

Review

A Literature Review on Methods and Metrics for the Analysis of Outdoor Air Displacement Conditions in the Urban Environment

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Abstract: The ongoing pandemic has driven the attention of both policy makers and professionals of the building sector towards the need for proper ventilation of the indoor environment. Despite accurate ventilation control only being available with mechanical ventilation systems, in several countries worldwide the renovation of indoor air relies mainly on natural solutions. In this context, in the design of new or renovated buildings, conventional natural ventilation rates are typically assumed to be in agreement with available technical standards, sometimes regardless of the actual external conditions. For instance, local wind speed and direction, as well as buoyancy-driven air displacements, are not considered, even if they can significantly affect the ventilation efficacy for the designed buildings. Moreover, the local outdoor temperature and the presence of pollutants are rarely accounted for, even though they can represent interesting inputs not only for naturally ventilated buildings but also for mechanical ventilation systems. In the framework described above, this review paper aims to provide an overview of the current state-of-the-art of the research regarding air displacement and conditions in the urban context, focusing on the main methods, parameters and metrics to consider in order to ensure a deeper and more accurate modelling of natural ventilation potential in the urban built environment. The analysis of the literature includes both experimental and numerical studies. As regards the latter ones, the features of the chosen urban areas—real or parametric ones—the adopted turbulence models and the indexes calculated as simulation outputs were analysed, with the purpose of defining a common framework to support future extensive numerical studies.

Keywords: computational fluid dynamics; natural ventilation; street canyon; turbulence models; urban ventilation; urban ventilation metrics; urban building design; wind tunnel



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1. Introduction

The United Nations (UN) estimates that by 2030 urban areas will house 60% of people globally and one in every three people will live in cities with at least half a million inhabitants [1]. This will happen because of the migration of the people from rural to urban areas and the transformation of the former into the latter [1], characterized by public and private services that are of higher quality and are more easily accessible [2]. Given this context, it is necessary, on one hand, to understand the key trends of urbanization and, on the other hand, to implement strategies to make cities and human settlements more inclusive, safe, resilient, and sustainable [1,2].

The growth of cities is also responsible for the alteration of natural surroundings, with an impact on the local micro-climatic characteristics [3]. Indeed, for instance, buildings can act as obstacles to the wind flow, channelling air into specific paths depending on the geometry, size and orientation of the urban layout. As an example, Figure 1 shows airflow streamlines around buildings acting as obstacles, causing the airflow to change its magnitude and direction. This diversion in the flow results in the occurrence of vortexes,

recirculations and flow separation depending on the size and geometry of the buildings, which are responsible for sufficient air availability for ventilation purposes.

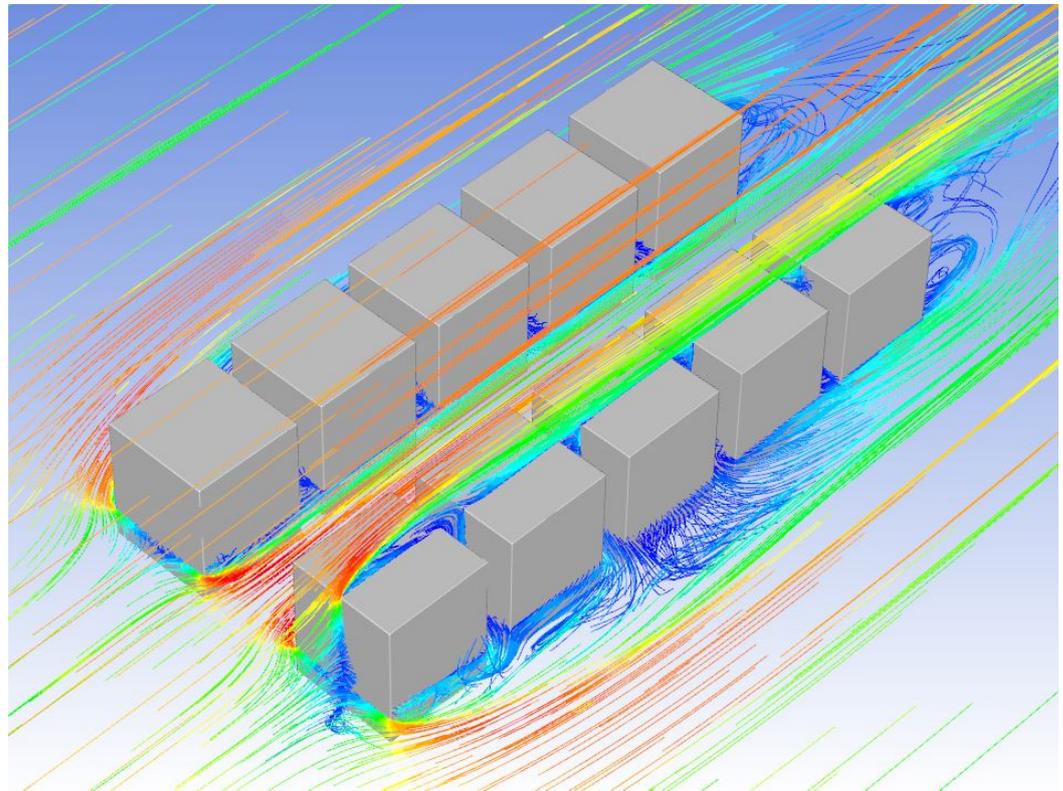


Figure 1. Streamlines representing air flow around buildings: change in colours represents the variation in magnitude intensity of air velocity.

As pointed out by many studies in the literature, understanding the wind flow behaviour around buildings in cities, with both generic and real layouts and at different geometric scales, can be beneficial to characterize the actual performance of the building's natural ventilation (NV) strategies, determining when they are a feasible solution for indoor air renovation [4,5]. For instance, some researches consider not only the more common wind driven-flows [6–11], occurring in the urban environment because of pressure differences generated by wind flow, or the buoyancy-driven ones [12–17], occurring as a result of air temperature and density differences in adjacent locations, but also the combined effects of both [18–23]. In the case of buildings, wind causes a positive pressure on the windward side and a negative pressure on the leeward side of buildings to have wind-driven flows, while in the case of buoyancy-driven flows, warm air goes up and cool air remains low, causing air displacement [15,24]. Figure 2 gives an example of wind-driven flows: the top side is the windward side, experiencing positive pressures, while the leeward side on the bottom registers negative pressures. The pressure gradient on different building sides can then ensure the natural ventilation of the indoor environments.

While understanding natural ventilation (NV) strategies, air displacement and wind flow behaviour, there are some parameters and metrics to take into consideration. These are related, in particular, to the building's geometries, the surface properties of the building's materials and the local microclimatic conditions. Some examples of parameters are building height, street aspect ratio, floor area ratio, wind velocity, mean air temperature, radiation and surface roughness. The scale of the analysis is particularly important for the assessment of the potential of natural ventilation in the urban context, with different aspects influencing the outcome of the analysis as reported by different contributions in the literature [25–31]. One of the most interesting cases is street canyons, whose study can help us to understand,

for instance, the dispersion of pollutants around the buildings and how this can affect human health [3,4,12–16,18,21–23,31–40].

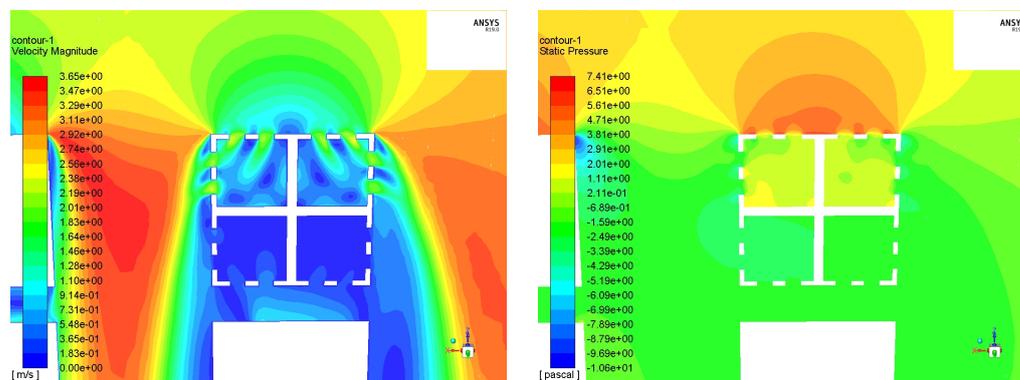


Figure 2. Wind-driven air flows inside and around buildings: velocity (on the left) and pressure (on the right) contour plots.

As mentioned before, these studies are often carried out experimentally or with CFD (computational fluid dynamics) simulations, as shown by Duan and Ngan [20], Chatzimichailidis et al. [32] and Lo and Ngan [38] in their studies on street canyon. As regards the experiments, they are either field measurements or performed in controlled environments. The field measurements prove to be useful to understand the climatic conditions of a given urban location, as demonstrated by Mosteiro-Romero, et al. [28], Chatzidimitriou and Yannas [31] and Zhao et al. [33]. On the contrary, wind tunnel tests are often used to validate the results obtained from either field measurements or with CFD simulations, as demonstrated by other authors, such as King et al. [6], Tan et al. [18], Zhao et al. [33], Yang et al. [34], Ricci et al. [41], Li et al. [42] and Izadyar et al. [43].

However, it is sometimes difficult to perform these experimental activities because of some constraints, such as a limited number of measurement points, limited availability of resources, size and time constraints, financial constraints, non-changeable or uncontrollable boundary conditions, etc. In these cases, many researchers have proposed performing studies at a reduced scale, by taking into consideration the similarity criteria. For instance, Zhao et al. [33], Yang et al. [34] and Chen et al. [35] performed reduced-scale experiments and CFD simulations of street canyons with natural ventilation.

In the framework described above, this review aims to provide an overview of the current state-of-the-art of the research regarding air displacement and conditions in the urban context, focusing on adopted experimental and numerical methods, as well as parameters, metrics and performance indicators, with the goal of identifying the main research trends and gaps to consider in order to ensure a deeper and more accurate modelling of natural ventilation potential in the urban built environment. The study was performed as a structured literature review, categorising the analysed papers according to some selected variables, such as year of publication, type of building/building layout, type of flow, type of CFD tools used, type of experiment and considered parameters. This allowed us to depict an objective overview of methods and metrics, facilitating the identification of the most common approaches as well as of the current gaps in the literature.

