fall under the category of Coal Mine Dust Lung

Diseases (CMDLDs). Among the CMDLDs, Coal Workers' Pneumoconiosis (CWP) and silicosis are well-known to those in the mining field. Similar diseases, such as mixed dust pneumoconiosis and dust-related diffuse fibrosis, result from inhaling Respirable Coal Mine Dust (RCMD). Moreover, overexposure to RCMD can lead to a more severe form known as Progressive Massive Fibrosis (PMF). Distinguishing PMF from other CMDLDs lies in the size of the opacities it leaves within the lungs, which can range from small (<1 cm) for CWP to larger (>1 cm) for PMF [3,4].

Miners diagnosed with CMDLDs often report symptoms such as reduced pulmonary function, shortness of breath, coughing, or sputum production. Diagnosis is typically made through radiographic imaging or pulmonary testing, prompted either by the presentation of respiratory symptoms or by a history of coal dust exposure [4]. Radiographs of CWP patients reveal lung scarring, predominantly in the lower lung regions and characterized by small, irregular shapes—distinct from PMF, which manifests larger opacities [5–7]. This presence of lung opacities in lower lung regions is also recognized as Interstitial Lung Disease (ILD) [8]. Understanding the deposition of dust within various regions of the respiratory system gains significance due to the existence of Chronic Obstructive Pulmonary Diseases (COPDs), which are associated with regional dust deposition. Emphysema and chronic bronchitis, the most common forms of COPD, pose substantial risks to coal miners. Further research into deposition patterns may shed light on how different sections of the respiratory system are affected [9].

The deposition of particles within the human respiratory tract is influenced by a combination of biological factors (such as lung morphology and breathing patterns) and physical factors (including fluid dynamics, particle properties, and deposition mechanisms). Current particle deposition models fall into two main categories based on the region of interest within the lung: whole lung models and local scale models. Whole lung models compute particle deposition in individual airways using analytical equations that consider particle deposition efficiencies and specific flow conditions (analytical models). These models require validation through comparison with experimental data from human subjects, and their validation is typically limited to total and regional deposition. However, once the model is validated in some cases available from experiments, this valid model can be used to expand the investigation and evaluate situations that were not examined in the experiment. In contrast, local scale models employ Computational Fluid and Particle Dynamics (CFPD) methods (standard CFD model with particle tracking algorithms) to solve particle transport and deposition equations, providing insights into deposition patterns within specific lung structures [10].

Airflow within the nasal cavities and oral airways exhibit complexity, including possible transitions to turbulent jet-like flow, recirculating flow, Dean's flow, vortical flows, large pressure drops, prevailing secondary flows, and merging streams during exhalation. Assumptions underpinning particle transport and deposition include spherical, non-interacting, monodisperse aerosols deposited upon contact with airway surfaces and each other. Such dilute particle suspensions are typically modeled using the Euler–Lagrange approach for micron-sized particles and the Euler–Euler framework for nanoparticles. Micron-sized particles tend to deposit non-uniformly, leading to high concentrations at specific local sites [8].

This literature review seeks to explore comprehensively the regional deposition of RCMD and the applications of Computational Fluid Dynamics (CFD) models in understanding lung deposition. Given the complexity and breadth of this subject, our objective is to provide an overview of research developments in this domain over time while also offering readers the most recent updates on occupational diseases related to coal dust. The prevalence of dust-related ailments continues to rise, making it crucial to examine innovative approaches, such as the utilization of the Mobile Aerosol Lung Deposition Apparatus (MALDA), which have the potential to revolutionize our understanding of lung deposition and its implications in combating dust-related diseases.

2. Methods of Review

2.1. Literature Search and Study Identification

To identify relevant studies up to September 2022, we conducted a thorough search across electronic databases, including PubMed, Web of Science, Scopus, and Google Scholar. The search terms employed included “RCMD”, “respirable coal mine dust”, “dust exposure”, “respiratory diseases”, “CFD”, “computational fluid dynamics”, “particle lung deposition”, “aerosol”, “airflow”, “validation”, “challenges”, and “benefits”. Additionally, we examined relevant reviews and scrutinized the reference lists of retrieved publications to ensure comprehensive coverage.

2.2. Study Selection and Eligibility Requirements

Following the removal of duplicate records, we assessed the relevance of the identified studies by examining their titles and abstracts. Subsequently, the full texts of potentially relevant studies were evaluated for inclusion based on the following criteria:

- The primary focus of the study must be on RCMD regional lung deposition, CFD modeling in relation to particle lung deposition, or related applications.
- The study should provide insights into the challenges, advantages, or validation methods of CFD models.
- The study must be a peer-reviewed publication in a journal or a conference proceeding.
- The study should be available in the English language.

Studies that did not meet these criteria were excluded, as were papers exclusively addressing Metal and Non-Metal (MNM) mining and conducted outside the scope of this review, which primarily covers the USA with occasional comparisons. Any discrepancies in study selection were resolved through discussion and consensus among the review authors.

2.3. Data Extraction and Synthesis

For the included articles, relevant data were extracted and synthesized. In the context of RCMD and dust lung deposition in coal mining, this synthesis encompasses studies published between 2000 and 2022 that specifically address exposure, inhalation, deposition, retention, and particle flow within the respiratory system in US coal mines. For CFD-related material, the synthesis includes study objectives, CFD modeling methods and assumptions, encountered challenges, benefits of employing CFD models, and validation approaches. These components were used to construct the review’s three main sections: challenges of CFD modeling, advantages of CFD for particle lung deposition, and validation of CFD models.

