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INVESTIGATING THERMAL EFFECTS AND POLLUTANT DISPERSION IN STREET CANYONS THROUGH CFD MODELING

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Abstract

This study investigates the thermal effects and pollutant dispersion patterns within urban street canyons using Computational Fluid Dynamics (CFD) modeling. Street canyons, formed by closely spaced buildings, often experience restricted airflow and elevated pollutant concentrations, impacting air quality and thermal comfort. CFD simulations were conducted to analyze airflow patterns, temperature distributions, and pollutant dispersion under varying meteorological and canyon geometry conditions. The model incorporates factors such as wind direction, building height, aspect ratios, and surface heating to capture realistic interactions between pollutants and thermal effects in street canyons. Results show that pollutant accumulation and thermal gradients are significantly influenced by canyon geometry and meteorological conditions, with increased heat retention in deeper canyons leading to higher pollutant concentrations. These findings underscore the importance of canyon design in urban planning to mitigate adverse thermal and air quality effects, promoting healthier and more sustainable urban environments.

Keywords Computational Fluid Dynamics (CFD), Street canyons, Pollutant dispersion, Thermal effects, Urban air quality, Airflow patterns, Heat retention.

INTRODUCTION

Urbanization has led to the proliferation of street canyons—narrow, enclosed spaces formed by buildings lining both sides of a street. While these structures maximize space in densely populated areas, they also create complex microenvironments characterized by limited airflow, increased heat retention, and higher pollutant concentrations. In street canyons, natural ventilation is often restricted, which can trap pollutants emitted from vehicles and other sources, leading to poor air quality and thermal discomfort for residents and pedestrians. The thermal and dispersion characteristics of these canyons depend on multiple factors, including canyon geometry, wind speed and direction, solar radiation, and the physical properties of surrounding buildings and surfaces.

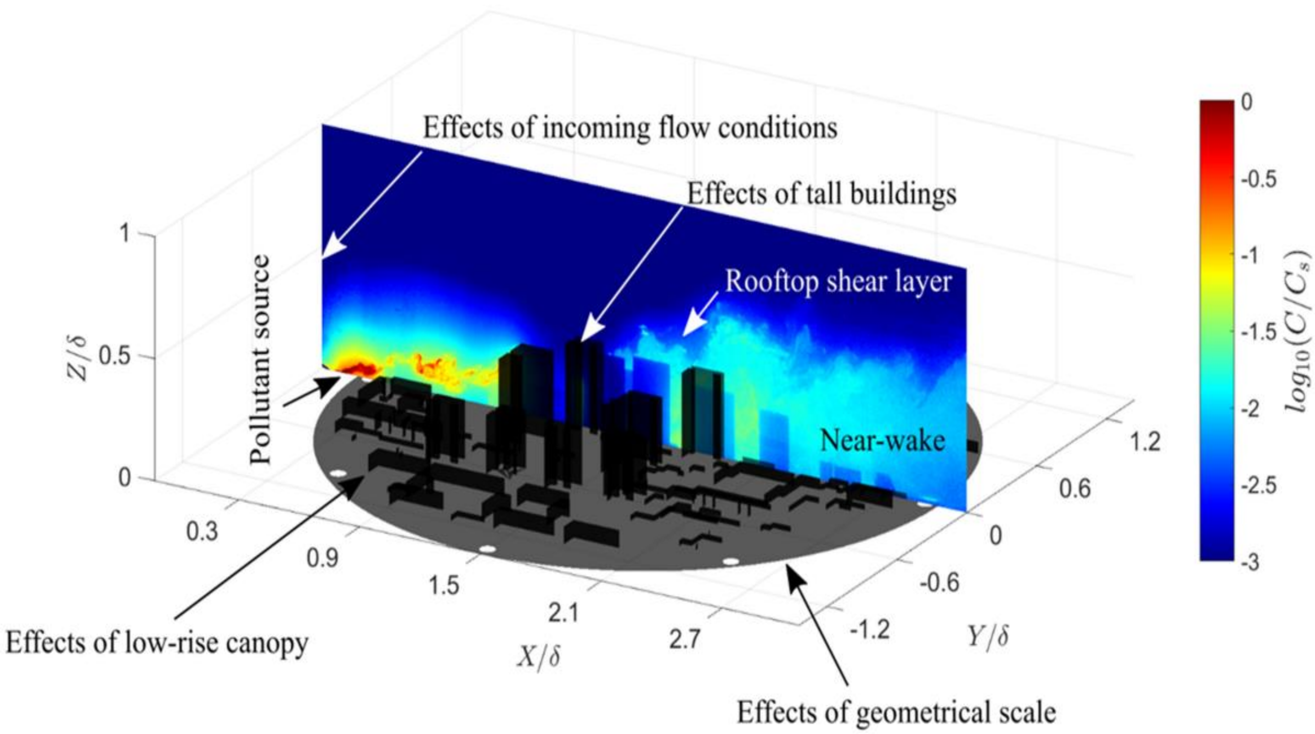
Understanding the interplay between airflow, thermal effects, and pollutant dispersion in street canyons is critical for urban planners and environmental scientists. This knowledge is essential for developing strategies to mitigate adverse health and environmental impacts in urban areas. Traditional observational methods, while valuable, are often limited in scope and fail to capture the detailed dynamics of these complex environments. Computational Fluid Dynamics (CFD) modeling, however, offers a powerful tool for simulating airflow, heat transfer, and pollutant transport under a variety of conditions. CFD can provide insights into how different canyon geometries and meteorological conditions influence pollutant dispersion and thermal effects, making it an invaluable tool in urban environmental studies.

