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Helium-heat similarity for urban wind and thermal flows: a CFD-based verification study

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SUMMARY

This study presents a computational assessment of the helium-heat similarity, aiming to model non-isothermal urban airflows using helium as the buoyancy surrogate in the experimentation. By using OpenFOAM simulations, we evaluate the feasibility of replacing physical heating of building surfaces with helium release to generate identical buoyancy effects. Based on Fr-preserved scaling and helium similarity, this work compares flow patterns and scalar dispersion between heated-air models and the proposed helium-based models in a street canyon. Results demonstrate that the helium-based model successfully replicates key buoyancy-driven flow features and heat dispersion characteristics across a range of wind-thermal conditions. This work verifies the helium-heat similarity, providing a foundational computational basis for its experimental implementation and future application in urban wind and ventilation studies.

Keywords: *CFD, Non-isothermal urban flow, Helium-heat similarity, OpenFOAM*

1. INTRODUCTION

Accurate modelling of non-isothermal flows in the wind tunnel is essential for understanding urban environments and mitigating urban heat. Due to technical constraints during in-laboratory implementation, experiments under non-isothermal conditions remain scarce (Yang et al., 2023; Zhao et al., 2020). Potential risks arising from traditional heating methods are one of the main concerns when imposing impractical heat to the building models in the wind tunnel facility (Zhao et al., 2023). To address this limitation, this study introduces a helium-heat similarity principle, proposing the release of a helium-air mixture from the heat sources as a safe and controllable alternative for generating the equivalent buoyancy effect (Zheng et al., 2025). Using helium to simulate the transport of hot smoke, hydrogen, or other environmental pollutants was proven effective by previous studies (Aram et al., 2023; He et al., 2016; Lin et al., 2020; Zheng, Zhang, et al., 2024). To verify the helium-heat similarity for urban flow applications, an OpenFOAM-based analysis is performed to determine the feasibility and accuracy of the proposed theory for studying complex thermal-wind interactions in urban areas.

2. METHOD

2.1. Similarity principle

The overall theoretical framework linking the full-scale protocol to the helium-based model through two key components: Froude-based scaling theory and helium similarity. The Fr-based scaling provides relations for matching wall temperature (T_w), wind velocity (U_r), and heat flux (Q) between full-scale ('*fs*') and sub-scale ('*ss*') models, while the helium-heat similarity determines the equivalent helium fraction and release rate that reproduce the same buoyancy effect as heated air (Zheng et al., 2025). By predicting air temperatures (T_{hot}) from helium concentration (χ_{he}) and normalizing the variables (U^* and T^*), the full-scale heat flow behaviours can be accurately represented without adding physical heating to the model.

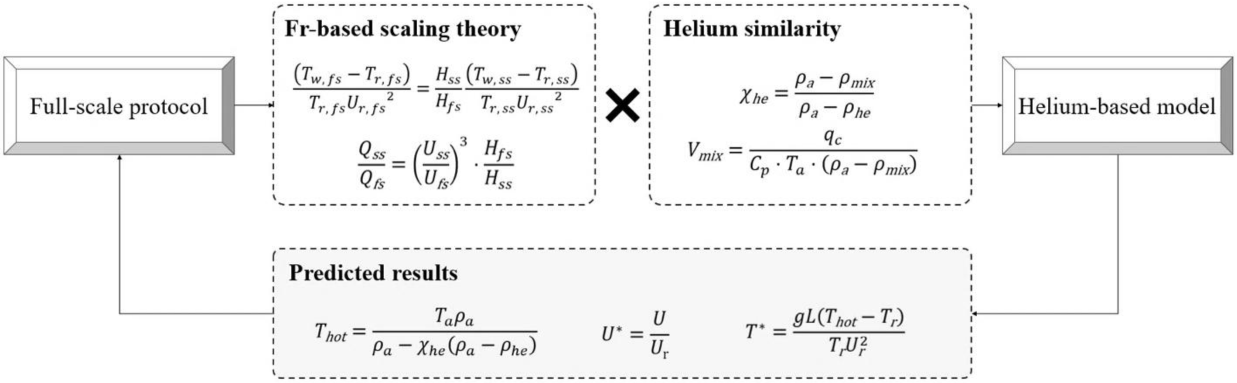

Figure 1: Theoretical framework of this study.

