environmental sciences proceedings

MDPI

Proceeding Paper

Risk Assessment of Toxic Pollutant Dispersion after a Methane Pool Fire Accident in a Street Canyon †

Anargyros Palampigik, Konstantinos Vasilopoulos *, Ioannis Lekakis and Ioannis Sarris

Laboratoty of Thermo Fluids Systems (LTFS), Department of Mechanical Engineering, Ancient Olive Grove Campus, University of West Attica, Thivon Str. 250, Egaleo, 12244 Athens, Greece; msrtf21x03@uniwa.gr (A.P.); lekakis@uniwa.gr (I.L.); sarris@uniwa.gr (I.S.)

* Correspondence: kvassil@uniwa.gr; Tel.: +30-2105381131

† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECAP 2023, Athens, Greece, 25–29 September 2023.

Abstract: A fire accident in an urban environment can result in injuries or death, as well as environmental and property damages. The 'street canyon', which is defined as an urban street with tall buildings on both sides, is an important geometric element covering an urban area. The interaction of wind with the street canyon can create complicated flow patterns and areas of large pollutant concentrations. This study focuses on the airflow characteristics and pollutant dispersion following a pool fire accident involving methane in an urban street canyon. Large eddy simulations (LES) are performed using the FireFoam solver with the PISO algorithm for the pressure correction equation and a simplified one-step combustion model. Flow and fire characteristics, such as, flame height, heat transfer, combustion chemistry and pollutant dispersion are computed and used to define the toxic areas inside the street canyon and subsequently identify the various risk zones, based on temperature, vertical velocity and CO_2 mass fraction fields. This study shows that a methane pool fire is transformed into a jet fire, which is influenced by the wind velocity and the heat transfer rate between the wind and the pool fire. The temperatures inside the street canyon create very dangerous and fatal conditions for pedestrians and rescue crews, whereas on the roof of the buildings the range of temperatures encountered cannot be lethal.

Keywords: urban street canyon; liquid fossil fuels; pollutant dispersion; combustion; CFD; turbulence

check for updates

Citation: Palampigik, A.; Vasilopoulos, K.; Lekakis, I.; Sarris, I. Risk Assessment of Toxic Pollutant Dispersion after a Methane Pool Fire Accident in a Street Canyon. *Environ. Sci. Proc.* **2023**, *26*, 132. https://doi.org/10.3390/environsciproc2023026132

Academic Editors: Konstantinos Moustris and Panagiotis Nastos

Published: 30 August 2023

1. Introduction

The basic geometry of an urban environment that of a street canyon, which forms the basis for most existing modern cities. Street canyons are formed by tall or narrow buildings on both sides of a street. Inside a street canyon exist complex flow patterns which have important implications for air quality and human health. For these reasons, several studies have been carried out in the last three decades, studying airflow and pollutant dispersion characteristics. Experiments under stable conditions are conducted both in water and wind tunnels [1–4]. The airflow and pollutant dispersion characteristics inside a real-scale street canyon have been also studied in several field experiments and outdoor scale models [5–7]. Although an extended amount of literature exists for pollutant dispersion inside and around a street canyon, only a small amount of it focuses on the study of toxic pollutant dispersion inside and around a street canyon for fire accidents [8–11].

The air velocity profile approaching a street canyon influences the airflow structure inside the canyon and in its leeward region. Increasing the velocity of the approaching flow leads to a vortex structure inside the street canyon, which helps passive pollutants to escape the canyon. The interaction of the free-stream flow and the vortex inside the canyon creates a zone of high-kinetic-energy and significant turbulent production. Through this zone, a large percentage of the pollutants escapes and the rest recirculate in the street canyon. Although toxic pollutants are produced in a pool fire, the strong buoyancy forces that are created prevent them from being assumed as passive scalars. Due to these buoyant forces, fire spreads quickly, releasing toxic pollutants at high temperatures, changing the air flow structure, and affecting the effective viscosity.

The objective of the present study is to identify the airflow structure in a street canyon, which is also influenced by buoyancy forces and the dispersion of toxic pollutants from a pool fire. This study simulates the breakage of an underground natural gas pipe, which creates a pool of liquid methane which quickly transforms into a gas phase. In addition, analytical tools are used to determine if accuracy in chemistry and of the flow field can give more accurate results for the physics of the flow inside in a street canyon. The free velocity of wind profile approaching the street canyon laterally will be used as a parameter to identify the effect of meteorological conditions. The geometry studied is that of a full-scale street canyon with a W/H aspect ratio of 1, and airflow and turbulent phenomena are computed using the LES (large eddy simulation) method. The dispersion of toxic pollutants will be modeled considering their thermodynamic state, and the influence of diffusion from the temperature field.