2.4. Limitations of the Review

Several limitations must be acknowledged in this review:

The review’s analysis is restricted to the literature available until September 2022, thereby excluding any developments, new findings, or emerging perspectives in CFD modeling for particle lung deposition beyond that date.

As a literature review, the representativeness of the selected research significantly influences our analysis. Consequently, the conclusions may be subject to bias based on the methodologies, assumptions, and limitations of the included research. Additionally, unpublished or non-peer-reviewed discoveries may have been missed, introducing potential biases.

While we have explored CFD modeling within the context of particle lung deposition, this review does not encompass all pertinent CFD modeling applications and aspects. Variations may exist in fields where CFD modeling is applied, limiting the applicability and generalizability of the discussed challenges, benefits, and validation methods. Furthermore, the study does not offer an exhaustive examination of specific CFD software, which could be a critical factor in model selection and evaluation.

Finally, it is essential to acknowledge that despite efforts to summarize information regarding CFD model challenges, advantages, and validation in the context of particle lung deposition, there may be additional relevant factors and perspectives not covered in this study. These limitations should be considered when interpreting the reported results.

3. RCMD Inhalation and Lung Deposition

The journey of inhaled dust particles through the respiratory system is crucial to understanding RCMD inhalation and lung deposition. Beginning at the nostrils or mouth, dust particles enter the respiratory airways, encountering various clearance mechanisms. These mechanisms are found in distinct areas of the respiratory system. The nasal cavity (nasopharynx, larynx, and trachea) contains small hairs and mucus that filter out the largest particles (10 to 6 μm). Moving down the respiratory tract, the tracheobronchial (TB) tree (trachea, bronchi, and smaller bronchioles) is equipped with ciliated columnar and goblet cells, which trap particles in the size range of 6 to 3 μm . Finally, in the alveoli region (smaller bronchiole balloons), alveoli macrophage cells play a pivotal role. Upon contact with dust or harmful particles, the macrophage cells engulf and transport particles to the TB region, where expulsion from the respiratory system occurs through coughing or swallowing [11,12]. Lung fluid in this region aids in respiratory processes by moisturizing inhaled air and enhancing macrophage function [13].

Furthermore, research indicates that these clearance mechanisms, particularly in the alveoli region, can be impaired by prolonged dust exposure and macrophage overload. The retention or accumulation of particles in the lungs depends on the rate of dust particle deposition within the lungs and the efficiency of macrophage clearance. The duration of dust particle exposure directly affects the rate and quantity of particle deposition in the lungs. An increase in unidentified particle deposition in the alveoli prompts the recruitment of additional macrophages to enhance the clearance process, emphasizing the importance of understanding these mechanisms for assessing RCMD inhalation and lung deposition in mining environments [14,15].

3.1. Factors Influencing Deposition

Particle physicochemical characteristics (e.g., size, shape, charge), airway physiological parameters (e.g., breathing patterns), and airway geometry collectively influence the deposition of inhaled dust particles [9,16,17].

1. **Particle Size:** Particle size plays a pivotal role in determining where particles deposit in the respiratory system. Particles in the respirable range (10 nm to 10 μm) tend to deposit differently in three distinct regions: the head, TB, and alveoli regions. Smaller particles (<3 μm) and nano-sized particles (<300 nm) have a higher likelihood of depositing in the alveoli region as illustrated in Figure 1 [18].
2. **Aerodynamic Diameter:** The aerodynamic diameter, which relates to particle density and composition, predicts deposition probability in specific respiratory tract regions [19–22].
3. **Particle Shape:** Particle shape affects interactions with respiratory tissue. Angular particles are more likely to deposit in the airways or lungs [23].
4. **Electric Charge:** Coal dust particles carry electric charge after pulverization, with this property varying by particle type. Electric charge can influence the deposition of very small particles (<4 μm) by allowing them to reach deeper respiratory zones [24].

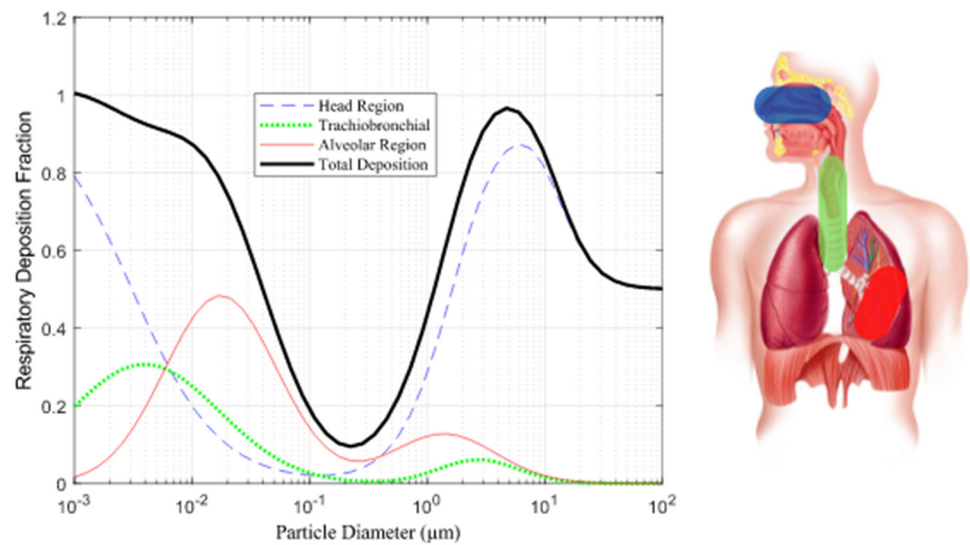


Figure 1. Prediction of deposition in the respiratory tract [24].

