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Computational Fluid Dynamics models to estimate pedestrian exposure to traffic related air pollution: A review†

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Abstract: In recent years, Computational Fluid Dynamics (CFD) has become a method widely used by the scientific community to study the dispersion of air pollutants in urban areas. This article seeks to analyze the effectiveness of computational fluid dynamics models and their validation methods used to estimate pedestrian exposure to Traffic Related Air Pollutants. This work proposes an exploratory methodology based on a literary review. A total of 28 articles were selected and analyzed from 455 literature published in the Scopus database between 2018-2023. The results show the effects of meteorological variables such as wind speed and wind direction on the dispersion of pollutants, especially that at higher wind speeds, they tend to disperse more quickly, which reduces the concentration of these hazards pollutants at the level of the pedestrian respiratory zone. Computational fluid dynamics is an advantageous tool; however, it is necessary to complement, with other models that consider the physical activity of people and thus evaluate more specifically the effect of inhaled pollutants on the entire respiratory system of pedestrians.

Keywords: CFD, air pollution, traffic, pedestrian exposure

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1. Introduction

A very important aspect to consider with computational fluid dynamics applied to the dispersion of pollutants is turbulence modeling, since, in urban areas, there is the presence of physical obstacles that affect the flow and therefore behavior of pollutants, which makes the selection of a good turbulence model essential for the reliability of the results obtained, In addition, this selection can impact the time and computational requirement that is available.

Special attention should also be taken with the issue of validation of data obtained from the computational model, validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

2. Methodology

This research was based on a literature review of models that use computational fluid dynamics to estimate pedestrian exposure to air pollutants from vehicular traffic. The search was conducted on research published in the last five years (2018-2023). 2 search codes were developed in the Scopus database. The first search code consisted of the following formula that we will call F1: ("AIR POLLUTION" AND "TRAFFIC" AND "PEDESTRIAN" AND "CFD"), while the second called F2 consisted of: ("AIR POLLUTION" AND "TRAFFIC RELATED" AND "PEDESTRIAN LEVEL" AND "EXPOSURE" AND "CFD"). The criteria for inclusion in the database were then applied with respect to the type of document (article, book chapter or book) and language of the document (English). From these searches and inclusion criteria, we found a total of 555 documents that went on to our next stage, which would be the PRISMA analysis, which consist in three steps: identification, screening and included, to search and select literature samples[1]. In **Error! Reference source not found.**, we can see the process followed to select the 28 articles reviewed in this article.

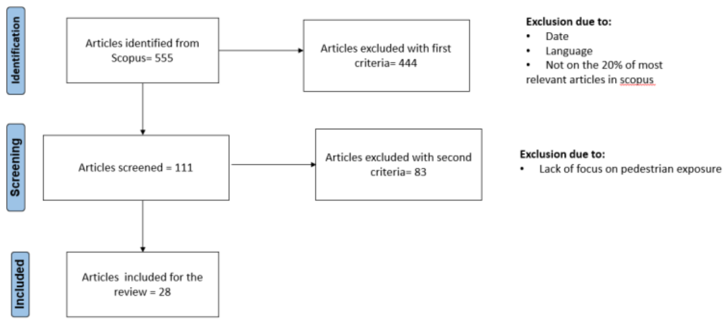

Figure 1. Flowchart outlining protocol of review using PRISMA.

3. Results

For this review, we choose 5 different criteria to evaluate the 28 selected articles: Softwares, boundary conditions, turbulence models, validation methods and assessment of pedestrian exposure.

3.1. Software

ANSYS Fluent is the most used option of the reviewed articles, a technical justification for this would be the fact that in Fluent, the meshing can be updated using a dynamic meshing method, which allows simulating air pollution under real situations of vehicle movement. STAR CMM+ is the second most used software of this research, which generally allows a good scalability of the physical model. OpenFOAM, which appears in three articles in this review, is an open access program developed in 2004, which has been continuously validated in the industry of CFD. Three of the articles do not specify with which program they worked; this makes it difficult to verify the results obtained in these investigations.

3.2. Boundary conditions

The boundary conditions of a model are very important since they must represent as close to reality the environmental and physical conditions of the processes to be investigated with the use of CFD. In most cases in this review, the division of the section being analyzed is presented in a cube form with six planes; One at the top, one at the bottom, two lateral and two others representing the input and output of the flow respectively, each of these planes must be assigned some boundary condition. At the inflow, the velocity inlet boundary condition specified in 20 articles, meanwhile at the outflow, there are two trends: specified a constant static pressure outlet with 9, and an outflow boundary, where all the flow derivatives are zero, with 8 articles. In the other walls of the domains, the predilected option was the symmetry condition.

3.3. Turbulence models

Among the most widely used turbulence models in the literature reviewed, we have only one article using a LES turbulence model, while the rest used RANS models in some way. In turn of these models of RANS, only one did not work with any derivative of the equations of κ-ε, where the κ represents the turbulent kinetic energy, and the ε represents the rate of dissipation of the turbulent kinetic energy, these equations that are widely used for their robustness and low computational cost, the other type of equation based on RANS is κ-ω, in this equation ω represents the specific rate of dissipation of turbulent kinetic energy. This equation has a higher nonlinearity and therefore its convergence is more challenging than the equations of the different k-ε models. In addition, it is more sensitive to the initial value assumed for the solution, which makes it less robust.