2. Methodology

2.1. Fluid Dynamics

The airflow behavior of a pool fire accident is studied using an open-source computational fluid dynamics (CFD) software package, OpenFOAM 4.1. This package provides a comprehensive set of solvers and tools for simulating and analyzing fluid flows and related phenomena and it is widely used for a range of applications, including aerodynamics, automotive design, chemical engineering, and environmental modeling. In order to simulate the fundamental equations of fluid dynamics, heat transfer, and combustion, including the behavior of a fire and its interaction with the surrounding environment a solver of OpenFOAM, called FireFoam, is used. This solver can define various aspects of fires, including flame spreading, heat release, smoke generation, and combustion products.

A simple fast chemistry reaction model for computing the heat released from the reactions occurring in a fire accident is combined with Navier–Stokes and energy equations, accounting for the buoyancy forces. The governing equations for the LES simulation are as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \quad (1)$$

Momentum equation:

$$\frac{\partial}{\partial t}\left(\rho \vec{u}\right) + \nabla \cdot \vec{u}\vec{u} + \nabla p = \rho g + \vec{f_b} + \nabla \cdot \tau_{ij}, \quad (2)$$

where τ_{ij} is the stress tensor

Transport and mass for individual species:

$$\frac{\partial}{\partial t}(\rho Y_a) + \nabla \cdot \rho Y_a \vec{u} = \nabla \rho D_a \nabla Y_a + \dot{m}_a''' + \dot{m}_{b,a}''', \quad (3)$$

Y_a is the mass fraction of the individual species, $\dot{m}_{b,a}'''$ is the production rate of species a via evaporation, and $\dot{m}_a'''$ is the mass rate production per unit volume.

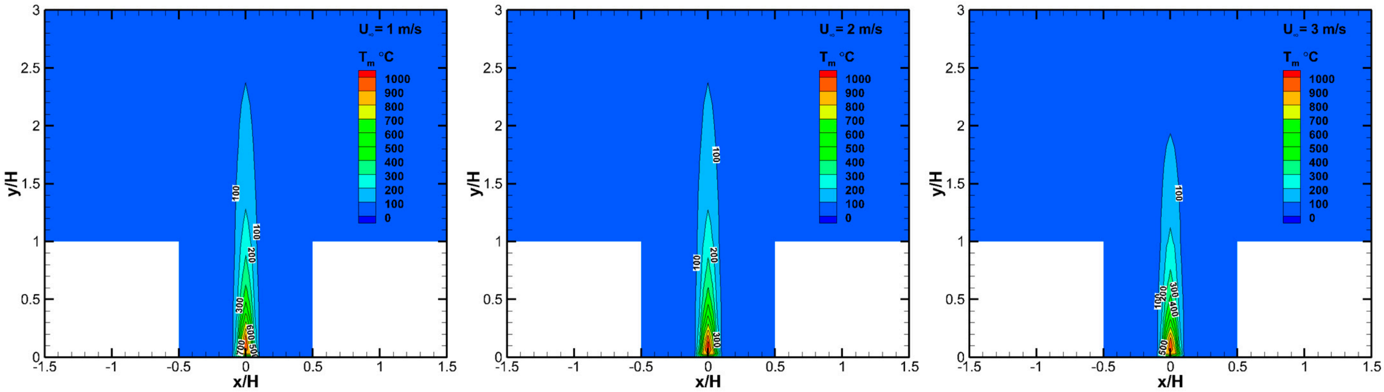
Transport of sensible enthalpy:

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla \cdot \rho h_s \vec{u} = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla \cdot \vec{q}'' + \varepsilon, \quad (4)$$

h_s is the sensible enthalpy and ε is the dissipation rate per unit volume.

