Modeling Approaches for Assessing the Impact of Air Pollution on Human Health in Serbia

Aleksandra Vulović
Faculty of Engineering University of Kragujevac
Kagujevac, Serbia
aleksandra.vulovic@kg.ac.rs

Petar Stanojević
Faculty of Security Studies University of Belgrade
Belgrade, Serbia
petstano45@gmail.com

***Abstract*— Air pollution has emerged as one of the most significant environmental issues in recent years, both globally and in Serbia. The high levels of pollutants in the air have been strongly linked to various adverse health outcomes, including increased mortality rates. One of the key factors in addressing this issue is the ability to assess and predict pollutant concentrations, especially when they exceed permissible limits for extended periods. These elevated concentrations can cause a range of health problems, particularly related to the respiratory system. This paper presents modeling approaches used to assess air pollution and its impact on human health. By utilizing different models and methods, we can simulate the emission, dispersion, and transport of pollutants. These models also help to evaluate the health risks associated with specific pollutants by estimating pollutant deposition in the human respiratory system. This study provides an overview of the modeling process in understanding air pollution patterns and their correlation with public health. The results highlight the importance of air quality models in identifying areas with elevated pollution levels and forecasting pollutant behavior under varying meteorological conditions. The insights gained from such research can inform policy decisions and contribute to the development of mitigation strategies aimed at reducing the environmental and health impacts of air pollution in Serbia.**

Keywords—air pollution, Gaussian model, Computer fluid dynamics, modeling

I. INTRODUCTION

Air pollution has been a persistent issue throughout human history. Over time, the sources of air pollution evolved, expanding from fire to agriculture, and later to industrial processes and the widespread use of fossil fuels [1].

Air pollution is a major global concern, ranked as the fourth leading risk factor for death in 2019, according to global health data [2]. However, air pollution is now the second leading risk factor for death globally, as it was responsible for approximately 8.1 million deaths worldwide in 2021. This marks a rise in its impact, surpassing even tobacco and poor diet as causes of death [3]. The health effects of air pollution, particularly exposure to fine particulate matter (PM2.5), include increased risks of cardiovascular diseases, respiratory conditions like chronic obstructive pulmonary disease (COPD), and various cancers [4-6].

Modern environmental challenges include increasing levels of pollutants released into the atmosphere from industrial chimneys, power plants, and transportation systems. Of particular concern is the dispersion of toxic gases not only from high emission sources but also from low and ground-level sources, especially under varying meteorological conditions. Such conditions are relevant both during accidental releases, such as pipeline failures, and in scenarios involving deliberate releases, such as the use of chemical agents in warfare or hazardous industrial applications.

Air pollutants, of natural or anthropogenic origin, are constantly present in the air. A hundred to a thousand different pollutants can be found in the air at any given time. Natural sources of particulate matter (PM) include dust, created by winds, fires and volcanoes, plant pollen, plants, fungi... Anthropogenic sources of PM are usually classified as mobile (cars, trucks, planes, ships, trains, construction and agricultural equipment) or stationary (power plants, factories, mines, farms, dairies and waste disposal sites).

What we consider clean air can contain tens of thousands of particles per liter and for most people will not have any negative health effect. The presence of pollutants in the air is measured by the concentration, which can be below or above the limit values. Air quality is determined based on these limit values. The presence of pollutants in concentrations above the limit values can lead to certain health problems. Meteorological factors such as wind direction, wind speed, and atmospheric stability play critical roles in the dispersion and concentration of pollutants. Understanding these meteorological factors is key to improving models that predict pollutant behavior, helping policymakers design better strategies for monitoring and mitigating air pollution risks [7].

The aim of this paper is to compare various modeling approaches for assessing the impact of air pollution on human health in Serbia. This paper aims to support the development of more accurate tools for monitoring and mitigating the adverse health effects of air pollution in Serbia, through analysis of pollutant dispersion, meteorological factors, and population health data.

II. AIR POLLUTION MODELING

Pollution measurements at control points determine the concentration of pollutants at a specific location and time point. Based on the obtained data, it is not possible to conclude what concentrations will be in other locations, or how pollutant concentrations will change in the future. In order to assess air pollution at different locations or time points, air dispersion models are used. These models can help to estimate the concentration of pollutants emitted from various sources of pollution, such as industrial facilities and regional public transport.