3.2. Deposition Mechanisms

Several mechanisms govern dust particle deposition, including inertial impaction, gravitational sedimentation, Brownian diffusion, interception, and turbulent diffusion [9,16]. This paper focuses on the main mechanisms based on particle size:

1. **Inertial Impaction:** Particles travel at a speed that may cause them to collide with airway surfaces due to changes in airflow direction. Particle size, charge, airflow, and airway geometry influence impaction, particularly in the early respiratory system, where larger particles travel.
2. **Gravitational Sedimentation:** Particles gradually settle over time due to gravity, influenced by breath maneuvers, particle aerodynamic diameter, and density. Holding one's breath increases the likelihood of sedimentation, with heavier particles settling faster.
3. **Brownian Diffusion:** Particles of a small enough size experience random trajectories influenced by molecular bombardment, allowing them to follow Brownian motion [Figure 2]. This phenomenon is also known as diffusion [13,14,25].

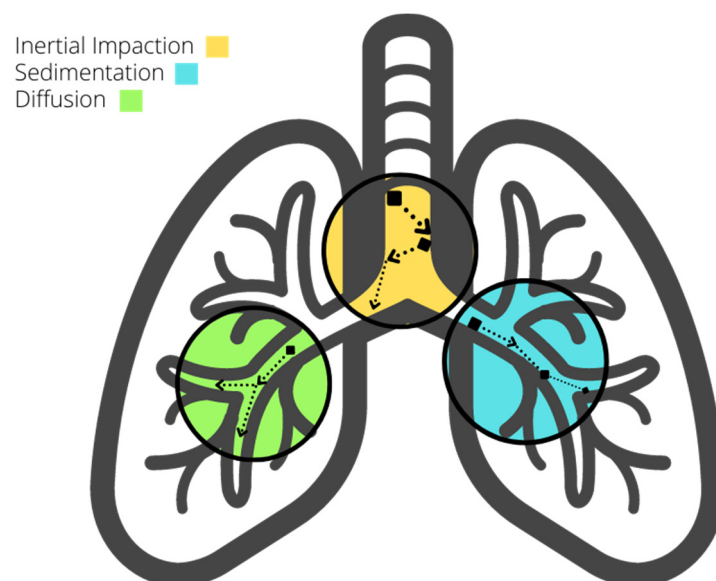


Figure 2. Deposition mechanisms in the respiratory system.

Comprehending these factors and mechanisms in conjunction with fluid dynamics enables us to discern the advantages of particle fragmentation into larger sizes, as such particles possess a greater likelihood of early settlement and extraction from the respiratory system, with the converse being true. In scenarios where fine fragmentation prevails, it necessitates the implementation of comprehensive protective measures.

4. Disease Prevalence, Severity, and Monitoring

As depicted in Figure 3, there has been a notable shift in the prevalence and severity of CMDLDs, including CWP and PMF, between 2000 and 2022. This change is in contrast to the preceding period, which witnessed a decline primarily attributed to the enactment of the Federal Coal Mine Health and Safety Act of 1969—a pivotal measure aimed at safeguarding miners nationwide [24,26,27]. The escalation in CMDLD prevalence and severity is attributed to various facets of mining, encompassing mine type, tenure, size, geographic location, and extended working hours [4,28,29].

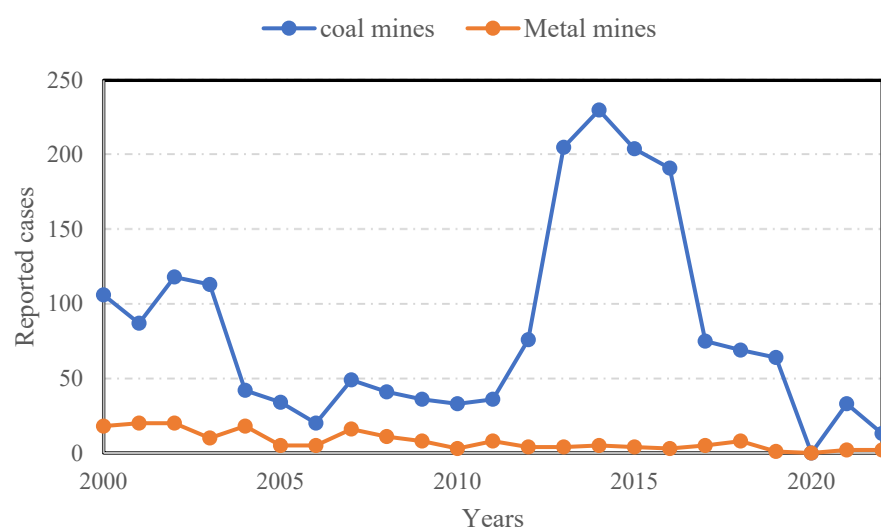


Figure 3. CMDLD reported cases over the years [24].

To address this upward trend, the Mine Safety and Health Administration (MSHA) implemented revised exposure limits in the USA, effective as of August 2016. These limits are set at 1.5 milligrams per cubic meter (mg/m^3) for coal dust (30 CFR §70.100 and §71.100), 0.1 mg/m^3 when quartz is present (30 CFR §71.101), and 0.05 mg/m^3 for crystalline silica (29 CFR §1910.1053). It is important to note that slight variations may exist in other countries [30]. Despite the enhancements made to exposure limits in the United States, the country continues to witness an unacceptably high number of reported cases of CWP.