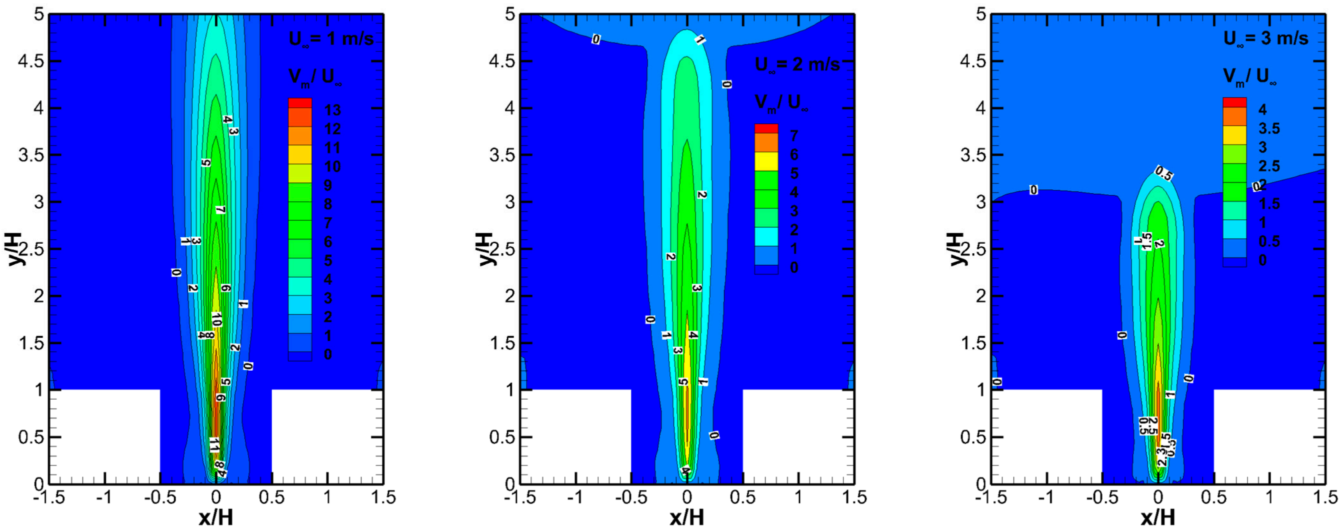
2.2. Physical Model Set Up

Street canyon geometry (as indicated in Figures 1–3) consists of buildings measuring 18 m in height (H) on both sides of the street with a width (W) equivalent to one building's height (H), resulting in a street-width-to-building-height aspect ratio of one (W/H = 1). According to this, flow is considered as wind-driven skimming flow.



(**a**) (**b**) (**c**)

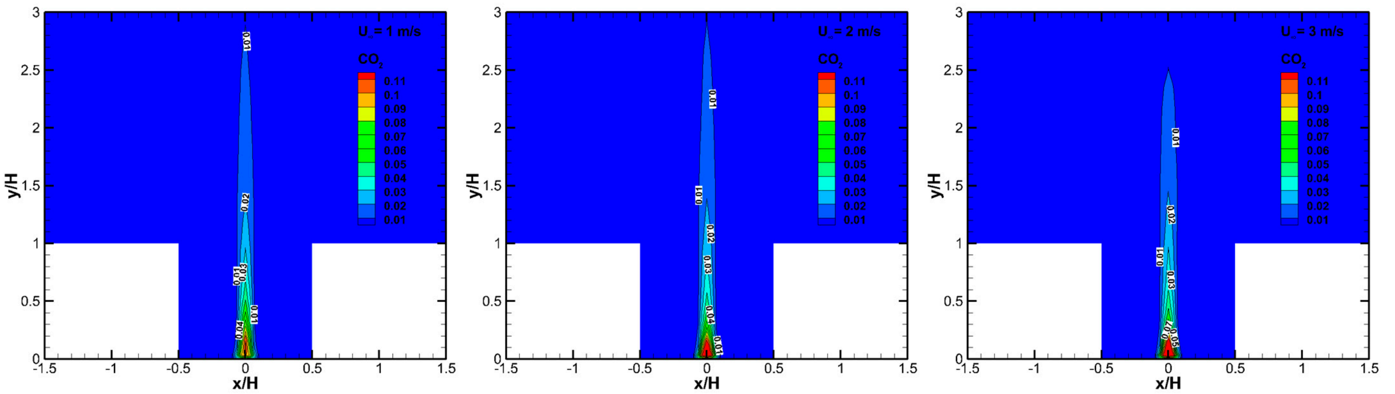
Figure 1. Temperature field in the street canyon for (**a**) 1 m/s (**b**) 2 m/s and (**c**) 3 m/s free-stream wind velocities.



(**a**) (**b**) (**c**)

Figure 2. Vertical velocity component in the street canyon for free-stream wind velocities of (**a**) 1 m/s, (**b**) 2 m/s and (**c**) 3 m/s.

To determine the impact of skimming flows on the dispersion of toxic pollutants, three different atmospheric-boundary-layer velocity profiles are studied. A methane fire source of a constant heat release rate (HRR) in the middle of the canopy is employed. The skimming flow pattern can be described as a single and strong recirculation region, which is influenced by the inlet atmospheric-boundary-layer profile.



(**a**) (**b**) (**c**)

Figure 3. CO_2 mass production in the street canyon for free-stream wind velocities of (**a**) 1 m/s, (**b**) 2 m/s and (**c**) 3 m/s.