2. Methods: Collection and Classification of Relevant Papers

For the review purpose, a total of 89 studies were investigated. These studies were collected from the Scopus database by using some specific keywords related to urban ventilation, and with a publication year after 1990. The most important selected keywords are “urban ventilation”, “urban CFD”, “natural ventilation”, “street canyon” and “wind tunnel”. The oldest study considered in this review is from the year 1991 and the most recent study is from the year 2021. Specific attention was given to the most recent methodological

trends, e.g., studies published later in 2021, which have been analysed in Section 6 “Recent developments in the review”. Figure 3 represents the yearly distributions of studies on natural ventilation (NV), which shows increased interest in this subject over time. A sudden increase in the number of studies can be seen in the graph looking at recent years. The explanation for this trend can be twofold. On one hand, with the increase in energy performance and requirements for buildings, the share of energy spent for ventilation purposes has increased, and so has its relative importance. On the other hand, the COVID-19 pandemic outbreak focused the attention of the scientific community on air quality, methods and solutions to limit the contagion risks, as shown by the large increase in contributions in the year 2020.

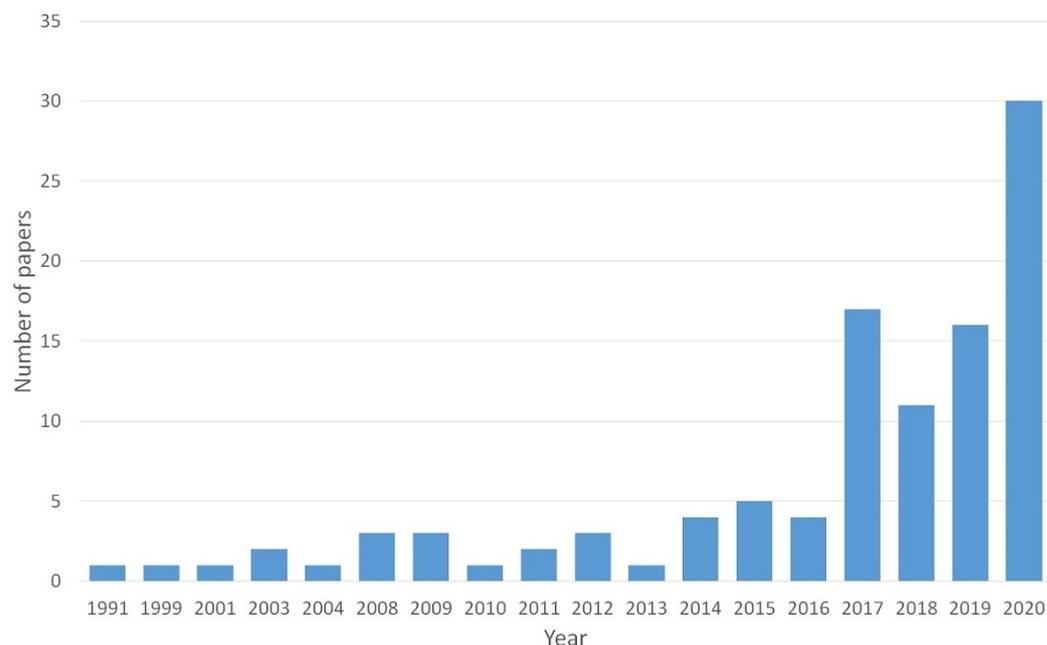


Figure 3. Yearly distribution of studies on ventilation.

As mentioned before, selected studies were categorized depending on the journals in which they were published, year of publication, keywords, first author’s institute of affiliation, climate, type of urban area chosen (generic or real), type of wind flow, indoor or outdoor, methodology, adopted parameters/indexes and dimensionless numbers. The three latter categories, in particular, were discussed in detail in order to analyse the methods and approaches typically adopted according to the current state-of-the-art, as well as those metrics which should be considered to design new experiments or simulations.

First, studies were grouped depending on the type of urban area that was chosen, i.e., distinguishing if an actual city or district or a fictive one was simulated. Furthermore, attention was paid to the presence of validation of numerical results by comparison with experimental data or analytical data. As it can be seen in Figure 4, most studies were carried out on fictitious urban layouts, and slightly more than the half of the dataset lacks any validation.

The following tables describe the studies taken into consideration for this review. These studies are arranged according to the first author’s name in alphabetical order. These tables are subdivided on the basis of the urban area (real or fictitious urban area) and whether comparisons with experimental or other numerical data were present. Other factors, such as on the building/city type, location taken into consideration, kind of experiments performed, type of simulation codes, turbulence models used, parameters and keywords, are also reported (Tables 1–10).

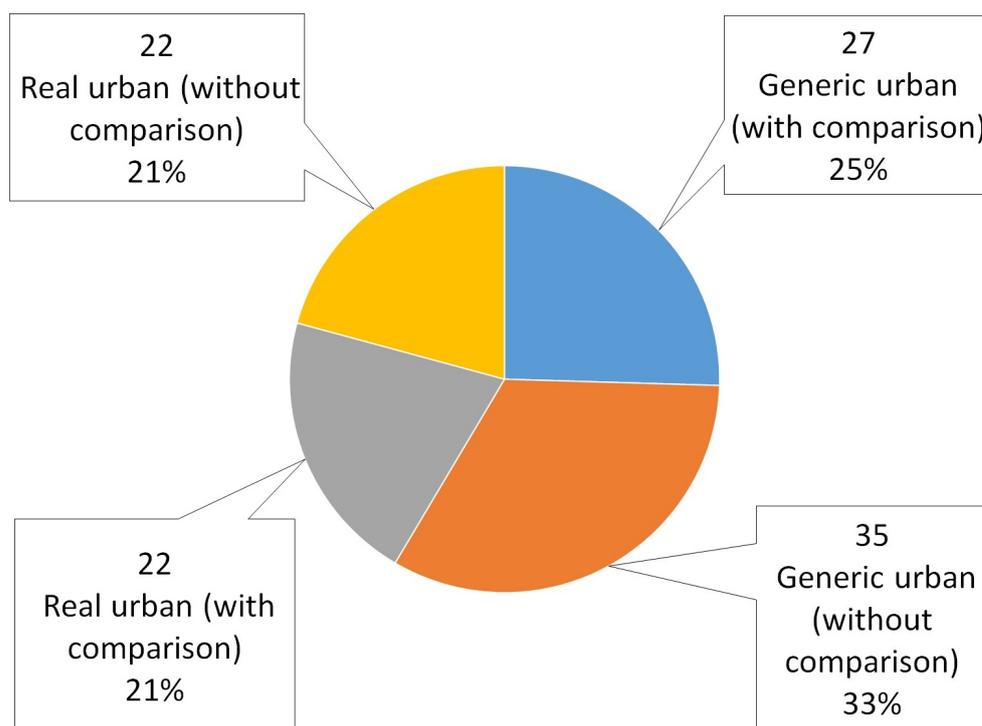


Figure 4. Grouping of studies depending on type of urban area (actual or fictitious) and by presence of comparison with experimental or analytical data.

Table 1. Overview of studies of fictitious urban areas with comparison with experimental or numerical data: type of building, city, experiment and simulation code.

No.	Author	Building/City Type	Experiment	Simulation Codes/Instruments Used
1	Aly et al., 2021 [44]	Low-rise building	WTE	-
2	Chen et al., 2001 [17]	Single-zone building	Fine-bubble technique	-
3	Dai et al., 2019 [5]	An isolated multi-story building, an array of multi-story buildings	Tracer gas decay method on a full-scale building model	Ansys Fluent 13.0
4	Hang et al., 2011 [3]	High-rise square building arrays	WTE	Code "Ventair" using Fortran language for CFD
5	Hang et al., 2020 [23]	Idealized 2D street canyons	WTE	Ansys Fluent
6	He et al., 2020 [45]	Square form and scattered configuration	WTE	Flow Simulation
7	Jiang et al., 2003 [46]	Cubic building	BL WTE with LDA	-
8	Kim and Baik, 2010 [22]	Group of infinitely repeated cubical buildings	WTE	-
9	Li et al., 2015 [47]	Non-parallel converging and diverging buildings	WTE	Ansys Fluent 14.0
10	Li et al., 2017 [37]	Constant height buildings	WTE	Ansys Fluent 14.0
11	Liu et al., 2020 [48]	Scaled high-rise building	WTE	Ansys Fluent 15.0
12	Mou et al., 2017 [49]	-	WTE	Ansys Fluent 14.0
13	Padilla-Marcos et al., 2017 [10]	Cubical building	WTE	Ansys Fluent 15.1
14	Park et al., 2020 [15]	16 step-up street-canyon with different aspect ratios	WTE	-
15	Salizzoni et al., 2009 [12]	Simplified model of the urban canopy, made up of a uniform array	WTE with PIV	-
16	Tan et al., 2019 [18]	-	Atmospheric diffusion WTE	Ansys Fluent

Table 1. Cont.

No.	Author	Building/City Type	Experiment	Simulation Codes/Instruments Used
17	Wang et al., 2017 [50]	7-row and 11-column cubic building array	WTE	Ansys Fluent 6.3
18	Yang et al., 2020 [34]	Simple cubic building	WTE	Ansys Fluent
19	Zhang et al., 2020 [51]	A tall building	WTE	Ansys Fluent v19.2
20	Zheng et al., 2020 [52]	-	BL WTE	Ansys Fluent 15.0
21	Zheng et al., 2020 [53]	Multi-floor and multi-row buildings	WTE	Ansys Fluent

Table 2. Overview of studies of fictitious urban areas with validation comparison with experimental or numerical data: adopted turbulence models and parameters, and listed keywords.