Comprehensive research conducted across the USA underscores that the prevalence of CWP and its most advanced manifestation, PMF, is notably higher in mines situated in the central Appalachian region. This conclusion is supported by data derived from the federal black lung program and the national surveillance database [31–34].

In 2005, the National Institute for Occupational Safety and Health (NIOSH) investigated the progression and severity of CMDLDs. Their findings revealed that 35% of miners with pneumoconiosis had an advanced form of the disease with a higher rate of progression, while 15% had the most severe form, known as PMF. These patterns prompted NIOSH to enhance its surveillance efforts [29,31].

5. RCMD Sources and Exposure in Coal Mines

Dust sources in mining activities stem from rock-related processes such as blasting, cutting, transportation, and rock dusting [35]. Underground coal miners face greater

risks compared to surface and metal mine workers due to higher dust concentrations in confined underground environments [36]. About 3% of airborne mine dust originates from excavations [37]. From normal operation to wear and tear, mining machinery emits harmful particles with varying chemical compositions [29]. These particles can linger in the air and enter the deepest parts of the human lung or be removed by the body's clearance mechanisms [38].

Approximately 1.7 million U.S. workers, spanning both mining and non-mining sectors, face potential exposure to hazardous dust containing crystalline silica on an annual basis [39]. Research indicates that miners may develop chronic simple silicosis after roughly 20 years of exposure, with some enduring exposure periods as long as 44 years [7,40]. Occupations characterized by high levels of risk encompass roles such as drill operators, roof bolters, and machine operators, among others. Conversely, positions like belt operators and shovel operators entail lower risks [41,42]. Notably, roof bolting alone can account for up to 50% of quartz particles in dust, with 20% falling within the respirable size range ($<10\text{ }\mu\text{m}$) [43,44]. Workers situated in intake and exhaust areas face heightened risks of inhaling fine particles compared to those stationed at the working face [45]. Nevertheless, a discernible distinction that provides enhanced protection to individuals in high-risk positions is currently lacking.

Methods for detecting coal and silica dust concentrations in mining operations encompass time-consuming laboratory techniques such as X-ray Diffraction (XRD) and Scanning Electron Microscopy with Energy Disperse X-ray (SEM-EDX). Meanwhile, field-portable devices such as the Fourier-Transform Infrared (FTIR) and Continuous Personal Dust Monitoring (CPDM) furnish essential data without necessitating laboratory assistance. In the context of both surface and underground coal mines, the responsibility for enforcing permissible exposure limits concerning coal dust and silica predominantly falls upon the mining operator, aided by contemporary monitoring devices such as the CPDM. This instrument yields estimations of dust concentrations at the conclusion of each work shift. Regrettably, it exhibits certain limitations, including bulkiness, noise emissions, and an inability to measure silica concentration [26,39,46]. This approach has demonstrated a relative inefficiency in enabling mine operators to make real-time decisions, as opposed to relying solely on end-of-shift data, while also incurring additional fatigue for the mine operator. Consequently, there is a discernible demand for more advanced equipment capable of enhancing precision. Notably, the aforementioned limitations of the CPDM have prompted research into alternative, more convenient solutions [47,48].

Continued inhalation of coal dust over time impairs respiratory tract clearance mechanisms, reducing their ability to expel particles and causing lung tissue lesions [28,49]. The International Labor Organization (ILO) classifies opacity caused by coal and silica dust inhalation into four categories (0, 1, 2, and 3) with twelve subcategories (0/1, 1/0, 1/1, etc.) [50]. Progression of pulmonary opacity is linked to higher exposure to silica dust, particularly in the mining of thin coal seams, where more host rock must be moved [7,51]. Opacity 1/0+ often advances more rapidly with exposure to quartz dust. Additionally, higher radiologic profusions are associated with ash content in low-rank coal and are influenced by both coal dust and ash content in high-rank coal [21].

6. RCMD Characterization Techniques

RCMD is typically characterized by mass concentration and mass fraction, but factors such as shape, size, and particle composition also influence its hazard potential [24]. SEM-EDX, a commonly employed laboratory technique for dust sample characterization, involves the examination of dust particle surfaces through X-ray spectra generated by the interaction between an electron beam and the particle's surface. However, it is worth noting that, on certain occasions, there is a potential for underestimating coal particles, which may lead to an unnoticed increase in exposure to coal dust due to the mischaracterization of RCMD [52].

In a study analyzing samples collected from a low-seam mine in central Appalachia (collected at the roof bolter, belt drive, and intake location), the results indicated that particles in the roof bolter and belt drive samples were primarily composed of aluminosilicate, with a presence of carbonaceous content in the roof bolter samples. These particles can be associated with coal mineral micro-agglomerates, which, despite being coal, may not always be classified as such by SEM-EDX. This observation becomes evident when comparing SEM-EDX results with Thermogravimetric Analysis (TGA) results, which often reveal reduced coal values and increased rock dust content. This discrepancy may occur when coal particles are coated with rock dust or Diesel Particulate Matter (DPM) [11,51].

7. Computational Fluid Dynamics in Investigating Particle Deposition

In the realm of computational fluid dynamics, numerous attempts have been made to simplify the intricate human respiratory system. These efforts involve focusing on specific respiratory system components or streamlining geometric representations. This section delves into various initiatives within this field.

Within this compiled dataset of references, spanning from 2010 to 2022, a total of 54 references were analyzed for the CFD section. Over the years, the distribution of references has been diverse, with the highest percentage (26.23%) found in 2021. The remaining years each have a percentage of references ranging from 3.28% to 9.84%, illustrating the sustained research interest in this field throughout the past decade. The following bar Chart 1 visually represents the variation in publication years and their corresponding percentages used in the article.