2.3. Computational Domain

The computational domain is 23 H × 6 H × 11 H and the mesh consists of 900,018 hexahedral cells with appropriate grading around the buildings. In the x direction, a distance of 5 H exists in front of the first building, of 15 H downstream of the second building, and of 5.5 H left and right of the x axis. This domain is large enough to adequately produce all the flow characteristics.

2.4. Boundary Conditions

At the inlet of the computational domain, an atmospheric velocity profile is applied. For the upper and downstream boundaries of the computational domain, the hydrostatic flux pressure is used to avoid errors in pressure due to the large buoyancy effects, a calculated Von-Neumann boundary condition. The pool fire source inside the street canyon is defined as a steady inlet methane mass fraction. The area of the fire source is four square meters (4 m^2), resulting in a net-volume methane fraction of 60 kg/h.

Inlet velocity profile:

$$U = \left(\frac{y}{z_0}\right)^{z_0} \cdot U_\infty, \tag{5}$$

where z_0 is the friction height and U_∞ is the free-stream velocity. The first part of the above equation is described as the form of the atmospheric boundary layer.

Because of the fire source assumption for a constant methane flowrate of 60 kg/h, the resulting vertical component of velocity is 0.0041 m/s.

The three different cases studied are for the free-stream wind velocities of (a) $U_\infty = 1$ m/s, (b) $U_\infty = 2$ m/s and (c) $U_\infty = 3$ m/s. The methane volume fraction source remains constant for all cases and with a constant aspect ratio of the street canyon.

3. Results

Three cases corresponding to three different inlet atmospheric-boundary-layer velocity profiles are simulated. The maximum simulation time for all cases studied is 50 s, which is good enough for the temperature field to be stabilized. The dominating factor is due to buoyancy forces. In all the cases, the temperature and velocity fields converge toward stationary state. Attention is given to the fields of temperature, vertical velocity and CO_2.

Figure 1 shows the temperature fields for the three cases. It is clear that the methane pool fire is transformed quickly into a jet fire. This is due to the thermodynamic properties of methane fuel and its products, as the methane which is coming out from a broken pipe in a liquid state is transformed into a gas state extremely quickly. As the free-stream velocity increases, the heat transfer rate from the fire plume increases, which results in a reduction in plume height. At the level of the pool, the temperature for all the three cases is constant, at a maximum temperature of approximately 1000 °C as a result of chemical reactions. At both sides of the street canyon, the temperature varies between 25 °C at the surface of the building and 100 °C at the outer boundary of the plume, as shown in the figure. This range of high temperatures inside the street canyon, from this effect alone, creates unbearable conditions for pedestrians and rescue crews at the time of an accident. On the roofs of the buildings, the temperature varies between 25 °C at their surface and 91 °C for the first case, 68 °C for the second case and 46 °C for the third case at a height of 2 m above them. From the above, it can be concluded that only in the third case are the conditions bearable for the crew and pedestrians.

As shown from the vertical velocity contours in Figure 2, a pool fire leads to a jet fire in all the three cases. In all three cases, the flow, temperature and concentration fields reached stationary conditions at approximately 34 s, which implies that the 50 s running time is adequate.

The interaction of the wind field's velocity and the fire plume depends on the ratio of the inertial forces of the wind and the buoyant forces of the plume. The level of the buoyant forces is also affected by the rate of heat transfer from the plume to the wind. In the first case, also due to a small rate of heat transfer, the buoyant forces of the plume dominate the inertial forces of the wind up to higher heights as in the other two cases. Based on this reasoning, the maximum vertical extent of the fire plume is approximately 5.5 H for the first case, 4.5 H for the second case and 3.5 H for the third case. Thus, for a lower wind velocity, the inertial force is lower and the buoyant force is larger, because of the small heat transfer, making the fire plume penetrate the wind at higher levels and the toxic pollutants escape in the atmosphere to the advantage of the pedestrians and the rescue team.

The vertical velocity contours, in Figure 2, also indicate the zero-vertical velocity contour line, the horizontal part of which acts as a dividing streamline between the wind flow and the two vortices that are formed on the left and right sides of the fire plume. Streamline plots, not presented here, show the vortices. These vortices are formed from the interaction of the wind and the plume. The aforementioned dividing streamline is placed at a lower height, the higher the wind velocity is.