2.2. OpenFOAM solver and case setup

This study examines the helium-heat similarity using OpenFOAM-based RANS simulations with a k-ε turbulence model (OpenFOAM Foundation, 2018). The steady-state solver *buoyantSimpleFoam* is employed for heated air cases. For helium-based simulation, a customized solver named *heliumFoam* is developed, featuring key modifications including: the implementation of a helium concentration field, removal of the energy equation, and a revised density calculation method for helium-air mixtures using mass fraction weighting. This modified solver introduces species-transport capabilities while maintaining computational efficiency through its isothermal assumption. It serves as a practical tool for simulating helium dispersion to replicate the thermal buoyancy generated by heated surfaces.

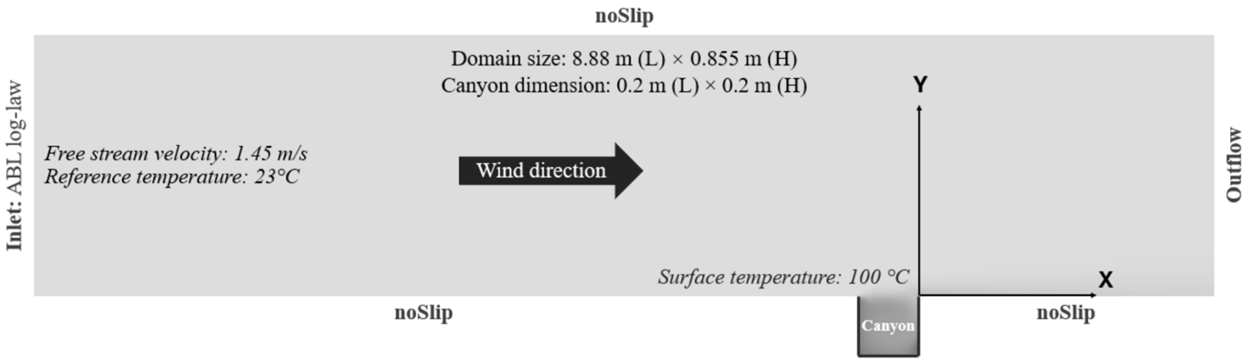

Figure 2: Computational domain and boundary conditions of this study.

A classical street canyon case derived from the wind tunnel experiments conducted by Allegrini et al. (2013) was used to assess helium-heat similarity. As illustrated in Fig. 2, the sub-scale canyon has dimensions of 0.2 m × 0.2 m and is placed inside a 2D domain of 8.88 m × 0.855 m. A corresponding full-scale model (scaling ratio 1:50) is constructed with canyon dimensions of 10 m × 10 m and a domain size of 444 m × 42.75 m. The inlet wind profile follows the neutral atmospheric boundary layer log-law, and the ambient temperature is 23°C. Free-stream velocity 1.45 m/s and surface temperatures of 100°C result in a Froude number of 4.71. A sub-scale helium model is created, in which helium release rates are computed to match the buoyancy effect of heated walls via helium similarity theory. A full-scale model is then solved with a wind speed of 4.0 m/s, consistent with moderate urban conditions in field studies. Beyond our mesh sensitivity analysis (Zheng et al., 2025), it is determined that all models use mesh resolutions of 44,000 cells (sub-scale) and 621,000 cells (full-scale), with first-layer thicknesses ensuring adequate near-wall resolution. This comprehensive framework enables a comparison among the heated-air model, the helium-based model, and the full-scale protocol under Fr-preserved scaling laws.