No.	Author	Turbulence Models	Parameters	Keywords
1	Aly et al., 2021 [44]	LES	-	aerodynamics, wind engineering, open-jet testing, wind tunnel, atmospheric boundary layer, low-rise buildings
2	Chen et al., 2001 [17]	-	M, g', B, Ra	buoyancy; modelling; natural ventilation; similarity
3	Dai et al., 2019 [5]	LES	PC, RER, Re	CFD simulation; coupled outdoor and indoor environment; natural ventilation; pollutant dispersion; Reynolds number independence criteria; coupled outdoor and indoor environment; Reynolds number independence criteria
4	Hang et al., 2011 [3]	$k - \epsilon$	SAR, BAD, H	high-rise building array; numerical simulation; turbulence; urban canopy; velocity; wind tunnel
5	Hang et al., 2020 [23]	RNG	AR, P_IF, Re, Ri, Fr	aspect ratio (AR); computational fluid dynamic (CFD) simulations; Froude number; street canyon; street intake fraction <P_IF>; wall heating
6	He et al., 2020 [45]	Modified $k - \epsilon$	-	CFD; integrated methodology; optimum design; parametric tools; wind environment
7	Jiang et al., 2003 [46]	LES	-	large-eddy simulation (LES); filtered dynamic subgrid-scale model; wind tunnel; laser Doppler anemometry (LDA); cross ventilation; single-sided ventilation
8	Kim and Baik, 2010 [22]	RNG	BAR, SCAR	building-roof heating; cfd model; street canyon flow; street-bottom heating
9	Li et al., 2015 [47]	SKE, RNG, RKE	-	building passage; pedestrian wind comfort; urban wind; ventilation
10	Li et al., 2017 [37]	SKE	-	dynamic mesh; moving vehicles; pollutant dispersion; urban street canyon; vehicle-induced turbulence
11	Liu et al., 2020 [48]	RNG	Ri	concentration; high-rise building; pollutant; temperature; vortex core
12	Mou et al., 2017 [49]	RKE	-	building dimensions; computational fluid dynamics; height–thickness scenario; height–width scenario; mean wind pressure; square-shaped tall buildings
13	Padilla-Marcos et al., 2017 [10]	$k - \epsilon$	OACH, OACE	age of the outdoor air; building shape impact; computational fluid dynamics (CFD) method; ideal control domain; indoor air quality; urban built environment; wind profile

Table 2. *Cont.*

No.	Author	Turbulence Models	Parameters	Keywords
14	Park et al., 2020 [15]	RNG	BHAR, BLAR, Ri	building-length aspect ratio; computational fluid dynamics; building-length aspect ratio; development and mature stages; flow characteristics; step-up street canyon dispersion models; street canyon; turbulent mass transfer; urban air pollution numerical simulation; pollutant dispersion; source shape; street canyon; thermal stratification
15	Salizzoni et al., 2009 [12]	-	-	air change rate per hour (ACH); computational fluid dynamics (CFD) simulation; concentration decay method; small open space; urban age of air age of air (τ); air change rate per hour (ACH); building natural ventilation; computational fluid dynamics (CFD); purging flow rate (PFR); urban ventilation
16	Tan et al., 2019 [18]	LES	-	building configuration; computational fluid dynamics simulation; pedestrian wind comfort; super-tall building; urban wind environment
17	Wang et al., 2017 [50]	SKE	-	tree drag coefficient; turbulent flow model; urban heat island; urban ventilation; wind tunnel test
18	Yang et al., 2020 [34]	RNG	SAR, WS, ACH, MAA, PFR	CFD simulation; rotation angle; shading louvers; wind pressure coefficient
19	Zhang et al., 2020 [51]	RKE	-	
20	Zheng et al., 2020 [52]	$k - \epsilon$	-	
21	Zheng et al., 2020 [53]	RKE	-	

Table 3. Overview of studies of fictitious urban areas without validation comparison with experimental or numerical data: type of building, city, experiment and simulation code.

No.	Author	Building/City Type	Experiment	Simulation Codes/Instruments Used
1	Ai and Mak, 2014 [54]	Building	-	Ansys Fluent 13.0
2	Aristodemou et al., 2020 [55]	High-rise buildings	-	FLUIDITY
3	Buccolieri et al., 2020 [56]	-	-	-
4	Carrilho da Graça and Linden, 2016 [57]	Non-domestic building	-	-
5	Chatzimichailidis et al., 2019 [32]	2 building blocks	-	OpenFoam
6	Chen et al., 2020 [35]	Hollow and sand building models	Scaled outdoor field experiment (sonic anemometers, thermocouples, infrared camera, weather station)	-
7	Cheng et al., 2008 [16]	2D idealized street canyon	-	Ansys Fluent, 2008
8	Cheng et al., 2009 [40]	13 identical 2D street canyons regularly placed in the streamwise direction	-	Ansys Fluent, 2008
9	di Sabatino et al., 2003 [14]	-	LDA	-
10	Ding and Lam, 2019 [58]	Urban form	-	scSTREAM v13

Table 3. Cont.

No.	Author	Building/City Type	Experiment	Simulation Codes/Instruments Used
11	Du et al., 2018 [59]	Isolated building surrounded by three building heights	-	Ansys 2010
12	Duan and Ngan, 2019 [60]	Regular building array	Wind tunnel data	-
13	Duan and Ngan, 2020 [20]	Cubical building array	-	PALM
14	Ernest et al., 1991 [61]	2 single-room models	BL WTE	-
15	Fellini et al., 2020 [21]	Idealized urban geometry	Closed-circuit WTE	-
16	Gupta and Tripathy, 2015 [62]	Cylindrical, cuboidal and back stair type buildings	-	Ansys (2D, 3D)
17	Ignatius et al., 2019 [63]	Urban canopy	-	BESCAM, EnergyPlus, CityGML, IFC-BIM
18	Li et al., 2020 [13]	5 street canyon structures	-	Ansys Fluent 15.0
19	Mittal et al., 2018 [64]	-	-	-
20	Nazarian et al., 2017 [37]	Idealized 3D urban configuration	-	PALM
21	Peng et al., 2017 [65]	Urban morphology	-	-
22	Peng et al., 2017 [39]	Ten identical buildings	-	-
23	Peng et al., 2019 [66]	Urban morphology	-	Ansys Fluent 15.06
24	Ramponi et al., 2015 [4]	Buildings with different urban densities and equal and unequal street widths	-	-
25	Rizk et al., 2018 [67]	Single rooms with different opening configurations	-	-
26	Sanchez et al., 2012 [68]	-	-	-
27	Toparlak et al., 2017 [69]	-	-	-
28	Zhang and Mirzaei., 2020 [29]	-	-	CFDf- CFX, CFDc- Ansys Fluent 19.1, BES-EnergyPlus
29	Zhao et al., 2020 [33]	Urban form	PIV	-

Table 4. Overview of studies of fictitious urban areas without validation comparison with experimental or numerical data: adopted turbulence models and parameters, and listed keywords.

No.	Author	Turbulence Models	Parameters	Keywords
1	Ai and Mak, 2014 [54]	RNG	-	CFD; mesh number; model scale; numerical resources; reduced-scale model
2	Aristodemou et al., 2020 [55]	Adaptive LES	-	air pollution dispersion; large eddy simulation; tall buildings; turbulence
3	Buccolieri et al., 2020 [56]	-	UCL, UCPs, ISL	-
4	Carrilho da Graça and Linden, 2016 [57]	-	-	day lighting; natural ventilation; single sided ventilation; stack; vortex shedding
5	Chatzimichailidis et al., 2019 [32]	LES	-	atmospheric dispersion models; large eddy simulations; machine learning; street canyon aspect ratio; daily temperature cycle; daily temperature range (DTR); scaled outdoor measurement of urban climate; street canyon; thermal storage
6	Chen et al., 2020 [35]	-	SAR	air quality; computational fluid dynamics (CFD); $k - \epsilon$ turbulence model; Reynolds-averaged Navier–Stokes (RANS) equations; street canyon
7	Cheng et al., 2008 [16]	RNG	ACH, PCH, θ , τ	

Table 4. Cont.

No.	Author	Turbulence Models	Parameters	Keywords
8	Cheng et al., 2009 [40]	RNG	ACH, PCH, Ri	RNG $k - \epsilon$ turbulence model; air exchange rate (ACH); ground heating; street canyons; ventilation
9	di Sabatino et al., 2003 [14]	-	-	dispersion modelling; low wind conditions; pollutant dispersion; street canyon; traffic produced turbulence; urban areas
10	Ding and Lam, 2019 [58]	RNG	UD, TBH, HV, OS, WD, OUC	coupled CFD simulation; data-driven model; early design support; high-density city; machine learning; urban ventilation
11	Du et al., 2018 [59]	RNG	OMVR	building height; building porosity; computational fluid dynamics (CFD) simulation; pedestrian level wind comfort
12	Duan and Ngan, 2019 [60]	LES	Rb	computational fluid dynamics; error statistics; flow-regime transition; large-eddy simulation; quadrant analysis; stratification
13	Duan and Ngan, 2020 [20]	LES	-	flow regime; pollutant dispersion; stable stratification; tracer age; urban boundary layer
14	Ernest et al., 1991 [61]	-	-	-
15	Fellini et al., 2020 [21]	-	CAR	solar radiation; street canyon; thermal effects; urban air pollution; wind-tunnel experiments
16	Gupta and Tripathy, 2015 [62]	Laminar flow	BAF	air flow affecting ventilation system; building aerodynamics; building ventilation
17	Ignatius et al., 2019 [63]	-	-	-
18	Li et al., 2020 [13]	SKE, RNG, RKE	IF_p	computational fluid dynamics (CFD); intake fraction; street canyon; wind catchers
19	Mittal et al., 2018 [64]	-	-	building design; CFD; urban wind climate; wind comfort; wind tunnel test
20	Nazarian et al., 2017 [37]	LES	-	computational fluid dynamics; pollutant dispersion; realistic heating distribution; three-dimensional street canyon; turbulent transfer
21	Peng et al., 2017 [65]	SKE, IMERSOL radiation model, Boussinesq approximation for buoyancy	FAR, BSC, VR_w, AT	correlation research; morphological parameter; ventilation performance
22	Peng et al., 2017 [39]	SKE	-	full numerical simulation; pollutants dispersion; urban street canyon; wind driven natural ventilation; window opening percentage
23	Peng et al., 2019 [66]	SKE	FAR, BSC, Q, MAA, NEV, PFR, VE, TP	building site coverage; outdoor ventilation; urban morphology; ventilation efficiency
24	Ramponi et al., 2015 [4]	SKE, RNG, RKE	-	building aerodynamics; CFD; natural ventilation; urban physics; urban wind flow; ventilation efficiency
25	Rizk et al., 2018 [67]	-	-	cross-ventilation techniques; hot; outdoor wind conditions; single room space; velocity and temperature; wind driven
26	Sanchez et al., 2012 [68]	$k - \epsilon$	-	windcatcher; passive elements; natural ventilation; pressure coefficient; CFD
27	Toparlar et al., 2017 [69]	-	-	adaptation measures; building energy consumption; computational fluid dynamics (CFD); sustainability; urban physics
28	Zhang and Mirzaei., 2020 [29]	CFD_f: modified $k - \epsilon$, CFD_c: SKE	-	computational fluid dynamics, cross-ventilation, coupling, urban climate, natural ventilation, building energy simulation
29	Zhao et al., 2020 [33]	RANS, LES	-	computational fluid dynamics; scaling analysis; turbulence models; urban street canyon flows; wind tunnel measurements

Table 5. Overview of studies of real urban areas with validation comparison with experimental or numerical data: name and type of studied location and type of experiments.