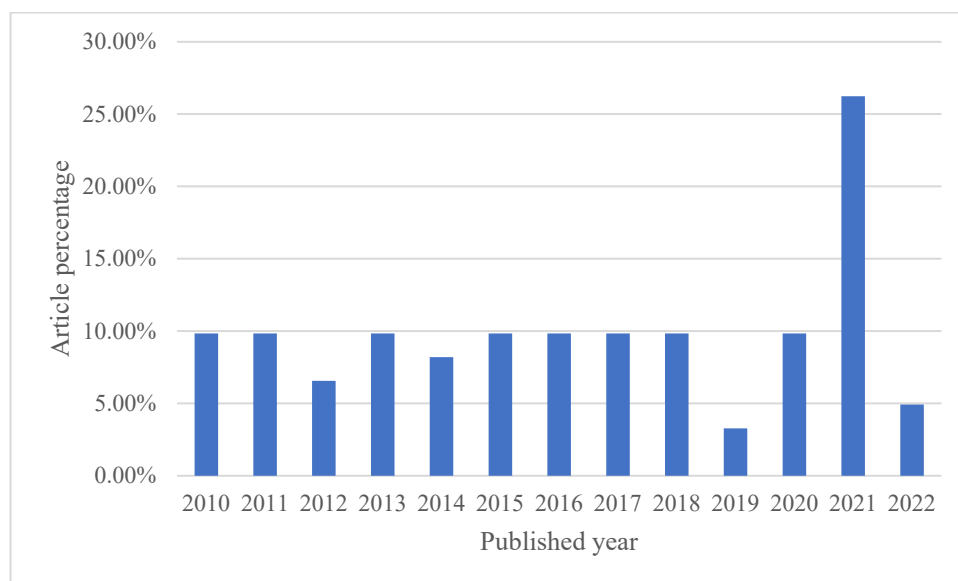


Chart 1. Articles distribution in the CFD section.

7.1. Model Geometry

The computational analysis of the complex geometry of the human lung presents considerable challenges and demands a substantial investment of time. Consequently, research in this field frequently employs varying degrees of simplification, influenced by the specific research objectives.

Basic Models: Some studies employ rudimentary models to explore the transport and deposition of microparticles and nanoparticles (1–50 nm) within the bronchial tree during inhalation [53].

Enhanced Models: In contrast, more sophisticated models, exemplified in Figure 4, are evident in various studies. These models incorporate additional airway generations and offer a more comprehensive representation of lung dynamics [54–57].

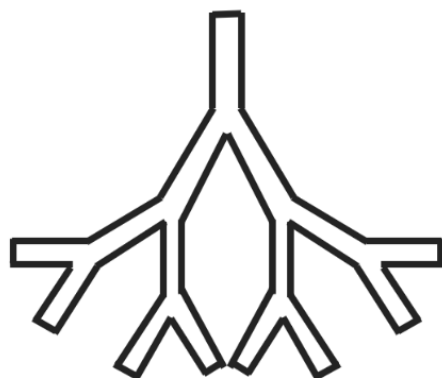


Figure 4. Schematics of an enhanced airway model.

The repercussions of these simplifications were explored and compared to actual lung models with their simplified counterparts, emphasizing the differences in material deposition [58].

Some research endeavors concentrate on specific regions within the respiratory system. For instance, certain studies examine particle deposition within the nasal airway [59,60]. Simultaneously, a distinct study delves into the ramifications of wall roughness on deposition rates within the nasal airway, as depicted in Figure 5 [61].

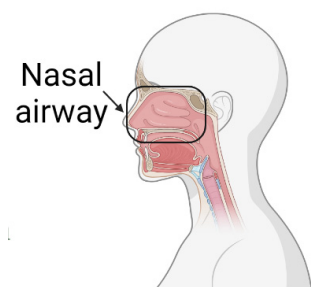


Figure 5. Nasal airway section under investigation.

To attain a comprehensive understanding of flow patterns and particle deposition, several studies expanded their modeling domain within the human upper airway system, as displayed in Figure 6 [62,63].

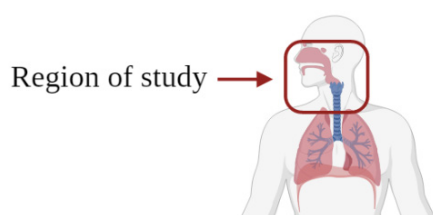


Figure 6. Region of study for [64,65].

Mouth–Throat and Upper Tracheobronchial Models: Research focusing on regions critical for drug delivery, such as the mouth–throat (MT) and upper tracheobronchial (TB) models, is well-documented [64–68]. An innovative Stochastic Individual Path (SIP) modeling approach was introduced to streamline tracheobronchial research [69,70].

Patient-Specific Models: Some studies have opted for models reconstructed from actual patient scans to provide an authentic representation of the respiratory system, as illustrated in Figure 7 [71–81]. The complexity of these realistic models is often dictated by the requisite precision and the scope of the research. Naturally, as these models grow in detail, the computational demands and processing times correspondingly increase.

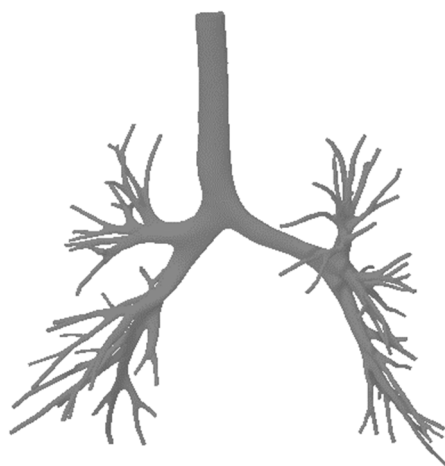


Figure 7. A realistic lung model.