The goal of pollutant dispersion modeling is to determine the concentration of the polluting substance at certain location. The models, which describe the dispersion of pollutants, are based on knowledge of chemical, physical and dynamic processes in the atmosphere [8]. The advantage that these models have is the ability to predict the concentration of the pollutant at any time and at any point, based on the appropriate input parameters. To successfully analyze pollutant dispersion, it is necessary to know the following data [9]:

- meteorological conditions - wind speed, wind direction, stability class, temperature, and mixing height;
- emission parameters - source location, source height, chimney diameter, gas outlet velocity, gas outlet temperature, and emission rate;
- topography of the terrain and building parameters - location, height, and width;
- chemical processes, if applicable.

When modeling, it is very important to take into account the duration of chemical reactions, as well as the distance to which particles can be transported. It is very important to know whether the particles have a short lifetime (minutes or hours) or a long lifetime (hours, days). In the case of short-lived particles, their range is short, so the effects will be noticeable only at the local level. In the case of particles with a longer lifetime, the range will be greater, so different models will be used, compared to particles with a shorter lifetime.

Air pollution models are generally divided into three categories [10]:

- Deterministic models: These models employ numerical methods to solve partial differential equations that represent atmospheric dispersion processes. To implement these models, an emissions inventory is required along with independent variables, often meteorological in nature. Deterministic models are particularly useful for long-term planning, as they provide detailed insights into how pollutants disperse over time and space.
- Statistical models: These models estimate air pollutant concentrations by establishing empirical relationships between meteorological factors and other relevant parameters. While they are not as precise as deterministic models, they are highly effective for short-term concentration forecasting due to their low computational demands. Statistical models can also be integrated with deterministic models to account for background concentrations, providing a hybrid approach to air quality assessment.
- Physical models: These models replicate real-world atmospheric processes at a reduced scale in a controlled laboratory environment. When field measurements or detailed deterministic simulations become costly, physical modeling, such as using wind tunnels or water channels, offers a more feasible alternative. Physical models allow for easy manipulation of variables like flow rates and geometry, making them ideal for investigating specific atmospheric conditions, especially when high accuracy is required in studying small-scale processes.

Deterministic models include the Lagrangian, Euler and Gaussian models [11]. They provide analytical solutions to the advective diffusion equation, which is the basic equation describing the transport of pollutants through the atmosphere. The Gaussian method is the simplest method that observes the instantaneous release of pollutants from a point source. It is used for a local dispersion, for the range up to 100 km. For modeling the regional dispersion, the Euler or Lagrange model are used (for a range of up to 1000 km). Euler's model is based on the idea of a fixed reference point through which air flows, while Langrange's model is based on a reference point, which moves downwind.

The pollutant dispersion models consist of four elements, presented in Figure 1.

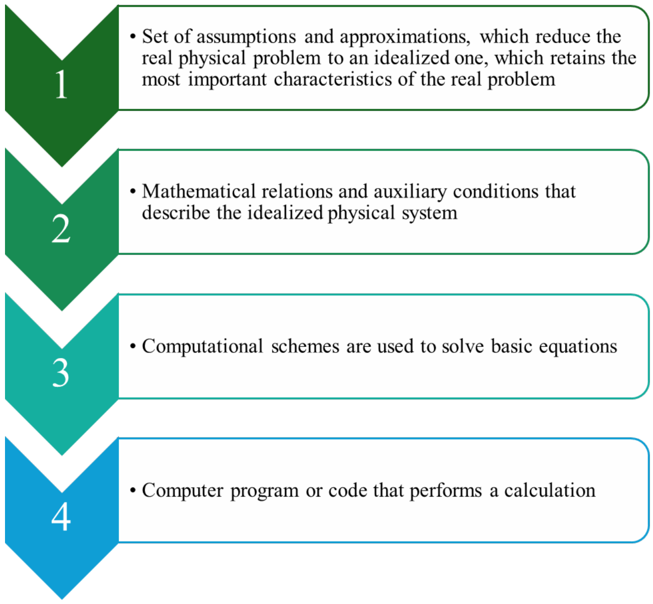

Fig. 1. Elements of pollutant dispersion models

III. Gaussian Model

Regardless of the importance that Lagrangian and Euler models have for analyzing air pollution, a simpler Gaussian model is still widely used as it is accepted by regulatory agencies [12].

At the base of that model lies the expression for the distribution of pollutants, which is obtained from the analytical solution for the dispersion of pollutants, when the wind speed u and the turbulent diffusion coefficients k_y and k_z are constant. The distribution of pollutants from a continuous point source, without the influence of the earth's surface and with an average wind speed, is:

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y(x)\sigma_z(x)} exp\left(-\frac{y^2}{2\sigma_y^2(x)} - \frac{z^2}{2\sigma_z^2(x)}\right) \quad (1)$$

Where $\sigma_y = \sqrt{\frac{2k_y x}{u}}$, $\sigma_z = \sqrt{\frac{2k_z x}{u}}$ are dispersions of pollutants along the corresponding coordinate axes. To calculate the concentration of pollutants, it is necessary to determine the values of the parameters σ_y and σ_z as a function of the distance from the source along the wind direction (as a rule along the x axis) and as a function of the stability of the atmosphere. There are several ways to estimate the value of these parameters, but there is no universal approach for their determination. Also, appropriate classification systems of atmospheric stability are used according to the weather conditions for which the calculations are made.