No.	Author	Study Location into Consideration	Building/City Type	Experiment
1	Balczó and Tomor, 2016 [11]	József Nádor Square, Budapest	Typical urban square	Göttingen-type WTE with LDV
2	Biao Wang, 2016 [70]	Beijing, China	Urban form, high residential buildings	WTE
3	Chatzidimitriou and Yannas, 2017 [31]	Thessaloniki, Greece	18 central street canyons	Airflow measurements during both summer and winter
4	Chen et al., 2020 [71]	Guangzhou, Kunming, Shanghai, Beijing, Harbin (China)	Idealized building arrays	WTE
5	Gao and Lee, 2012 [8]	Hong Kong, China	Residential estate	Prevailing wind conditions measurements around representative building
6	Hii et al., 2014 [25]	Singapore	High-density Central Business District (CBD)	Weather station, roadside measurements
7	Izadyar et al., 2020 [43]	Brisbane, Australia	Residential building	Measurements using anemometer, relative humidity sensors, temperature sensors
8	Javanroodi et al., 2018 [72]	Tehran, Iran	High-rise building surrounded by different urban configurations	Available in-site measurements and wind tunnel tests data
9	Kangkang et al., 2020 [73]	Bozhou, China	Central area of the city	Hourly wind speed data of Bozhou Weather Station
10	King et al., 2017 [6]	Bedford, UK	An isolated cube and an irregular nine-cube array	Experiments using the Silsoe cube
11	Masoumi et al., 2017 [74]	Bushehr, Iran	Compact urban form	Wind velocity measurements by anemometer
12	Mora-Pérez et al., 2016 [75]	Valencia, Spain	Residential house	Wind measurements and statistics data measurement
13	Mosteiro-Romero et al., 2020 [28]	Central Zurich, Switzerland	District level	Wind speed, air temperature and relative humidity measurements from weather station
14	Poh et al., 2020 [76]	Singapore	Reduced-scale tree	WTE with PIV
15	Ricci et al., 2020 [41]	Quartiere La Venezia, Livorno, Italy	District of Livorno, Italy	Closed-loop subsonic WTE
16	Song et al., 2018 [19]	Clarence Centre in Borough of Southwark, London	Three-storey test building	WTE
17	Tong et al., 2017 [9]	Miami, Houston, Los Angeles, New York City, Chicago, Minneapolis (USA)	High-rise buildings in 6 climate zone in US	Hourly air velocity surface data measurement
18	Tong et al., 2018 [77]	Tianjin, China	Sino-Singapore Tianjin Eco-city (SSTEC) in Tianjin, China	Wind speed, air temperature and relative humidity measurements
19	Wang et al., 2020 [78]	Gangnam-gu, Yangcheon-gu in Seoul; Pyeongtaek City in Gyeonggi-do, Republic of Korea	Three target areas with high-rise buildings	Wind speeds measurement
20	Wong et al., 2021 [79]	Kent Ridge campus, National University of Singapore (NUS), Singapore	-	Wind speed, dry-bulb temperature, relative humidity, solar radiation and rainfall measurements
21	Yahia et al., 2018 [80]	Dar es Salaam, Tanzania	Single- or two-story houses	On-site long-term measurements of wind speed, air temperature and relative humidity

Table 6. Overview of studies of real urban areas with validation comparison with experimental or numerical data: adopted simulation codes, turbulence models and parameters.

No.	Author	Simulation Codes/Instruments Used	Turbulence Models	Parameters
1	Balczó and Tomor, 2016 [11]	MISKAM flow and dispersion microscale model	Modified $k - \epsilon$	-
2	Biao Wang, 2016 [70]	Ansys 12.0	-	-
3	Chatzidimitriou and Yannas, 2017 [31]	ENVI-met v4	-	-
4	Chen et al., 2020 [71]	CitySim	SKE	Ri
5	Gao and Lee, 2012 [8]	AIRPAK (Ansys, 2008)	RNG	MAA, BVC, KCA
6	Hii et al., 2014 [25]	Ansys Fluent 14	RKE	-
7	Izadyar et al., 2020 [43]	Ansys Fluent V19.0	RNG	IAD, IAV
8	Javanroodi et al., 2018 [72]	Autodesk CFD, Ansys Fluent, Energy Plus	SKE	UD, UBF, UP
9	Kangkang et al., 2020 [73]	Help of GIS	-	SVE, SR, UHI
10	King et al., 2017 [6]	OpenFoam, Ansys Fluent	OpenFoam: SAS; Fluent: SAS, SST	-
11	Masoumi et al., 2017 [74]	Ansys 14.5 CFX	$k - \epsilon$	-
12	Mora-Pérez et al., 2016 [75]	STAR-CCM+	SKE	-
13	Mosteiro-Romero et al., 2020 [28]	ENVI-Met 4.4, CEA	LES	-
14	Poh et al., 2020 [76]	OpenFOAM 2.4	$k - \epsilon$ and LES with porous media	TA, LAD
15	Ricci et al., 2020 [41]	OpenFOAM 2.3.0	SKE, RKE, RNG, SKO, SST	FB, R
16	Song et al., 2018 [19]	FLUIDITY	LES	-
17	Tong et al., 2017 [9]	MATLAB	-	-
18	Tong et al., 2018 [77]	3D GIS model	-	GnPR, SVE, PAVE, BDG
19	Wang et al., 2020 [78]	LDAPS-CFD tool	RNG	-
20	Wong et al., 2021 [79]	WRF, OpenFOAM, EnergyPlus	-	-
21	Yahia et al., 2018 [80]	Envi-Met	-	MRT, PET, SP, H

Table 7. Overview of studies of real urban areas with validation comparison with experimental or numerical data: listed keywords.

No.	Author	Keywords
1	Balczó and Tomor, 2016 [11]	urban square, flow field, velocity fluctuation, urban vegetation, wind tunnel
2	Biao Wang, 2016 [70]	urban wind energy, wind environment, urban form, urban block, CFD simulation
3	Chatzidimitriou and Yannas, 2017 [31]	canyon aspect ratio; canyon axis orientation; monitoring; outdoor thermal comfort; PET; simulations; street canyon geometry; urban design; urban microclimate
4	Chen et al., 2020 [71]	atmospheric stability; CFD; CitySim; solar-induced thermal boundary conditions; urban airflow
5	Gao and Lee, 2012 [8]	natural ventilation; openings configurations; prevailing wind; residential buildings; surrounding buildings; window types
6	Hii et al., 2014 [25]	anthropogenic heat; CFD; high density; high rise; pedestrian height; site measurement; tropical
7	Izadyar et al., 2020 [43]	balcony; CFD; geometry; indoor air distribution (IAD); natural ventilation; residential
8	Javanroodi et al., 2018 [72]	cooling load; high-rise buildings; hot-arid climate; urban energy; urban morphology; ventilation

Table 7. Cont.

No.	Author	Keywords
9	Kangkang et al., 2020 [73]	ventilation corridors; heat island intensity; urban climatology; ventilation potential; wind environment
10	King et al., 2017 [6]	benchmark; CFD; external airflow; indoor air quality; OpenFoam; Silsoe; ventilation
11	Masoumi et al., 2017 [74]	compact urban form; hot-humid climate; natural ventilation; passive cooling; urban sustainability; vernacular architecture
12	Mora-Pérez et al., 2016 [75]	computational fluid dynamics; energy efficient buildings; low carbon technologies; natural ventilation; wind energy
13	Mosteiro-Romero et al., 2020 [28]	City Energy Analyst (CEA); ENVI-met; building energy demand; district scale; model coupling; urban microclimate
14	Poh et al., 2020 [76]	ecology; centre for urban greenery; department of mechanical engineering; national parks board; National University of Singapore; Singapore botanic gardens
15	Ricci et al., 2020 [41]	3D steady RANS; roughness height; turbulence models; urban canopy layer; urban wind flow
16	Song et al., 2018 [19]	air pollutants; air quality; buildings; dispersion; microclimates; modelling; natural ventilation; urban design
17	Tong et al., 2017 [9]	natural ventilation; high-rise building; mixed-mode ventilation; meteorology; atmospheric boundary layer (ABL); NV hour
18	Tong et al., 2018 [77]	air temperature evaluation; geographical information system; multiple linear regression; northern China; urban morphology parameters
19	Wang et al., 2020 [78]	CFD model; local data assimilation and prediction system; morphological parameter; wind speed estimation; wind speed reduction rates
20	Wong et al., 2021 [79]	multi-scale; multi-physics; urban microclimate; virtual buildings and modelling; field measurement
21	Yahia et al., 2018 [80]	-

Table 8. Overview of studies of real urban areas with validation comparison with experimental or numerical data: name and type of studied location and type of experiments.

No.	Author	Study Location into Consideration	Building/City Type	Experiment
1	Belleri et al., 2013 [81]	Bolzano (Italy), Palermo (Italy), San Francisco (USA)	Four-story office building north-south oriented	-
2	Du and Mak, 2020 [82]	Hong Kong Polytechnic University, Hong Kong (China)	-	WTE
3	Du et al., 2017 [83]	Hong Kong Polytechnic University, Hong Kong (China)	University campus	Closed-circuit subsonic BL WTE
4	He et al., 2019 [26]	Greater Sydney, Australia	Urban city	-
5	Ignatius et al., 2015 [84]	Singapore	9-hectare office precinct	-
6	Javanroodi and Nik, 2019 [85]	Tehran, Iran	Twelve-story office building	-
7	Javanroodi and Nik, 2020 [27]	Stockholm, Sweden	Complex geometric urban forms (mesoscale to microscale)	-
8	Jiang et al., 2020 [30]	Wuhan, China	Six typical parallel type residential building layouts	-
8	Kouhirostami et al., 2018 [86]	Lubbock, USA	Classroom	-
10	Lee, 2017 [7]	Copenhagen, Denmark	Actual city model of Copenhagen	-
11	Li et al., 2019 [42]	Nanjing, China	Typical urban area	Back-flow, ABL WTE
12	Lo and Ngan, 2017 [38]	Hong Kong, China	Idealized and realistic urban domain	-
13	Luo et al., 2020 [87]	Los Angeles, California	City	-
14	Nugrahanti et al., 2018 [88]	Cilincing, Indonesia	Walk-up apartment (vertical housing)	-

Table 8. *Cont.*

No.	Author	Study Location into Consideration	Building/City Type	Experiment
15	Pawar et al., 2020 [89]	Singapore	High-rise commercial buildings set	-
16	Qi et al., 2012 [90]	Hong Kong, China	Typical local hotel building	Hourly meteorological data measurement
17	Shi et al., 2020 [91]	Singapore	Built urban form	-
18	Yang et al., 2004 [92]	Beijing, Shanghai, Guangzhou, Urumqi (China)	Low-rise residential buildings	-

Table 9. Overview of studies of real urban areas with validation comparison with experimental or numerical data: adopted simulation codes, turbulence models and parameters.