7.2. Computational Analysis

When analyzing the breadth of computational methodologies utilized across different studies, the significant influence of the computational environment and boundary conditions on the accuracy of results becomes evident [54]. Delving into specifics, they harnessed fluent to solve the Navier–Stokes equations, factoring in key elements like drag and gravity that impact particle motion. Their assumptions of steady and incompressible flow resonate with the approaches taken by researchers who defined inlet conditions with a fully developed (parabolic) velocity [82]. In a similar vein, another study anchored their research on Fluent 6.3, focusing on the intricate human upper airway dynamics and incorporating the effects of Brownian motion alongside drag and gravity using the Lagrangian approach [80].

Moreover, the adoption of varied software platforms and techniques, such as Farhadi’s use of Fluent 14.0 and the Eulerian technique, contrasted with the use of ANSYS’ CFX, Version 15, by others, signifies the versatility researchers find necessary in modeling the intricate behaviors within the lungs [62,72]. Notably, one study introduced a distinctive perspective by integrating lung motion modeling into their OPENFOAM CFD simulations [83]. Concurrently, utilizing ANSYS FLUENT 15, another study cast a spotlight on particle–fluid interactions, ensuring that steady-state, incompressible Newtonian flow was aptly represented [84]. This spectrum of methodologies, culminating with the employment of the Low Reynolds Number (LRN) k turbulence model by another group, offers a profound reflection of the depth and diversity of approaches in the realm of computational analysis of the respiratory systems [85].

7.3. Difficulties of CFD Modeling

The realm of CFD modeling, especially when simulating intricate airflow patterns and pollutant dispersion in real environments, is fraught with challenges [84]. One of the primary hurdles arises from the quality and representativeness of input parameters. For instance, boundary conditions, turbulence models, and material properties play pivotal roles in ensuring the accuracy of the simulations. Yet, acquiring these with high precision remains a formidable task [54,55]. Compounding this issue, CFD simulations often resort to simplifications, either by assuming steady-state conditions or overlooking minute turbulence effects, which consequently sews seeds of uncertainty in the results [58,66,67,72,77,86]. The dynamic nature of airflow, characterized by transient behaviors like turbulent flows skirting obstacles or mutable ventilation conditions, adds another layer of complexity [56,59,62,67,76,79,80,87]. Even choices made at a technical level—such as the adoption of numerical schemes, meshing techniques, or CFD software—bear consequences on the accuracy and reliability of findings [57,60,64,65,72,74]. Nevertheless, a judicious approach to CFD modeling, which includes a meticulous evaluation of its inher-

ent constraints and uncertainties, can act as a beacon to steer clear of biases, ultimately refining the validity of results [81].

7.4. Advantages of CFD for Particle Lung Deposition

While CFD modeling poses certain challenges, its benefits, especially in studying airflow patterns and particle dispersion within the lung, are indispensable [54]. A paramount advantage of CFD is its ability to accurately simulate intricate and evolving airflow patterns within the human respiratory system [57,70,73,83,84,86,87]. Conducting such detailed simulations through experimental methods could be either practically challenging or ethically questionable. This capability of CFD provides unparalleled insights into the trajectory and settling of pollutants within the lung's airways [59,61,62,66,71,72].

Furthermore, CFD provides a versatile platform for researchers, allowing them to make modifications to design parameters and simulate varied scenarios, such as changes in ventilation or structural layouts [55,64,68]. This adaptability is pivotal in evaluating the efficiency of various respiratory interventions and understanding the effectiveness of diverse control measures. In a real-world context, CFD modeling is invaluable for decision-makers. It can pinpoint areas of high particle exposure, offer evaluations of different treatment strategies, and project their outcomes [15,63,67,74,76,78,79].

Collectively, these advantages underscore the immense potential of CFD in delivering a comprehensive, contextual, and practical understanding of particle deposition dynamics within the respiratory system [54,56,60,62,75,80,82].

7.5. CFD Model Validation

From the reviewed literature, it is apparent that while the significance of CFD model validation is well acknowledged, the methods and metrics used for validation vary across studies [54,55,69,84].

Several papers have emphasized the importance of comparing CFD outcomes with experimental or real-world data to ascertain model accuracy [61,62,76,79,82]. For instance, some studies utilized empirical field observations to identify discrepancies in CFD predictions, ensuring rectification and refined results [63,64,73,78,85,87].

Furthermore, the implications of these validations are multifaceted. They not only enhance the credibility of research conclusions [57,58,70,75] but also solidify the basis for interpreting CFD-based findings in real-world scenarios [54,56,63,70]. The process of validation, as highlighted by several sources, aids in unmasking biases and uncertainties, ensuring a comprehensive understanding of the CFD model's applicability and limitations [53,59,68,88].

8. Experimental Studies on Particle Deposition Investigations

Describing an ideal experimental setting for particle deposition investigations is challenging due to various influencing factors, such as the aerosol type, particle detector, choice of breathing pattern, and more [88]. Nonetheless, this section aims to present a comprehensive overview of the diverse efforts made in experimental studies concerning partial lung deposition.