This study employs CFD modeling to investigate thermal effects and pollutant dispersion within street canyons under various configurations. By simulating different wind directions, building heights, and aspect ratios, we aim to understand how these factors interact to influence air quality and thermal comfort within the canyon. The findings from this research can inform urban planning and policy, helping to design healthier, more sustainable cities by mitigating the adverse effects of pollutant accumulation and heat retention in street canyons.

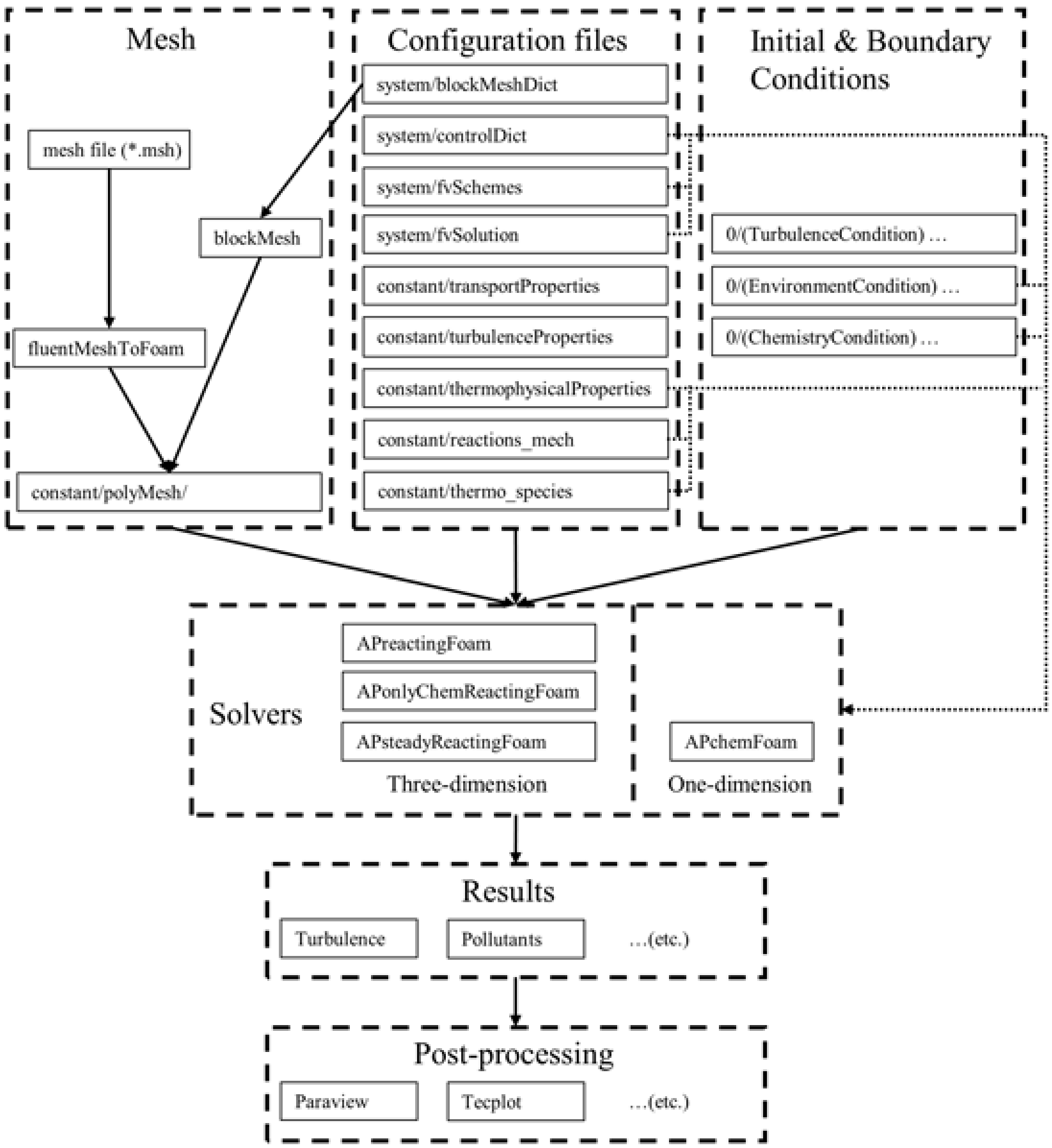
METHOD

The study utilized Computational Fluid Dynamics (CFD) to model the airflow, thermal distribution, and pollutant dispersion within urban street canyons of varying geometries. Initially, a standard urban street canyon configuration was defined, with adjustable parameters such as building height, aspect ratio, and street width to simulate different canyon geometries commonly observed in urban environments. The CFD model was set up using the ANSYS Fluent software, incorporating a 3D domain with boundary conditions to represent an open canyon environment, allowing for realistic airflow and heat transfer dynamics.