There are a number of tools that are used to assess air pollution. One of the commonly used is ADMS 6 which is used to assess industrial installations using Gaussian plume air dispersion model. The steps for using ADMS 6 are presented in Figure 2.

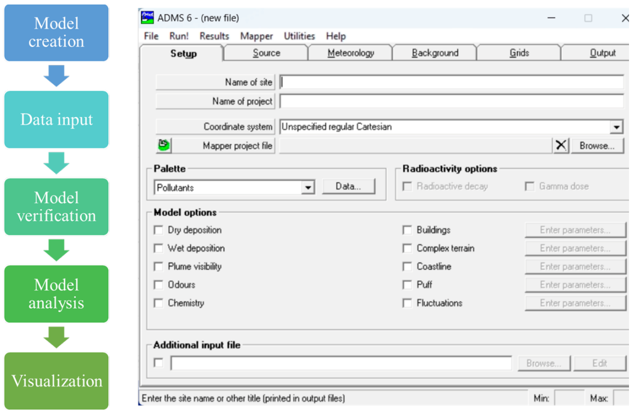

Fig. 2. Steps for analysis using ADMS 6 tool

All data that needs to be input in order to analyze a problems can be divided into following groups:

- Setup where general information about site and model options are defined
- Source where information about source location, emission, dimensions and release conditions are defined
- Meteorology where information regarding site and meteorological data are added
- Background where information about concentration data needs to be defined
- Grids where grid or specific point location for output are defined and
- Output where sources that need to be included in the calculation are defined.

Tools such as ADMS 6 are useful for the analysis of pollution transport as the obtained results can be used as one of the parameters, when assessing human health risks. These tools, can help us determine areas with increased concentrations of pollution, during different weather conditions. Also, these results are useful for analysis of effect that air pollution has on human health using numerical models, such as lower respiratory tract model that will be presented in the next segment of this paper.

IV. NUMERICAL MODELS

Mathematical problems described by partial differential equations (PDEs) are very present in science and engineering. Solving PDEs with numerical methods is affected by many aspects, such as the dimensionality and geometry of the independent variables, nonlinearities in the system, sensitivity to boundary conditions. The technological progress of the previous decades made it possible to create realistic 3D models of the respiratory tract. These models greatly assist in the assessment of health risks. The goal of geometry reconstruction is to create a realistic anatomical 3D geometry, based on the patient's 2D scans. The development of the model starts with the segmentation of the lower respiratory tract. Information about used scans are presented in Table 1.

TABLE I. SCAN INFORMATION

Number of 2D scans	***Resolution***	***Image thickness***	***Spacing between scans***
569	512 x 512 pixels	1.250 mm	0.625 mm

Segmentation of the lower respiratory tract model was done using automatic and manual segmentation. After extracting the contours of the lower respiratory tract, the 3D model is calculated. The end result of the segmentation is a model whose surface mesh follows the anatomical shape of the lower respiratory tract (Figure 3). The lower respiratory tract was analyzed using the finite element method software - PAK-F. PAK-F is a tool developed at the Faculty of Engineering, University of Kragujevac, which enables the analysis of fluid mechanics with heat transfer. The program is based on the application of the finite element method and the basic equations of viscous fluid flow, such as the Navier-Stokes equation. The presented model had 123304 3D linear elements with 4 nodes.