Understanding the precise particulate dose deposited within the human respiratory tract, as measured in terms of number, surface area, and mass, constitutes a crucial element in comprehending the health implications linked to diesel particulate emissions [89]. As illustrated in Figure 8, this process entails volunteers inhaling particle-laden air via a unidirectional valve, collecting their exhaled air in a reservoir, and employing a particle sizer to quantify differences in particle size between their inhaled and exhaled air. Notably, this particular experiment involved the participation of ten healthy volunteers. In a parallel study, analogous equipment was utilized to characterize aerosols emanating from eight distinct e-cigarettes, each differing in nicotine content and flavor [90]. Furthermore, the investigation into experimental particle deposition necessitated the utilization of three distinct mouth-throat models [64].

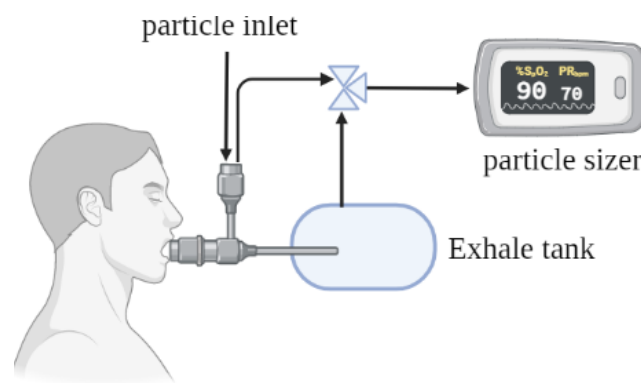


Figure 8. Schematic diagram of the experimental setup used by [87].

An *in vitro* experiment aimed at investigating deposition in the inhaler, mouth, throat, and tracheobronchial upper TB airways was conducted. This experiment employed a three-way solenoid valve to generate square wave inhalations at flow rates of 37 and 75 L/min for a duration of four seconds while simultaneously maintaining continuous airflow at a constant inhalation flow rate of 30 L/min [91]. In a separate study, participants adhered to a predetermined schedule involving normal and deep tidal breathing patterns [92]. To quantify particle numbers, a condensation nuclei counter was utilized, and their size distribution was monitored using a laser spectrometer with high time resolution. Furthermore, this investigation explored the correlation between body plethysmography measurements of pulmonary function and the physical properties of inhaled aerosols, encompassing variations in particle emission both within and between subjects.

Instruments such as the Aerodynamic Particle Sizer (APS) and Droplet Deposition Analysis (DDA) are commonly employed for the measurement of aerosol size distribution within wind tunnels, akin to the one depicted in Figure 9. This particular wind tunnel design is specifically tailored for use in particle deposition research [93,94].

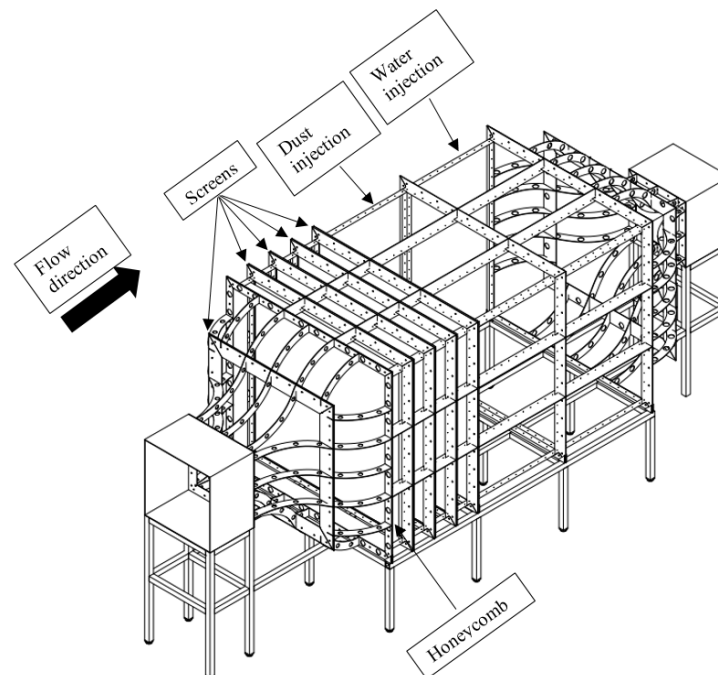


Figure 9. Schematic of the wind tunnel for particle deposition research [94].

The assessment of oscillatory flow velocity in computed tomography (CT)-scanned extra-thoracic airway (ETA) was carried out using the particle image velocimetry (PIV)

method in a study [94]. To address transparency issues in their model, optical index matching was employed [81].

The direction of deposited carbon fibers and particle deposition fractions was examined using a lung model featuring a single horizontal bifurcation under various steady breathing conditions [95]. Micrographs were employed to determine the orientation of the deposited fibers, as shown in Figure 10.

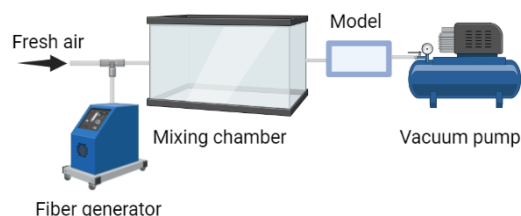


Figure 10. Schematic diagram of the experimental setup [20].

Researchers developed a specialized MALDA to assess the pulmonary deposition of ultrafine 3D printing particles. The MALDA comprises replicas of various human airway sections, including the mouth, throat, trachea, and the 11th bifurcation generation of bronchiolar airways. Numerous pulmonary deposition studies were conducted in the laboratory using the MALDA in conjunction with a desktop 3D printer to measure the deposition of ultrafine 3D printing particles in distinct lung generations [95]. Figure 11 provides an illustration of this setup.