No.	Author	Simulation Codes/Instruments Used	Turbulence Models	Parameters
1	Belleri et al., 2013 [81]	EnergyPlus	-	IG, SG, EC, WG, WOT
2	Du and Mak, 2020 [82]	-	-	MVR, OMVR
3	Du et al., 2017 [83]	-	-	OMVR
4	He et al., 2019 [26]	-	-	-
5	Ignatius et al., 2015 [84]	-	-	FAR, GSC, OSR, ST
6	Javanroodi and Nik, 2019 [85]	Autodesk CFD	SKE	UD, VAR, SC, PAR
7	Javanroodi and Nik, 2020 [27]	Autodesk CFD, Ansys Fluent	SKE with radiation	MF
8	Jiang et al., 2020 [30]	Envi-Met	-	UTCI
9	Kouhirostami et al., 2018 [86]	Autodesk CFD	-	-
10	Lee, 2017 [7]	Ansys Fluent 18.0	RKE	-
11	Li et al., 2019 [42]	-	-	Openness, area, shape
12	Lo and Ngan, 2017 [38]	PALM	LES	RT, ET
13	Luo et al., 2020 [87]	WRF-UCM 4.1.2, EnergyPlus 9.1.0	-	-
14	Nugrahanti et al., 2018 [88]	Ansys Fluent	-	-
15	Pawar et al., 2020 [89]	STL, Cham-Phoenix	$k - \epsilon$	-
16	Qi et al., 2012 [90]	-	-	-
17	Shi et al., 2020 [91]	City Energy Analyst	-	-
18	Yang et al., 2004 [92]	-	-	PDPH

Table 10. Overview of studies of real urban areas with validation comparison with experimental or numerical data: listed keywords.

No.	Author	Keywords
1	Belleri et al., 2013 [81]	-
2	Du and Mak, 2020 [82]	evaluation criterion; general design framework; pedestrian level wind environment; improvement measures, high-density cities
3	Du et al., 2017 [83]	exceedance probability; pedestrian level wind comfort; threshold mean wind velocity; wind comfort criteria
4	He et al., 2019 [26]	microclimate; performance-based planning; precinct ventilation zone; urban morphology; urban ventilation
5	Ignatius et al., 2015 [84]	district energy performance; district heat gain; outdoor temperature; outdoor thermal comfort; thermal load units; urban heat island; urban ventilation
6	Javanroodi and Nik, 2019 [85]	-
7	Javanroodi and Nik, 2020 [27]	air temperature; extreme weather conditions; metrological mesoscale model; numerical simulations; urban microscale model; wind speed
8	Jiang et al., 2020 [30]	ENVI-met; microclimate; residential building layout; universal thermal climate index

Table 10. Cont.

No.	Author	Keywords
9	Kouhirostami et al., 2018 [86]	windows, CFD, natural ventilation, classroom, cross ventilation, air flow rate, air velocity magnitude, Louver, wind direction, building orientation
10	Lee, 2017 [7]	building layers; CFD simulations; outdoor airflow; pedestrian level wind; urban wind simulations
11	Li et al., 2019 [42]	correlation research; pedestrian level wind; urban space; wind tunnel experiment
12	Lo and Ngan, 2017 [38]	air pollution; Lagrangian circulation/transport; large eddy simulations; Urban meteorology
13	Luo et al., 2020 [87]	anthropogenic heat; building heat emissions; heat wave; urban building energy model; urban microclimate; WRF-UCM
14	Nugrahanti et al., 2018 [88]	wind-driven natural ventilation; green design; passive thermal comfort; walk-up apartment
15	Pawar et al., 2020 [89]	-
16	Qi et al., 2012 [90]	climate warming; latent load; sensible load; urban heat island effect; ventilation load
17	Shi et al., 2020 [91]	solar energy penetration; capital costs; urban form; block typology; energy-driven urban design
18	Yang et al., 2004 [92]	natural ventilation; natural ventilation potential; prediction method; pressure difference Pascal hours

Each study also reports some keywords, the use of which makes it possible to look for correlations among the different topics. A list of the most common keywords is reported below:

- Age of air (τ);
- Air change rate per hour (ACH);
- Air quality;
- Ansys;
- Anthropogenic heat;
- Aspect ratio;
- Building aerodynamics;
- Building site coverage;
- Buoyancy;
- Climate;
- Computational fluid dynamics;
- Cross ventilation;
- EnergyPlus;
- ENVI-met;
- Field measurement;
- Floor area ratio (FAR);
- Flow characteristics;
- Froude number;
- High-rise building;
- Indoor air distribution (IAD);
- Indoor air quality;
- $k - \epsilon$ Turbulence model;
- Large-eddy simulation (LES);
- Low-rise building;
- Mean radiant temperature (MRT);
- Microclimate;
- Mixed-mode ventilation;
- Natural ventilation;
- Numerical simulation;
- OpenFoam;
- Outdoor airflow;
- Outdoor temperature;
- Outdoor ventilation;

- Outdoor wind comfort;
- Pedestrian wind comfort;
- Pollutant dispersion;
- Realizable $k - \epsilon$ turbulence model;
- Residential buildings;
- Reynolds number;
- Reynolds-averaged Navier–Stokes (RANS) equations;
- Richardson number;
- RNG k-epsilon turbulence model;
- Roughness height;
- Single sided ventilation;
- Site measurement;
- Street canyon;
- Temperature;
- Thermal comfort;
- Thermal stratification;
- Turbulence models;
- Urban air pollution;
- Urban airflow;
- Urban areas;
- Urban boundary layer;
- Urban built environment;
- Urban canopy;
- Urban canopy layer;
- Urban climate;
- Urban heat island;
- Urban meteorology;
- Urban microclimate;
- Urban morphology;
- Urban ventilation;
- Urban wind flow;
- Wind driven natural ventilation;
- Wind energy;
- Wind environment;
- Wind speed;
- Wind tunnel.

The VOSviewer (<https://www.vosviewer.com/>, accessed on November 2022) was used to map the keywords to understand the connections of keywords with each other. VOSviewer is a software tool for constructing and visualizing bibliometric networks, which may for instance include journals, researchers or individual publications, and can be constructed based on citation, bibliographic coupling, co-citation or co-authorship relations. The extraction of data from the literature was performed by the following procedure (detailed description is mentioned in the reference [93–95]):

An occurrence matrix O is defined first with N columns and M rows, where N represents the number of investigated research articles and M the number of found items (in this case, “keywords”). Each entry of O , where the column, corresponding to a certain item, meets the row, corresponding to a certain article, is either of a value of one if at least one keyword of this article appears in the keywords set corresponding to the item, or zero otherwise. Matrix multiplication is performed between matrix O^T and the original matrix O and the squared matrix C is obtained with the dimension $M \times M$ which denotes the respective co-occurrences of the keywords from all the investigated articles. Both rows and columns of matrix C refer to the items. The elements in the main diagonal of matrix C represent the total occurrence of each item, which is the number of research papers in which at least one of the keywords out of the keyword set assigned to the specific item is

listed. Every other element of C represents the co-occurrence of the respective item pair, which is the number of research articles in which at least one keyword out of each of the two keyword sets assigned to the two items appears.

3. Overview of Types and Methods of the Selected Papers

As mentioned before, the studies were categorised as per the type of journal in which they were published, year of publication, keywords, first author's institute countries, type of urban area used, whether the study was carried out at real or reduced scale, type of flow, type of study, i.e., whether a street canyon was included or not, methodology, parameters/indexes and dimensionless numbers. As specified previously, the variable "type of urban area used for the study" considers whether the urban area is generic or real and whether it is validated. Validation refers to comparison with experiments and/or with CFD simulation results. "Type of flow" considers whether the flow is wind-driven or buoyancy-driven or a combination of both. In total, 60.7% of the studies considered in this paper mainly deal with the wind-driven flow (54 out of 89 studies), 10 studies (11.2%) include a combination of both wind- and buoyancy-driven flow, and only 2 studies (2.2%) deal with buoyancy-driven flow, while the remaining 23 studies (25.8%) do not refer to a specific type of flow. Likewise, these studies focus only on outdoor environments, on indoor ones or a combination of both: 66 (74.6%) are outdoor studies, 6 (6.7%) indoor ones, 13 (14.6%) are combination of both and the remaining 4 studies (4.5%) are related to reviews.

Methodology deals with the type of activities (if experimental or numerical investigation), performed experiments, numerical simulations and applied governing equations. As regards the latter ones, they depend on the type of simulation tool used, the discretization method selected, governing parameters and boundary conditions chosen, etc. For the experimental part, field measurements, wind tunnel tests and other experimental activities are performed, and for numerical simulations, CFD software and other tools are used. As far as the experimental studies are concerned, 23 studies (63.9%) used wind tunnel tests while 13 studies (36.1%) performed other experimental activities. The most common CFD tools, instead, are ANSYS (21 studies, i.e., 75%) and OpenFoam (4 studies, i.e., 14.3%); EnviMet (3, i.e., 10.7% studies) is also used to run CFD simulations, and EnergyPlus to perform building energy simulations.

While performing experiments in controlled environments, the analysis of the scale of the experiment plays a crucial role in the representativeness of the findings. In most cases of street canyon and pedestrian-level natural ventilation studies experimentally replicated in wind tunnel setups, different reduced-scale models can be used [3,10,11,19,23,34,41,42,44,48,50,82,83]. Jian Hang et al. [23] and Xia Yang et al. [34] used 1:10 reduced scale; Aly Mousaad Aly et al. [44] and Xiaoping Liu et al. [48] a 1:100 reduced scale; and Qun Wang et al. [50] and Yaxing Du, Cheuk Ming Mak [82] chose 1:200.

Focusing on simulation methods, the most common governing equations used in the considered studies are either Reynolds-averaged Navier–Stokes (RANS) equations or large-eddy simulations (LES). The commonly used turbulence models for simulations are standard $k - \epsilon$ model [27,50], Realizable $k - \epsilon$ model [7,51], RNG $k - \epsilon$ turbulence model [8,58], standard $k - \omega$ (SKO) model [41], shear-stress transport (SST) $k - \omega$ [6] and LES [18,46]. Ramponi et al. [4], Li et al. [13] and Li et al. [47] selected more than one turbulence model to verify their data or to compare the results with other turbulence models.

While working with the outdoor air displacement and street canyons, pollution-related factors are sometimes included. Pollutant concentration [5,58], pollutant exchange [16], type of pollutant, etc., are some of the examples found in 14 studies in the analysed group mentioning pollution-related factors.