CO_2 mass production due to fire, in Figure 3, is given for all three cases. Although CO_2 is not toxic as a chemical, it can be fatal if the concentration is high. In all cases, the mass concentration of CO_2 outside of the plume is quite low (1%). The higher concentrations exist within the plume and are carried by the plume to the higher levels of the atmosphere, due to the high temperature of the reaction and the resulting strong buoyant forces. Based on this, the CO_2 concentration is not as dangerous to the pedestrians and rescue workers as are the high temperatures.

4. Conclusions

Airflow characteristics and pollutant dispersion following a pool fire accident involving methane in an urban street canyon, using large eddy simulations (LES), are determined using the FireFoam solver. The important flow and fire characteristics of this study, based on the temperature, the vertical velocity component and the CO_2 mass fraction fields, are the following:

- The methane pool fire is transformed quickly into a jet fire, making the accident more severe.
- As the free stream velocity increases, the heat transfer rate from the fire plume increases, which results in a reduction in the buoyant forces of the plume and consequently its penetration into the wind field, leading the toxic pollutants to escape into the atmosphere.
- There is a dividing streamline separating the wind flow and two vortices that are formed on the left and right sides of the fire plume.
- The high temperatures inside the street canyon create very dangerous and fatal conditions for pedestrians and rescue crews at the time of the accident. On the roof of

the buildings, the range of temperatures encountered are not lethal for the latter two cases studied.

- The higher concentrations exist within the plume and are carried by the plume to the higher levels of the atmosphere, so they do not lead to life-threatening conditions.
- The best-case scenario for this problem is that of the second case studied.

Author Contributions: Conceptualization, A.P. and K.V.; methodology, A.P., K.V., I.S. and I.L.; software, A.P.; validation, A.P. and K.V.; formal analysis, A.P.; resources, I.S.; data curation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, A.P., K.V., I.S. and I.L.; visualization, A.P.; supervision, K.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported via the computational time granted by the National Infrastructures for Research and Technology S.A. (GRNET S.A.) in the National HPC facility—ARIS—under project ID pr011045-UrbanFirePlan2.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kastner-Klein, P.; Plate, E.J. Wind-tunnel study of concentration fields in street canyons. *Atmos. Environ.* **1999**, *33*, 3973–3979. [CrossRef]
2. Salizzoni, P.; Marro, M.; Soulhac, L.; Grosjean, N.; Perkins, R.J. Turbulent Transfer Between Street Canyons and the Overlying Atmospheric Boundary Layer. *Bound.-Layer Meteorol.* **2011**, *141*, 393–414. [CrossRef]
3. Baik, J.-J.; Park, R.-S.; Chun, H.-Y.; Kim, J.-J. A Laboratory Model of Urban Street-Canyon Flows. *J. Appl. Meteorol.* **2000**, *39*, 1592–1600. [CrossRef]
4. Baik, J.-J.; Kim, J.-J. On the escape of pollutants from urban street canyons. *Atmos. Environ.* **2002**, *36*, 527–536. [CrossRef]
5. DePaul, F.T.; Sheih, C.M. Measurements of wind velocities in a street canyon. *Atmos. Environ.* **1986**, *20*, 455–459. [CrossRef]
6. Eliasson, I.; Offerle, B.; Grimmond, C.S.B.; Lindqvist, S. Wind fields and turbulence statistics in an urban street canyon. *Atmos. Environ.* **2006**, *40*, 1–16. [CrossRef]
7. Inagaki, A.; Kanda, M. Turbulent flow similarity over an array of cubes in near-neutrally stratified atmospheric flow. *J. Fluid Mech.* **2008**, *615*, 101–120. [CrossRef]
8. Zhang, X.; Hu, L.; Tang, F.; Wang, Q. Large Eddy Simulation of Fire Smoke Re-circulation in Urban Street Canyons of Different Aspect Ratios. *Procedia Eng.* **2013**, *62*, 1007–1014. [CrossRef]
9. Pesic, D.J.; Blagojevic, M.D.J.; Zivkovic, N.V. Simulation of wind-driven dispersion of fire pollutants in a street canyon using FDS. *Environ. Sci. Pollut. Res.* **2014**, *21*, 1270–1284. [CrossRef]
10. Hu, L.H.; Xu, Y.; Zhu, W.; Wu, L.; Tang, F.; Lu, K.H. Large eddy simulation of pollutant gas dispersion with buoyancy ejected from building into an urban street canyon. *J. Hazard. Mater.* **2011**, *192*, 940–948. [CrossRef] [PubMed]
11. Vasilopoulos, K.; Sarris, I.E.; Lekakis, I.; Tsoutsanis, P. Diesel Pool Fire Incident Inside an Urban Street Canyon. In *Proceedings of the 1st International Conference on Numerical Modelling in Engineering*; Springer: Singapore, 2019; pp. 339–350.