3.4. Validation methods

Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model [2]. Table 1 shows the three validation techniques used in the reviewed articles, with their advantages and disadvantages.

Table 1. Advantages and disadvantages of different validation methods.

Validation method	Advantages	Disadvantages	Articles using the validation methods
Wind tunnel	Data are readily available in the literature.	As they are not data obtained from the same physical domain that is being modeled, these results do not reflect the actual behavior of pollutants in that domain.	[3]–[16]
Wearable sensors	They are easy to transport and place at measurement sites, and are more accessible.	The calibration of these sensors should be performed for each measurement and ideally compared with data from monitoring stations.	[17]–[26]
Monitoring stations	The data they provide is the most reliable and allows long-term measurements.	They are not available in all places, and it is difficult to cover pollution levels at pedestrian height.	[27]

4. Assessment of pedestrian exposure

A very common type of analysis found in the articles was to use CFD to assess pedestrian exposure to pollutants from vehicular traffic under different tree configurations. In one article they performed CFD simulations with 6 different green infrastructure configurations. The results obtained show that the presence of high vegetative barriers can bring negative impacts on pedestrians and cyclists, this could be because this type of vegetation offers a temporary retention to particles from traffic, so it increases the time in which these particles are in the environment [18]. Similar results conclude that the effect of planting trees along the road to prevent emissions of reactive traffic pollutants from entering the sidewalk was low because trees also increase pollutant concentrations by weakening the wind [27]. It has also been found that the position where vegetation is planted could be more critical than the area and volume of vegetation for the reduction of particulate matter concentration [4].

The turbulence induced by traffic is another factor that affects the exposure of pedestrians, this phenomenon has been studied under different conditions of movement, both vehicles and pedestrians. It is recommended that cars maintain 3.5 m from each other, and that pedestrians walk on sidewalks, since the farther they are from the road, the lower the concentration of PM10 [5]. Another article notes that, if they neglected the effects of induced turbulence, the CO concentration would be overestimated by 78% [14]. It is also appreciated that an extreme level of exposure during the hours of heavy traffic, due to high emissions product of the exhaust of the vehicles. The vehicle arrangement plays an important role in the dispersion of exhaust pollutants, as well as vehicle speed, as speed increases, the higher the vehicle-induced turbulence occurs, accelerating the diffusion of exhaust pollutants, making this pollution more distributed [3].

In some articles, models were used to simulate mobility of both pedestrians and vehicles with CFD simulations. For example, using the VISSIM model, a greater exposure of pedestrians at bus stops, and pedestrian crossings, in addition to buying these results with the monitoring stations, it is concluded that in these the spatial variation of the concentration of pollutants [17] cannot be observed. Another similar model, but this time with SUMO, was used to simulate the flow of pedestrians, and their exposure to two different types of traffic, one continuous and one interrupted by an obstacle on the road, and the results reflect that the presence of obstacles increases the exposure of pedestrians to pollutants product of vehicular traffic significantly [12]. Another strategy used in this field is to perform simulations to study the effect of reversing lanes and evaluate how this influences the concentration of PM2.5 at road level. In a reviewed article, the results indicate that, under certain urban configurations and appropriate speed ranges, lane reversing could be very positive in reducing PM2.5 concentrations at pedestrian height [16].

In the topic of quantifying exposure indices, two stand out: the first is the personal intake factor (P_IF), which is defined as an index to analyze the impact of factors such as vehicle speed, and wind speed on exposure at pedestrian level [28], and the second is the respiratory dose of inhaled particles (RDD), which depends on the concentration of the particles during the measurement campaigns, the exposure time of people and the ventilation rate of people [29]. This ventilation rate is a variable that depends on indicators of physical activity in people, such as palpitations per minute, respiratory rate, and vital capacity [30].

It is important to note that the use of both indices mentioned in the articles of this review only quantifies exposure at the entrance of the respiratory system, that is, at an average height of 1.5 m, that is, it does not consider how the particles or gases emitted by vehicular traffic affect the entire respiratory system. Models have been found in the literature that can more accurately predict the rate of inhalation from pollutants, such as the cascade impact model to simulate regions of the respiratory system and how different particle sizes affect each region [31]. As for studies using CFD to assess disease risk in particular, an innovative approach is found to estimate the incidence of lung cancer in Street canyons due to exposure to traffic-generated particles, where results show that as wind speed increases in the canyon, the risk of lung cancer decreases, due to dispersion [32].

Quantifying exposure due to vehicular traffic remains very complex, as there are many factors involved, leading to uncertainty in the health effects caused by vehicle fleets, as mentioned in an article exploring pedestrian exposure to PM2.5 in two vehicle fleet configurations in Hong Kong [25].

5. Conclusions:

- Tree planting near avenues does not necessarily improve the issue of pollutant dispersion since meteorological factors such as wind speed and direction must be considered.
- Ignoring the effect of vehicle-induced turbulence can lead to significant error in computational models.
- There is no standardized methodology for validating computational results.
- Most CFD simulations only quantify pedestrian exposure at the entrance to the respiratory system.
- For future work on this topic, we recommend: Complement the results of CFD simulations with other models that consider the physical activity of people, as well as variables related to respiratory capacity, and thus evaluate more completely how pollutants product of vehicular traffic affect pedestrians.

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