There are some target parameters and dimensionless numbers which were found to be relevant to develop proper research about air displacement in urban environments, such as

- Age of air (τ) [34];
- Air change rates per hour (ACH) [16,34], purging flow rate (PFR) [34];

- Air exchange rate (ACH), pollutant exchange rate (PCH) [40];
- Aspect ratio (AR) [21,23];
- Building and street canyon aspect ratio [22];
- Cavity aspect ratio [21];
- Characteristic roughness of the canyon walls, Prandtl no. (Pr), Schmidt no. (Sc) [21];
- Floor area ratio (FAR) [84];
- Froude number (Fr) [21,23];
- Indoor air velocity (IAV), indoor air distribution (IAD) [43];
- Mean radiant temperature (MRT) [80];
- Mean wind velocity ratio (MVR) [82];
- Outdoor air change (OACH), outdoor air change efficiency (OACE) [10];
- Overall mean wind velocity ratio (OMVR) [59,82,83];
- Personal intake fraction (P_{IF}) [13,23];
- Pollutant concentrations [5,16];
- Pollutant exchange rate (PCH), retention time (τ) [16];
- Pressure difference Pascal hours (PDPH) [92];
- Residence and exposure time [38];
- Reynolds number (Re) [5,21,23];
- Richardson number (Ri) [15,23,40,48];
- Street aspect ratio [3,34,35], building area (packing) density [3];
- Universal Thermal Climate Index [30];
- Urban canopy layer (UCL) [56].

4. Comparative Analysis of the Air Displacement Considering the Effects of Street Canyon and Natural Ventilation Potential

4.1. Type of Building/City Layout

While working on a study related to outdoor air displacement, it is necessary to define the location and/or structure that is going to be studied. A total 56 out of 89 (62.9%) studies considered in this paper focused on a street canyon and out of these 56 studies, 23 studies (41.1%) referred to real locations and the remaining 33 (58.9%) used fictitious buildings or urban layouts. Generic buildings or building layouts considered here are standard-shaped cubical or cuboidal buildings and standard arrays of buildings. As mentioned before, there are 23 studies which chose real locations for their research activity: 7 studies with Chinese cities (Nanjing [8], Wuhan [38], Hong Kong [30,42,82,83], Beijing, Shanghai, Guangzhou, Urumqi [92]); 7 studies with European cities (Bedford, UK [19], Copenhagen, Denmark [27], Budapest, Hungary [11], London, UK [41], Stockholm, Sweden [6], Thessaloniki, Greece [31], Livorno, Italy [7]); 4 studies with Singaporean locations [25,79,84,89]; 2 studies with Australian cities (Greater Sydney [26], Brisbane [43]); 1 study with South Korean locations (Seoul, Gyeonggi-do [78]); 1 study with a American locations (Miami, Houston, Los Angeles, New York, Chicago, Minneapolis [9]); and 1 study with a Tanzanian city (Dar es Salaam [80]). It can be noticed that the majority of the considered studies are carried out in large and highly populated cities, often in China and Singapore. Most of these cities are mainly from the subtropical climatic regions, hot and humid climatic regions according to the Köppen climatic classification.

4.2. Methodology

As specified earlier, out of 89 papers considered, 56 papers dealt with street canyon effects and natural ventilation potential. Out of these 56 studies, 13 (23.2%) just ran real-scale experiments while 26 of them (46.4%) only ran CFD simulations, 32 studies (57.1%) used wind tunnel testing and 11 out of them (19.6%) also included the experimental data from other sources. For example, Zheng et al. [53] conducted their study using the experimental data from Jiang et al. [96]. Similarly, Dai et al. [5], Park et al. [15] and Li et al. [47] obtained the experimental data from Dascalaki et al. [97], Addepalli and Pardyjak [98] and Blocken et al. [99], respectively.

To perform experiments in wind tunnels, attention has to be paid to the similarity criteria when deciding on the reduced-scale model. While doing that, the blockage ratio has to be less than 5%. For example, Hang et al. [23] and Yang et al. [34] used a 1:10 reduced-scale model of their simple cubic building and idealized 2D street canyons, while Wang et al. [50], Ai and Mak [54] and Du and Mak [82] used a 1:200 reduced-scale model. Some authors also performed other experiments rather than wind tunnel experiments and field measurements. For instance, Chen et al. [17] applied an experimental fine-bubble technique in a large water tank to model buoyancy-driven flows in buildings.

Ansys, OpenFoam and EnviMet are often used as CFD tools for the fluid flow simulation whereas EnergyPlus is considered for building energy simulations (BES), sometimes coupled together to also calculate building energy consumption. Sometimes, EnergyPlus can also be coupled with these tools to set some boundary conditions.

Other authors preferred customized codes or less popular tools. For instance, Hang et al. [3] developed the “Ventair” code using Fortran language for their CFD simulation, to study the flows through and within high-rise building arrays and their link to ventilation strategy. Aristodemou et al. [55] implemented the FLUIDITY tool, which allows remeshing of the considered domain based on a posteriori error estimates, whilst achieving certain targets for error. Ding and Lam [58] preferred to use scSTREAM to carry out their 3D steady-state incompressible flow simulations. Luo et al. [87] employed the WRF-UCM modelling framework to capture microclimate dynamics under extreme heat conditions; Nazarian [36] and Lo and Ngan [38] used PALM (parallelized LES model) to perform their simulations.

In 27 studies, comparisons have been carried out against experimental data or CFD results. Song et al. [19], Ricci et al. [41] and Balczó and Tomor [11] represented normalized horizontal velocity magnitude distributions in wind tunnel measurements and CFD simulations for different chosen heights. Likewise, Hii et al. [25], Chatzidimitriou and Yannas [31], Izadyar et al. [43], Gao and Lee [8], Wang et al. [78], Yahia et al. [80] and Wong et al. [79] conducted field measurements and made comparisons against CFD results. The remaining studies either performed experimental activities or CFD simulations [7,27,30,38,82,83,89].

While using these CFD tools, it is also necessary to set governing equations, turbulence models and boundary conditions for simulating the models. The turbulence models more frequently used are standard $k - \epsilon$ turbulence model, renormalization group (RNG) $k - \epsilon$ turbulence model, realizable $k - \epsilon$ turbulence model, standard $k - \omega$ turbulence model, and shear stress transport (SST) $k - \omega$ turbulence model. The typical governing equations are the Reynolds-averaged Navier–Stokes (RANS) equations and the large-eddy simulation (LES) model, with RANS being less computationally demanding compared to LES, although less accurate. It was found that the selection of turbulence models was often decided upon the availability computational resources. The standard $k - \epsilon$ turbulence model is preferred widely in the literature because of its simplicity and lower computational time [37,39]. The standard $k - \omega$ model provides a satisfactory performance for swirling flows in the near-wall region but this model is prone to overpredicting the shear stresses of adverse pressure gradient boundary layers and it has issues with freestream conditions. This model, however, is extremely sensitive to inlet BCs as opposed to $k - \epsilon$ models [41].

Li et al. [13], Javanroodi and Nik [27], Li et al. [37], Peng et al. [39] and Wang et al. [50] used a standard $k - \epsilon$ turbulence model because of its lower computational resource requirement and simplicity. In total, 12 (out of 56) papers, i.e., 21.4%, employed the renormalization group (RNG) $k - \epsilon$ turbulence model [8,15,16,22,23,34,40,43,48,58,59,78] and 4 (out of 56) papers, i.e., 7.1%, used the realizable $k - \epsilon$ turbulence model [7,25,49,51]. These two turbulence models give some advantages over the standard $k - \epsilon$ turbulence model in terms of results and sometimes they also overestimate the results. The RNG $k - \epsilon$ and realizable $k - \epsilon$ turbulence models are more accurate than the standard $k - \epsilon$ at modelling the mean flow of complex structures, flows involving rotation, flow separation and recirculation. A total of 9 (out of 56) papers, i.e., 16.1%, considered large-eddy simulation (LES) [5,18–20,32,38,44,46,55]. Overall, 29 out of 56 studies, i.e., 51.8%, considered RANS

equations to simulate their models, whereas 6 (out of 56) papers, i.e., 10.7%, preferred more than one turbulence model [4,6,13,33,41,47].

4.3. Parameters/Indexes/Dimensionless Numbers

It is necessary to specify some parameters, indexes or dimensionless numbers to reach the goal of the research activity. As shown from Tables 1–10, the majority of studies considered more than one parameter, index and dimensionless number. These parameters are categorised based on the characteristics required for the research activity, such as geometrical properties, physical, flow-related and other properties. The key parameters considering these characteristics, while dealing with outdoor air displacement, are the following: street aspect ratio (AR) [3,15,21,22,34,35], building height [3,58,79], building floor area ratio (FAR) [65,66,84], street and urban pattern [72,79], urban density [58,72,85] and geometrical and physical properties. Age of air (τ) [8,66], air temperature (AT) [65], purging flow rate (PFR) [34,66], pollutant (concentration, exchange) [5,16,40], overall mean wind velocity ratio (OMVR) [59,82] are the air-flow-related properties, while the common dimensionless numbers are: Reynolds number (Re) [5,21,23], Richardson number (Ri) [15,23,40,48,71] and Froude number (Fr) [21,23].

For instance, Gao and Lee [8] analysed the mean age of air to understand the influence of surrounding buildings on the natural ventilation performance of residential dwellings in Hong Kong and found an increase in the mean age of indoor air by 0.6 to 1.5 times due to the presence of surrounding buildings.

Park et al. [15] investigated the flow characteristics around step-up street canyons with various building ARs and found that the in-canyon flows undergo two stages, i.e., development and mature stages, as the building-length ratio increases above 2. In the development stage, the position of the primary vortex changes, and the incoming flow closely follows both upstream and downstream building sidewalls, while in the mature stage, the primary vortex stabilizes, and the incoming flow no longer follows building sidewalls. Yang et al. [34] aimed to quantify the influence of AR and window size on indoor–outdoor ventilation in two-dimensional streets with single-sided naturally ventilated buildings, discussing air change rates per hour (ACH), age of air (τ) and purging flow rate (PFR). They found that shallower streets experience better indoor–outdoor ventilation, but in extremely deep canyons with AR = 5, two-counter-rotating vortices produce much smaller velocity at low-level regions, resulting in small air change rates. Peng et al. [65] and Peng et al. [66] discussed the correlation between the urban morphological characteristics and ventilation performance by keeping the floor area ratio (FAR) constant and changing building site coverage (BSC), using mean age of air and purging flow rate (PFR) as metrics. They found that, at FAR = 5, the ventilation performance is closely related to BSC. Javanroodi et al. [72] and Javanroodi and Nik [85] used urban density (UD), urban building form (UBF) and urban pattern (UP) as morphological parameters to investigate ventilation potential in a high-rise building surrounded by different urban configurations in Tehran.