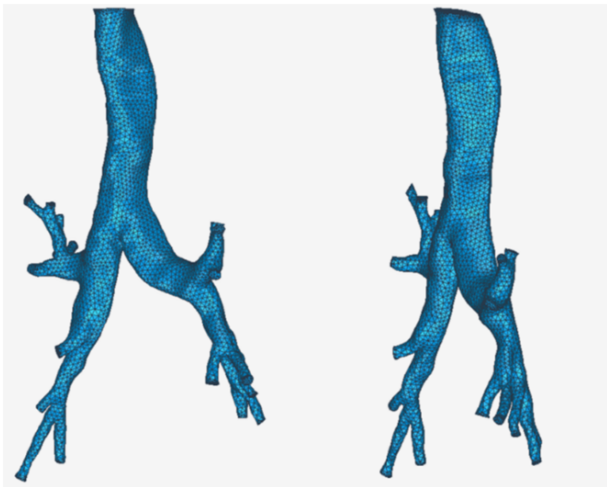

Fig. 3. Lower respiratory tract model

The characteristics of air flow in the lower respiratory tract are very complex, due to the anatomy. One of the main problems when analyzing the lower respiratory tract is that the boundary conditions are not fully defined, and as a result different approaches are used to analyze it [13-15]. When defining the boundary conditions, very often a constant zero pressure is defined at the exits of the model, because it has been shown that this condition is accurate enough to calculate the air flow characteristics [16]. Although airway stretching occurs during breathing, this process is rarely modeled [17]. Walls are generally considered to be rigid. This, of course, has a great influence on the obtained results of the air flow characteristics, but it also has an effect on the particle deposition process. For the analysis of the lower respiratory tract model, the airflow was assumed to be laminar. Also, stationary air flow was analyzed.

The characteristics of air flow in the lower respiratory tract were calculated for the inhalation phase, at the moment when the velocity is the highest. The distribution of air velocity in the lower respiratory tract, is shown in Figure 4. The maximum value was 15 m/s, and it was located at the end of the third generation branch. Based on this, we can conclude that the largest deposition of particles would be in the places of the highest velocity.

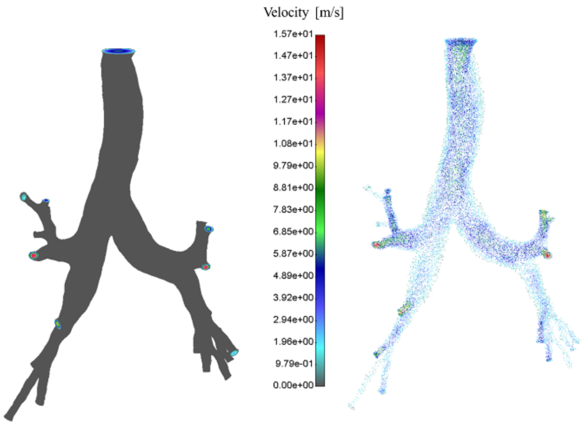

Fig. 4. Velocity distribution in the lower respiratory tract

The shear stress distributions are presented in Figure 5.

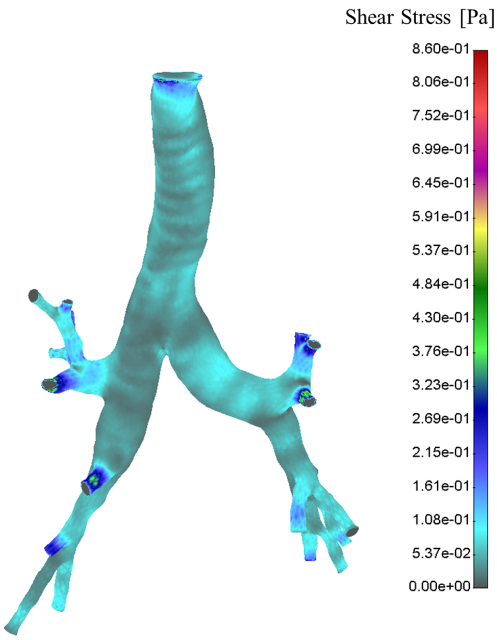

Fig. 5. Shear stress distributions in the lower respiratory tract

The maximum shear stress value was 0.86 Pa. As for the velocity distribution, the location of the maximum value was in the same location as where maximum shear stress was calculated.

Particles deposited in the respiratory system can cause health problems, as a result of inflammation of the tissue in which the particles are deposited. Inflammation of the airways leads to increased sensitivity of the airways to irritants, such as particulate pollutants. Also, inflammation leads to damage to the cells of the respiratory tract and thus threatens the integrity of the respiratory system. Inhalation of particulate pollutants affects the development of diseases of the respiratory system, due to the emergence of new inflammatory processes in the tissue of the respiratory system. Frequent exposure to particulate pollutants leads to chronic tissue inflammation, which reduces the effectiveness of our body's defense mechanism and can lead to the progression of inflammatory respiratory diseases, including asthma.

V. Conclusion

The issue of air pollution is one of the most pressing environmental challenges of today, as the air we breathe is contaminated by particles and vapors from both natural and anthropogenic sources. These pollutants can travel great distances, often contaminating water and soil far from their origin. To ensure that air quality in the future meets established standards, it is essential to predict how pollutant concentrations will change over time. Air quality models, which use input data on emissions, topography, and meteorological conditions, are crucial tools in this process.