3. RESULTS

Figure 3 compares the air temperature (or helium concentration) fields and normalized streamwise velocity distributions across the Sub-Heat, Sub-Helium, and Full-Heat cases. Overall, the general buoyancy-driven canyon flow patterns are consistent across all cases. The Sub-Helium contours reproduce those of the Sub-Heat case, indicating that the helium-based surrogate successfully captures the recirculation patterns, and vertical stratification produced by heated surfaces. Compared to the Full-Heat model, the sub-scale results show minor deviations in the upper canyon region but preserve the general vortex structure and air temperature (helium concentration) distribution.

The helium-heat similarity was confirmed by NRMSE values, 1.66% for velocity and 2.42% for temperature (as shown in Table 1), indicating that a helium-based surrogate can successfully simulate the buoyancy-driven effects of heated surfaces under sub-scale conditions. When comparing scaled models to the full-scale scenario, the Sub-Heat and Sub-Helium results yield similar discrepancies across all variables. These values fall within an acceptable range (below 12%) for urban environmental flow studies (Wang et al., 2024).

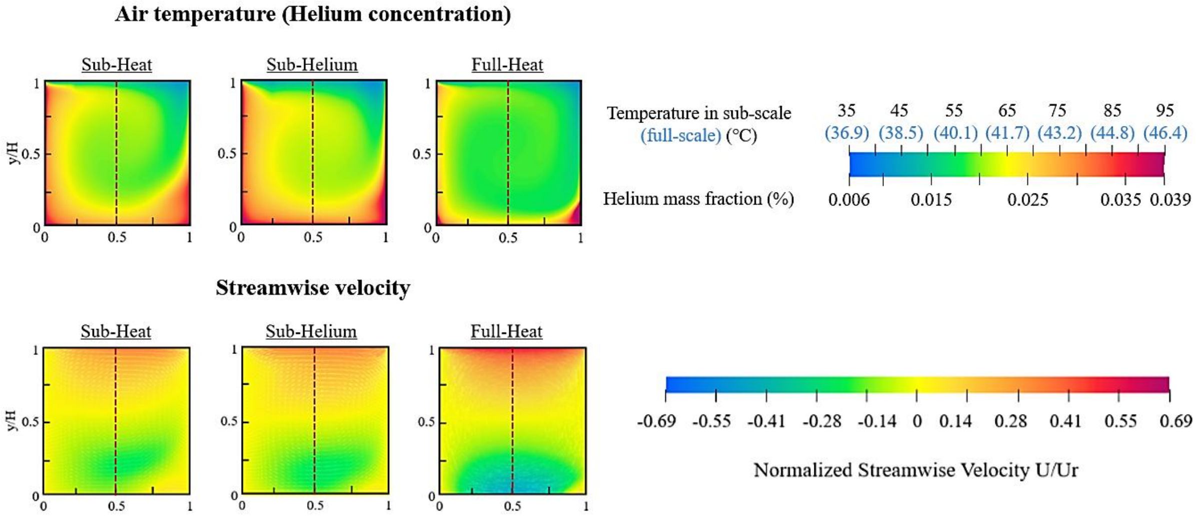

Figure 3: Comparisons of air temperature (or helium concentration) fields and normalized streamwise velocity distributions across the Sub-Heat, Sub-Helium, and Full-Heat cases.

Table 1: NRMSE comparison of streamwise velocity or air temperature at the centreline

	Sub-Helium vs Sub-Heat	Sub-Heat vs Full-Heat	Sub-Helium vs Full-Heat
Streamwise velocity	1.66%	10.88%	10.49%
Air temperature	2.42%	10.90%	11.78%

4. CONCLUSIONS

This study introduces and verifies the helium-heat similarity as a safe and practical alternative for investigating thermally induced urban airflow in sub-scaled experiments, replacing direct heating with controlled helium release from the heat sources. Beyond the analysis of scaling laws and buoyancy similarity, the method establishes helium as a surrogate for heated air. Its performance was evaluated through OpenFOAM-based simulations. This work contributes to a verified theoretical framework supporting urban thermal airflow research and a practical tool for future studies of buoyancy-driven flows in urban environments. Further studies, including wind tunnel experiments for more complex geometries are needed to fully evaluate the method under realistic experimental conditions.

ACKNOWLEDGEMENTS

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