Fellini et al. [21] and Hang et al. [23] used Reynolds number (Re) and Froude number (Fr) to evaluate the combined effects of street canyon geometry, wall roughness and wall heating on pollutant dispersion in street canyons. In order to do that, they performed CFD simulations and wind tunnel tests on their street canyon geometry. Cheng et al. [40] used Richardson number (Ri) to assess the relative contributions of the wind- and buoyancy-driven flow. They stated that the negative Ri corresponds to unstable stratification and more negative Ri represents a larger contribution from the buoyancy. Liu et al. [48] used Ri to study the effects of surface temperature rise induced by the solar radiation on near-wall flow and found that, if $Ri < 0.1$, the effects on small-scale models should not be ignored.

Du and Mak [82] and Du et al. [59] utilised mean wind velocity ratio and overall mean wind velocity ratio to understand the effects of building height and porosity on pedestrian-level wind velocity in high-density cities. They also found that using these parameters instead of actual wind velocity can be convenient in scaled models.

Some authors introduced new quantities or employed less common parameters and variables to discuss the urban air displacement and the natural ventilation potential. Lina Yang et al. [92] introduced the concept of pressure difference Pascal hours (PDPH), which is defined as the hourly sum of the positive differences between hourly effective pressure and required pressure. Ding and Lam [58] discussed the CIOI, which is a dimensionless index to assess indoor cross-ventilation potential while considering the outdoor wind environment.

4.4. Pollution Related Factors

As specified in the overview in Section 2, pollution is often considered in ventilation studies. Tan et al. [18] performed simulations to study the impact of source shape on pollutant dispersion in a street canyon under neutral and unstable thermal stratification, considering airborne particulate matter (PM) to quantify the pollutant concentration in the street canyon. Aristodemou et al. [55] carried out numerical tests (adaptive LES) to assess the effect of the location of a tall building on the surrounding area in terms of air flow turbulence and pollution dispersion. Ding and Lam [58] used velocity, pressure or pollutant concentration to calculate the CIOI index to assess indoor cross-ventilation potential. Song et al. [19] monitored carbon dioxide (CO₂), carbon monoxide (CO) and nitrogen dioxide (NO₂) to monitor the indoor and outdoor environment in the UK as a full-scale field measurement and performed the CFD simulation in FLUIDITY. CFD results obtained by Li et al. [13] suggested that the leeward personal intake fraction of CO is far higher in concentration than the windward wall in the shallow, regular, step-up and step-down street canyons, but lower than the windward side in the deep street canyon under different traffic tidal flow (TTF) conditions. Dai et al. [5] adopted the tracer gas technique, using carbon dioxide (CO₂), to simulate the concentration decay and the gaseous pollutant dispersion. Li et al. [37] employed a combined numerical simulation of a species transport model and the tracer gas technique to simulate pollutant dispersion and summarized the effects of driving lanes and vehicle speeds on pollutant dispersion. They concluded that the pollutant distribution on the windward side is related to that on the leeward and the concentration of pollutant behind the vehicle decreases with increasing vehicle moving speed on the leeward side. Lo and Ngan [38] introduced the analysis of Lagrangian residence and exposure residence times to the characterization of urban pollutants and dispersion. Cheng et al. [16] evaluated the street canyon ventilation and pollutant removal performance using CFD and found that the turbulent components of air exchange rate and pollutant exchange rate are about an order of magnitude larger than their mean components. Peng et al. [39] indicated that the exchange of air current between the upside and bottom of street canyons gradually enhances with the enlargement of window opening percentage. It also gradually dilutes the pollutant concentration in the target street canyon, bypassing those pollutants into the adjacent regions. Liu et al. [48] mentioned that, in the case of high-rise buildings, the windward wall surface temperature rise brings more serious pollutant accumulation and near-wall concentrations increase with the rise in temperature when the pollutant is released from the bottom and middle of leeward wall surface. Hang et al. [23] stated that a single vortex pattern is more efficient in removing the pollutants at the street level for both high and low wind speeds and buoyancy-induced wall heating scenarios can sometimes raise or reduce pollutant exposure, depending on the aspect ratios, ambient wind speed and wall heating types. This can be observed from Figures 7 to 10 of the study performed by Hang et al. [23].

4.5. Keywords Analysis

As mentioned in Section 2, an overview of the relationships between the different studies can also be found with the help of keywords. Computational fluid dynamics is the keyword which is used more often, 31 times in the chosen 89 studies, followed by “street canyon” (13 times), “natural ventilation” (11 times), “wind tunnel experiment” (10 times), “pedestrian wind comfort” (7 times), “large eddy simulation” (5 times). Then, “high-rise building”, “numerical simulation”, “urban morphology” and “urban ventilation”

cubical building. They performed a wind tunnel experiment and a CFD simulation with the help of Ansys Fluent using the RNG $k - \epsilon$ turbulence model and validated their results for different configurations.

Studies with generic urban areas with CFD comparisons usually deal with standard shapes of buildings and positioning layouts and arrays. These studies can be the ideal fit for the experimental and numerical CFD simulation studies. The standard building/structure shapes can either be cubical or cuboidal and a frequently used layout is either square array or rectangular array, depending on the goal of the study [3,10,22,34,45,46,50].

Relating to the studies included in this paper, there are very few considered study locations if the whole world is taken into consideration, and they typically are large cities. On the contrary, generic urban areas represent the ideal situations, the results of which can be used as a reference for future studies.

5.2. CFD Tools Used

There are many CFD tools available to perform the numerical simulations. Ansys, EnviMet and OpenFoam are those which have been utilised most often in the investigated studies. In particular, Ansys has been used more than other simulation tools, in 21 (out of 56) studies.

As there are different turbulence models available, one can check and select them as per necessity. The results obtained can be compared with each other to obtain the better outcome and then finalize it. Not all the turbulence models are suitable for all the required activities, and each one of them has its own limitations. The standard $k - \epsilon$ turbulence model is commonly used because of its simplicity but the production of kinetic energy near the frontal corners of buildings might sometimes be overestimated and the turbulent kinetic energy in wake regions underestimated [41,69]. Recently, the RNG $k - \epsilon$ turbulence model and the realizable $k - \epsilon$ turbulence model are gaining popularity [69]. Other than these turbulence models, LES has also gained popularity because of its high result accuracy compared with measurements. However, huge computational requirement and higher time consumption can be the main limitations of the LES. Nevertheless, advancements in technologies in the future can lead to a greater use of LES due to its higher accuracy.

5.3. Experimental and Numerical Findings

Although the focus of this literature review is on experimental and numerical methods and parameters and indicators used for their design, it is also worth discussing the findings of some contributions selected to provide, as a whole, an overview of the potential outcomes obtainable with such methodologies and the accuracy of results.

The methodology proposed by He et al. [45] shows that making parametric tools and the CFD tool work in coordination can provide efficient iterative analysis and implement quantitative comparisons for studying the influences of buildings on winds, especially for wind environment studies of large amount of buildings and their modifications. They applied this methodology to study the relationships between winds and building variables for square form and scattered configurations. They found that a reduction in windward surface areas of buildings and an increase in intervals of building clusters can increase outdoor ventilation.

Gao and Lee [8] compared field measurements, performed in Hong Kong, China, and CFD simulation data, obtained using AIRPAK (ANSYS, 2008) with the RNG turbulence model. From CFD simulation, it can be seen that surrounding buildings can lower the wind power available in the vicinity of buildings by 2.5% to 86.8%, increasing the angular spread of prevailing winds (the average direction was shifted anti-clockwise by 5° to 32°) and adversely affect natural ventilation in residential dwellings. After analysing the mean age of air, the authors suggested that, in actual urban environments, natural ventilation performance in dwellings can be enhanced by positioning two groups of window openings in opposite directions or perpendicular to each other.

Wang et al. [50] validated CFD simulations (with SKE model) with wind tunnel data to verify the exponential concentration decay occurring in urban canopy layer models. They concluded that a larger urban size attains smaller ACH. For square overall urban form, the parallel wind attains greater ACH than non-parallel wind, but experiences smaller ACH than the rectangular urban form under most wind directions. Open space increases ACH more effectively under oblique wind than parallel wind.

Hang et al. [3] studied experimentally and numerically wind flows from rural to urban areas through high-rise square building arrays, with the wind parallel to the main streets. As mentioned earlier, they used “Ventair” code using Fortran language, where 3D urban airflow field was modelled with the RANS SKE turbulence model. The horizontal profile of the normalised velocity along the street centreline was predicted generally well by the SKE turbulence model, however, turbulent kinetic energy near the windward street entry was not. Furthermore, numerical simulations predicted vertical profiles of velocity at centre points behind taller buildings relatively better than at centre points in front of them. The authors also observed that, by optimizing building heights and street widths, it is possible to optimize wind speed, enhancing ventilation in high-rise urban areas.

King et al. [6] measured façade pressures and ventilation rates in the Silsoe cube (a $6 \times 6 \times 6$ m hollow metallic cube located in a rural location in Bedford, UK) under single-sided and cross-flow ventilation configurations, and compared them with CFD simulations conducted in OpenFoam and ANSYS Fluent. Simulation results suggested that vortex shedding from upwind buildings provide pulsating ventilation in the studied window configurations, which may attenuate the negative effects of upwind flow obstruction. The obtained results showed that the simulations compare well to the experimental data on the front face of the isolated cube, but discrepancies appear at reattachment points on the roof.

Balczó and Tomor [11] were able to predict velocity magnitudes with their CFD and experimental results, observing that simulated wind speed can increase up to 50% in connecting streets. Nevertheless, they found that the numerical turbulent kinetic energy was often not in good agreement with the experimental data.

Ricci et al. [41] performed CFD simulation and wind tunnel tests (1:300 reduced-scale model) on Quartiere La Venezia district in Livorno, Italy, for three reference wind directions (i.e., 240° , 270° and 300°). They found that the CFD simulations using the SKO turbulence model showed the worst agreement with the obtained wind tunnel data, and the SKE and RKE turbulence models generally showed the best agreement with the wind tunnel data. The authors found deviations between simulated velocities and measured ones ranging from 20–30% to about 60–70% depending on the wind direction, observing that the impact of the selected turbulence models was larger than the impact of the imposed surface roughness height.

Padilla-Marcos et al. [10] performed wind tunnel experiments and CFD simulations to define a simplified procedure to identify air movement patterns in the immediate surroundings of a simplified building. A significant distortion effect of the airflow was found at a distance of five times the height of the building from its rear face (in a leeward position). The internal stresses generated before reaching the obstacle modified the upstream air particles’ motion pattern and created a “pressure bubble” facing the building. The authors found that air regions of low turbulent energy had a higher age of the air than the rest of the domain, reducing its quality.