This paper has given overview of different approaches used to assess pollution transport and capture the relationship between air pollution and human health. These types of models contribute to a deeper understanding of pollutant behavior and play a critical role in both industrial and regulatory contexts. The paper highlights how air pollution models can describe the origins of pollution, analyze cause-and-effect relationships between emissions and environmental factors, and propose measures to mitigate pollution’s adverse effects.

The ability of numerical simulations to model a wide range of pollution sources and conditions provides an opportunity to enhance our understanding of particulate matter transport and deposition. This, in turn, allows for the development of more effective strategies to control pollution sources, helping to minimize their environmental impact. The results can be used to improve numerical simulations of particle movement in the respiratory system, offering valuable information on how pollution exposure affects human health based on proximity to pollution sources. By determining how pollutants are distributed in the respiratory tract, these findings can be applied to improve health outcomes and inform the design of industrial facilities to reduce their harmful effects.

Acknowledgment

This paper has been published as a part of the project that is financed by the Science Fund of the Republic of Serbia within its program “IDEAS” — Management of New Security Risks — Research and Simulation Development, NEWSIMR&D.

References

[1] S. Mosley, “Environmental history of air pollution and protection,” The basic environmental history. Cham: Springer International Publishing, 2014, pp. 143-169.

[2] A. Juginović, M. Vuković, I. Aranza, and V. Biloš, "Health impacts of air pollution exposure from 1990 to 2019 in 43 European countries," Scientific Reports, vol. 11, no. 1, 22516, 2021.

[3] "State of Global Air 2024." Health Effects Institute, Special Report. Boston, MA:Health Effects Institute, 2024.

[4] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, and E. Bezirtzoglou, "Environmental and health impacts of air pollution: a review," Frontiers in public health, 8, 14, 2020.

[5] P. Thangavel, D. Park, and Y-C Lee, "Recent insights into particulate matter (PM2. 5)-mediated toxicity in humans: an overview," International journal of environmental research and public health, vol. 19, no. 12, 7511, 2022.

[6] J. T. Pryor, L. O. Cowley, and S. E. Simonds, "The physiological effects of air pollution: particulate matter, physiology and disease," Frontiers in Public Health, vol. 10, 882569, 2022.

[7] Y. Liu, Y. Zhou, and J. Lu. "Exploring the relationship between air pollution and meteorological conditions in China under environmental governance," Scientific reports, vol. 10, no. 1, 14518, 2020.

[8] N. S. Holmes, and L. Morawska, "A review of dispersion modelling and its application to the dispersion of particles: An overview of different dispersion models available," Atmospheric environment, vol. 40, no. 30, pp. 5902-5928, 2006.

[9] J. B. Johnson, "An Introduction to Atmospheric Pollutant Dispersion Modelling," Environmental Sciences Proceedings, vol. 19, no. 1, 18, 2022.

[10] S. Srivastava, and I. N. Sinha, "Classification of air pollution dispersion models: a critical review," In Proceedings of National Seminar on Environmental Engineering with special emphasis on Mining Environment, 2004.

[11] P. Goyal, and A. Kumar, "Mathematical modeling of air pollutants: an application to Indian urban city," Air Quality-Models and Applications, InTechAir, 2011.

[12] H. Snoun, M. Krichen, and H. Chérif, "A comprehensive review of Gaussian atmospheric dispersion models: current usage and future perspectives," Euro-Mediterranean Journal for Environmental Integration, vol. 8, no. 1, pp. 219-242, 2023.

[13] T. Gemci, V. Ponyavin, Y. Chen, H. Chen, and R. Collins, "Computational model of airflow in upper 17 generations of human respiratory tract," Journal of Biomechanics, vol. 41, no. 9, pp. 2047-2054, 2008

[14] P. Longest, P. Worth, G. Tian, R. L. Walenga, and M. Hindle, "Comparing MDI and DPI aerosol deposition using in vitro experiments and a new stochastic individual path (SIP) model of the conducting airways," Pharmaceutical research, vol. 29, pp. 1670-1688, 2012.

[15] M. S. Islam, S. C. Saha, and P. M. Young, "Aerosol particle transport and deposition in a CT-based lung airway for helium-oxygen mixture," In Proceedings of the 21st Australasian Fluid Mechanics Conference, AFMC 2018. 2018

[16] D. K. Walters, and W. H. Luke, "A method for three-dimensional Navier–Stokes simulations of large-scale regions of the human lung airway," J. Fluids Eng, vol. 132, no. 5, 051101, 2010.

[17] R. Mead-Hunter, A. King, A. N. Larcombe, and B. J. Mullins, "The influence of moving walls on respiratory aerosol deposition modelling," Journal of Aerosol Science, vol. 64, pp. 48-59, 2013.