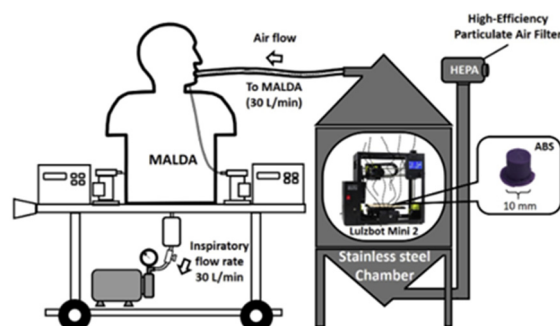


Figure 11. The experimental set-up of the ultrafine 3D printing particle deposition study using MALDA [96].

9. Discussion

The literature extensively discusses the recent surge in cases of CMDLD and its potential correlation with evolving mining practices. This proposition suggests that miners may have encountered varying quantities and characteristics of the same particulate matter due to changes and advancements in mining technologies. As the mining industry evolves, new technologies are integrated to enhance extraction efficiency, which can influence the size and nature of particles miners are exposed to. Several aspects of mining operations have undergone modifications, potentially leading to increased exposure levels, particularly driven by the exploration of thin coal mines in response to demand pressures.

However, it is essential to emphasize that particle size remains a crucial factor in determining regional deposition within the respiratory tract and lungs. The majority of particles posing the highest health risks to miners fall within the fine to very fine category, with a size of less than $3\ \mu\text{m}$. These small particles can penetrate the alveoli region of the respiratory system, making them particularly hazardous. Therefore, understanding particle deposition mechanisms and developing strategies to prevent it in these critical anatomical regions is of utmost importance.

Furthermore, the advancement of CFD holds promise for more accurate assessments of particle deposition within the lung. Still, the choice of an appropriate CFD model requires careful consideration due to its significant influence on computational time. The size of the model directly affects solver time estimates for flow characterization within the lung. Researchers have explored various approaches, some focusing on specific lung regions, while others use mathematically simplified models to reduce computational demands. Additionally, the accuracy of the computational solver depends on thoughtful choices of boundary conditions and turbulence models.

It is worth noting that, despite the availability of CFD tools, experimental validation remains a crucial aspect of research. Validation is necessary to confirm the reliability of CFD solutions before engaging in broader computational investigations. While there is no one-size-fits-all validation setup, its specifics should be tailored to the chosen CFD model and associated boundary conditions.

In summary, recommended action for future studies is listed as follows:

1. Prioritize quantifying the impact of modern mining technologies on particulate attributes and consequent exposure.
2. Collaborative endeavors can work towards establishing a comprehensive database delineating particle deposition mechanisms across varying sizes.
3. A consortium of CFD experts can be envisioned to curate guidelines for model selection, ensuring both computational efficiency and result accuracy.
4. Standardization initiatives should be championed to foster a universally accepted CFD validation protocol.

This discussion highlights the critical importance of thorough model validation in ensuring the precision and reliability of CFD simulations. Proper validation substantiates CFD models based on robust scientific principles, ensuring their accuracy in reproducing real-world phenomena. Neglecting model validation can lead to erroneous predictions, potentially resulting in ill-informed decisions or actions based on flawed simulations.

10. Conclusions

The escalating incidence of confirmed CMDLDs is a persistent concern warranting a comprehensive investigation. This research has illuminated the extensive body of work dedicated to understanding the exposure, deposition, and clearance mechanisms of hazardous dust particles responsible for CMDLDs. Despite efforts within mining operations to mitigate coal dust exposure, the rise in miners afflicted with lung damage remains puzzling. Existing literature suggests a connection between CMDLD cases and evolving mining practices, but the precise causal factors behind this trend remain unclear.

Particle size emerges as a critical determinant when examining regional deposition within the respiratory tract and lungs. The majority of hazardous particles fall within the fine to very fine range, measuring less than 3 μm , and are capable of penetrating the alveoli region. Therefore, prioritizing particle deposition simulations is crucial to unraveling the complexities of particle transport within the deepest recesses of the respiratory system and exploring strategies for mitigation.

Furthermore, the advancement of CFD holds promise for more accurate assessments of lung particle deposition. However, choosing an appropriate CFD model is crucial, as it affects computational time. Various approaches have been explored, but the accuracy of the computational solver depends on judicious choices of boundary conditions and turbulence models.

It is essential to emphasize that, despite the availability of CFD tools, experimental validation remains indispensable. Validation ensures the reliability of CFD solutions and should be tailored to the chosen model and boundary conditions.

In conclusion, this review underscores the critical significance of thorough model validation to ensure the precision and reliability of CFD simulations. Proper validation substantiates CFD models based on robust scientific principles, ensuring their faithfulness

in reproducing real-world phenomena. Neglecting model validation can lead to erroneous predictions, potentially resulting in ill-informed decisions based on flawed simulations.

Specifically, this study highlights the implications of using validated versus invalidated CFD models. It demonstrates that validated CFD models can offer insights into complex flow patterns and particle dispersion while underscoring the risks of relying on inadequately validated models, including potential errors and uncertainties. To maintain the integrity of findings and mitigate the risks associated with invalidated models, researchers and practitioners must diligently assess the validity of CFD models in their investigations.

Future research in CFD modeling should focus on developing standardized validation techniques, exploring novel CFD model applications, and addressing emerging challenges and opportunities. Establishing robust validation practices and reducing uncertainties associated with CFD modeling demand further investigation. Continued research and development in this field will undoubtedly enhance the precision and reliability of CFD modeling and its practical applications.

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