Meteorological conditions, such as wind speed and direction, solar radiation, and ambient temperature, were varied in the simulations to assess their impact on pollutant dispersion and heat retention. Wind profiles were configured to mimic urban atmospheric boundary layers, with a focus on examining the effects of both parallel and perpendicular wind directions relative to the canyon orientation. Solar radiation effects were incorporated using a radiation model within CFD, accounting for diurnal changes in solar intensity and heat accumulation on building surfaces. This setup allowed us to evaluate thermal gradients and heat islands that typically form within street canyons due to solar exposure and limited ventilation.



For pollutant dispersion analysis, a continuous source of carbon monoxide (CO) was introduced at street level, representing typical vehicular emissions in urban settings. The pollutant was modeled as a passive scalar within the CFD environment, with dispersion tracked under varying canyon and wind conditions. Turbulence within the canyon was modeled using the standard k-ε model, providing a balance between computational efficiency and accuracy for airflow and pollutant transport. Additionally, heat flux from building surfaces was included to simulate heat retention, particularly in cases of deeper canyons, where thermal effects are often more pronounced.



The simulation results were analyzed to assess the spatial distribution of pollutants, temperature gradients, and airflow patterns within each canyon configuration. Cross-sectional and longitudinal data were extracted from the CFD outputs, focusing on areas with high pollutant concentration and heat accumulation. Comparative analyses were conducted across simulations to identify how different factors, such as building height, aspect ratio, and meteorological conditions, influence pollutant retention and thermal effects in street canyons. Statistical methods were used to quantify the correlation between these variables, helping to clarify the interactions that contribute to urban heat retention and reduced air quality in street canyon environments.

The findings from these simulations provide insights into the impact of street canyon geometry and environmental conditions on thermal comfort and air quality. These results are intended to inform urban design practices, suggesting specific configurations and mitigation strategies that could reduce the adverse effects of pollutant accumulation and heat retention in urban street canyons.

RESULTS

The CFD simulations revealed distinct patterns of airflow, pollutant dispersion, and thermal gradients within the street canyons, highly dependent on the geometry and meteorological conditions. In deeper street canyons with high aspect ratios, pollutant concentration was significantly elevated, especially near ground level, due to limited air circulation. Shallower canyons exhibited better pollutant dispersion, with pollutants diffusing more readily into the surrounding environment. Thermal analysis indicated that deeper canyons retained more heat, particularly in cases with high solar exposure. Wind direction played a critical role: perpendicular winds resulted in higher pollutant accumulation within the canyon, while parallel winds facilitated greater pollutant removal. Additionally, surface temperatures on building facades exposed to solar radiation were consistently higher, contributing to heat buildup in the canyon environment.

DISCUSSION

The findings illustrate the impact of street canyon geometry and environmental factors on both air quality and thermal comfort. High aspect ratio canyons restrict natural ventilation, causing pollutants to accumulate and posing a health risk to pedestrians and residents. This restricted airflow, coupled with high solar exposure, leads to substantial heat retention, which exacerbates the urban heat island effect. The results indicate that wider canyons or those with lower aspect ratios can help reduce these adverse effects by promoting airflow and reducing pollutant retention. Furthermore, the study highlights the role of wind orientation; when aligned parallel to the canyon, wind can effectively transport pollutants out of the canyon, while perpendicular winds create recirculation zones, trapping pollutants and increasing exposure levels.

Thermal dynamics within the canyon were heavily influenced by solar radiation on building surfaces, resulting in temperature gradients that could affect pedestrian comfort and local microclimates. These insights into the thermal and dispersion patterns emphasize the need for urban planning strategies that consider canyon geometry and orientation. By strategically designing street canyons with optimal aspect ratios and orientations, urban planners can mitigate pollution accumulation and heat retention, ultimately contributing to more sustainable and health-supportive urban environments.

CONCLUSION

This study demonstrates that the geometry and orientation of street canyons significantly influence pollutant dispersion and thermal effects. Through CFD modeling, it was shown that high aspect ratio canyons are more prone to pollutant accumulation and heat retention, especially under perpendicular wind conditions. Conversely, shallower canyons and those aligned with prevailing wind directions exhibit improved ventilation and thermal regulation. The findings suggest that urban design adjustments, such as optimizing canyon width, height, and orientation, can enhance air quality and reduce thermal discomfort in urban street environments.

Overall, this research underscores the importance of integrating CFD analyses into urban planning for better environmental management in densely built areas. Future work should explore additional meteorological variations and canyon configurations, along with potential mitigation measures such as green facades and natural ventilation features. By adopting these insights, cities can reduce the health and environmental impacts of urban street canyons, promoting healthier and more livable urban spaces.

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