The selected papers analysed above allowed us to underline some of the main features of ventilation studies in urban contexts. First, both numerical and experimental techniques (in particular, wind tunnel tests) can contribute to the optimization of urban layouts and buildings’ windows in order to enhance outdoor and indoor ventilation. CFD simulations can support significantly the assessment of the actual ventilation potential, for instance in high-rise building districts and in the optimization of ventilation in urban environments, especially if coupled with other numerical tools. However, numerical accuracy is not always the same or sufficient. This can be observed at both the single-building scale and at the larger, urban scale. Consequently, comparisons with empirical tests (in situ or in wind

tunnels) can contribute to the discussion of the accuracy of state-of-the-art tools and help in selecting the best models (e.g., turbulence models).

5.4. Parameters/Indexes/Dimensionless Numbers

As defined before (Section 4.3), the used parameters are related to specific domain characteristics and properties. For example, age of air (τ), air flow rate (Q) and air velocity are characteristics of air flow. Likewise, convective heat transfer coefficient (CHTC) is the heat transfer property and the aspect ratio (AR), building area density, building site coverage (BSC), building height (H), floor aspect ratio (FAR) are geometrical properties. Dimensionless numbers are also necessary to understand the behaviour of the physical properties under variable conditions. For example, Reynolds number (Re) differentiates between laminar and turbulent flow and Froude number (Fr) signifies whether the flow has sub-critical or super-critical flow characteristics. Richardson number (Ri) is the dimensionless number that expresses the ratio of the buoyancy term to the flow shear term and in thermal convection problems and represents the relative importance of natural convection with respect to the forced convection. These dimensionless numbers are also useful to select the similarity criterion when the size of the methodological activity is scaled.

The parameters which were used to verify the studies are often related to air velocity, temperature and radiation measurements, or geometrical parameters. The dimensionless numbers help to reduce the long calculations and provide reasonable suggestions toward the goal of the study. For the case of air displacement, street canyon effects and natural ventilation potential, the geometrical parameters, air flow parameters, temperature parameters and their dimensionless numbers are of great importance and they can be dealt with to optimize the outcomes efficiently for indoor and outdoor ventilation.

6. Recent Developments in the Review

As already mentioned, this review consists of the studies from the year 1991 to 2020. Considering the recent developments, some of the studies from year 2021 have been included in this section. As it can be observed, publications in 2021 continued the analyses discussed in the previous sections, with similar methodologies and new contributions added to the literature in this field. As an example, Xu et al. [100] discussed the effects of roadside morphologies and moving vehicles on street canyon ventilation. They performed CFD simulation using ANSYS Fluent 2019R3 for their research. Likewise, Peng et al. [101] correlated the urban ventilation of a typical street and the impact of building form variation with the help of different parameters such as age of air and air delay, and mentioned some design strategies for residential streets. Zheng and Yang [102] compared the effects of RANS with LES to understand the effect of both the turbulence models on wind flow and pollutant dispersion in a street canyon with traffic flow. Papp et al. [103] analysed street-level pollutant emissions in long, parallel street canyons of constant and variable building height, using numerical models and wind tunnel experiments. Zhao et al. [104] studied the effect of different buoyancy conditions due to heated building and ground surfaces on flows in and around the two canyons using PIV measurements. Chen et al. [105] examined the effects of urban geometry on the thermal environment in 2D street canyons with the help of a scaled experimental study. Nosek et al. [106] investigated the effects of turbulent coherent structures to understand the driving mechanisms of street canyon ventilation. Cui et al. [107] studied the effects of building layouts and envelope features on wind flow and pollutant exposure in height-asymmetric street canyons.

7. Limitations

As this review is mainly focused on outdoor air displacement, effects of street canyon and natural ventilation potential, some other studies have been excluded, such as studies specifically focused on outdoor comfort for pedestrians. For the review of the experimental parts, more importance is given to wind tunnel experiments and field measurements as these are the possible ways to perform the experiments while focusing on air displacement

and natural ventilation. Finally, studies in languages other than English have been omitted from this review.

8. Conclusions

Considering the migration of populations to urban areas and the transformation of rural areas into urban ones, there is a need to find solutions to make cities more and more sustainable, reducing their energy demand and improving environmental quality both indoors and outdoors. One of the aspects to consider is ventilation of the built environment, which can be exploited to ensure human comfort and reduce the impact of pollution and of other contaminants on human health. Natural ventilation, in particular, can be of interest because it does not require installation and operation costs and is, consequently, a sustainable solution. However, natural ventilation potential is not always the same, especially in the urban context. Consequently, research is needed to develop guiding tools for engineers, architects, urban planners and policy makers for the challenges of future cities. Examples are given by studies on outdoor air displacement surrounding buildings and in street canyons.

With the aim of analysing the recent trends in this field and providing an overview of the most common methods, metrics and parameters adopted, this work reviewed 89 papers, out of which 56 related to street canyon effects and natural ventilation potential, ranging from 1991 to 2021. A systematic approach was adopted, categorizing the selected papers based on type of building/city layout and location, methodology (either experimental and CFD simulations), parameters/indexes/dimensionless numbers and keywords.

Thanks to this analysis, it has been possible to observe the following:

- Although the literature includes already significant studies on outdoor air displacement, especially in street canyons, more studies should be performed in order to obtain more general findings, considering the effects of geometry, size, orientation of the street canyons and the obstacles present on the street.
- From a methodological point of view, comparisons among the findings of different studies or methods (e.g., experimental validation of CFD simulations) are not always present. This should be encouraged in future research, in order to not only confirm the validity of the results and ensure their generalization, but also to identify the best methodologies and approaches to replicate.
- Fictitious urban areas are useful for parametric studies and they are an ideal fit for understanding the scenarios for ideal conditions. However, studies on real urban layouts are necessary to discuss the actual conditions and the potential of urban and natural ventilation. Up to now, the number of studies in real districts is still low and often focused on large developed cities. An expansion of this set of case studies could include also suburban and semi-rural environments, completing the overview of typical conditions. Furthermore, many studies in this review involve subtropical cities and their results are deeply affected by local microclimatic conditions. New studies in different climates could facilitate the creation of a comprehensive dataset of cases helping in the identification of common trends and solutions to apply.
- As regards CFD simulations, attention is generally given to RANS equations. Many studies included $k - \epsilon$ and $k - \omega$ turbulence models for further development because of their lower computational cost and time consumption compared to the LES turbulence model, even if LES is more accurate. With the increase in the available computational resources and advancements in the technology in the future, LES could be used more extensively due to its higher accuracy and ability to capture more detailed and real behaviour of air flows.
- Most of CFD simulations rely on commercial or open access tools such as ANSYS Fluent and OpenFOAM. However, some authors preferred to develop customized codes or adopt different numerical approaches, mostly based on finite differences and finite volumes.

- Parameters/ indexes/ dimensionless numbers are of significant importance for studies to proceed with the research activities. As mentioned in the previous sections, some of the parameters more frequently adopted in the reviewed studies are age of air (τ), street aspect ratio (AR), building floor area ratio (FAR), building height (H), air exchange rate (ACH), Reynolds number (Re), etc.

To conclude, this review of the literature on studies about air displacement in urban layouts and street canyons for the assessment of the ventilation potential has allowed for a description of the state-of-the-art of experimental and numerical methods, approaches and case studies often adopted in the last 30 years. For many reasons, and above all the increase in urbanisation, the analysis of urban ventilation and air displacement is receiving growing attention and importance. With the increase in computational resources, new potential for research in this field is expected to develop. CFD, in particular, on one hand will support the design of targeted and accurate experimental tests, both in situ and in controlled environments such as wind tunnels, and on the other hand will facilitate the analysis of more and more configurations of climate conditions and urban layouts. This, in turn, will give engineers, architects and urban planners a robust dataset of case studies to drive their design activity and improve the quality of the urban built environment. By keeping this in mind, considering the recent pandemic outbreak, it is necessary to carry out more studies related to air displacements and natural ventilation in urban and rural areas.

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Abbreviations and Symbols

τ	Age of air
ABL	Atmospheric boundary layer
ACH	Air exchange rate
AR	Aspect ratio
AT	Mean air temperature
B	Buoyancy flux
BAD	Building area density
BAF	Building aerodynamic factor
BAR	Building aspect ratio
BDG	Building area percentage
BHAR	Building-height aspect ratio
BL	Boundary layer
BLAR	Building-length aspect ratio
BSC	Building Site Coverage
BVC	Bi-variate correlations
CAR	Cavity aspect ratio
CEA	City energy analyst
EC	Envelope characteristics
ET	Exposure time
FAR	Floor Area Ratio
FB	Fractional bias
Fr	Froude number
g'	Reduced gravity
GSC	Gross Site Coverage
H	Building height
HV	Buildings' Height Variation
IAD	Indoor air distribution
IAV	Indoor air velocity

IG	Internal gains
ISL	Inertial sublayer
KCA	K-means cluster analyses
LDA	Laser doppler anemometry
M	Turbulent entrainment flux
MF	Mesoscale Factor
MRT	Mean radiant temperature
MVR	Mean wind velocity ratio
NEV	Net escape velocity
OACE	Outdoor air change efficiency
OACH	Outdoor air change
OMVR	Overall mean wind velocity ratio
OS	Opening size
OSR	Open Space Ratio
OUC	Orientation of Urban Canyons
P _{IF}	Personal intake fraction
PALM	Parallelized LES model
PAR	Plot area ratio
PAVE	Pavement area percentage
PC	Pollutant concentrations
PCH	Pollutant exchange rate
PDPH	Pressure difference Pascal hours
PET	Physiologically equivalent temperature
PFR	Purging flow rate
PIV	Particle image velocimetry
Q	Air flow rate
R	Correlation coefficient
Ra	Rayleigh number
RANS	Reynolds-averaged Navier–Stokes equation
Rb	Bulk Richardson number
Re	Reynolds number
RER	Re-entry ratio
Ri	Richardson number
RKE	Realizable $k - \epsilon$ turbulence model
RNG	Renormalization group $k - \epsilon$ turbulence model
RT	Residence time
SAR	Street aspect ratio
SC	Site coverage
SCAR	Street canyon aspect ratio
SG	Solar gains
SKE	Standard $k - \epsilon$ turbulence model
SKO	Standard $k - \omega$ turbulence model
SP	Street patterns
SR	Surface roughness
SST	Shear-stress Transport $k - \omega$ turbulence model
ST	Number of Stories
SVF	Sky View Factor
TA	Tree anisotropy
TBH	Target building heights
UBF	Urban Building Form
UCL	Urban canopy layer
UCPs	Urban canopy parameterizations
UD	Urban Density
UHI	Urban heat island
UP	Urban Pattern
UTCI	Universal Thermal Climate Index
VAR	Volume area ratio
VF	Visitation frequency
VRw	Spatially-averaged wind velocity ratio

WD	Wind direction
WOT	Window opening type
WS	Window size
WTE	Wind tunnel experiment

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