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CFD simulation of urban microclimate: Validation using high-resolution field measurements

Nestoras Antoniou^{a,b,*}, Hamid Montazeri^{b,c}, Marina Neophytou^a, Bert Blocken^{b,c}

^a Department of Civil and Environmental Engineering, University of Cyprus, Nicosia, Cyprus

^b Department of the Built Environment, Eindhoven University of Technology, Eindhoven, the Netherlands

^c Department of Civil Engineering, KU Leuven, Leuven, Belgium

HIGHLIGHTS

- High-resolution on-site measurements of wind speed, air and surface temperature
- Validation of URANS simulations of urban microclimate with high-resolution field measurements
- URANS can accurately predict air temperature, surface temperature and wind speed in real urban areas.
- Possible reasons for deviations between CFD and measurement are discussed.

GRAPHICAL ABSTRACT

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ABSTRACT

Heat stress in urban areas can have detrimental effects on human health, comfort and productivity. In order to mitigate heat stress, Computational Fluid Dynamics (CFD) simulations of urban microclimate are increasingly used. The validation of these simulations however requires high-quality experimental data to be compared with the simulation results. Due to lack of available high-resolution high-quality experimental data, CFD validation of urban microclimate for real urban areas is normally performed based on either a limited number of parameters measured at a limited number of points in space, or on experiments for idealized generic configurations. In this study, CFD simulations of urban microclimate are performed for a dense highly heterogeneous district in Nicosia, Cyprus and validated using a high-resolution dataset of on-site measurements of air temperature, wind speed and surface temperature conducted for the same district area. The CFD simulations are performed based on the 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations and the simulated period covers four consecutive days in July 2010. It is shown that the CFD simulations can predict air temperatures with an average absolute difference of 1.35 °C, wind speed with an average absolute difference of 0.57 m/s and surface temperatures with an average absolute difference of 2.31 °C. Based on the comparative results, conclusions are made regarding the performance of URANS for the selected application and possible reasons for deviations between measured and simulated results are discussed.

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* Corresponding author at: Department of Civil and Environmental Engineering, University of Cyprus, Nicosia, Cyprus.

E-mail address: antoniou.nestoras@ucy.ac.cy (N. Antoniou).

1. Introduction

The world is undergoing the largest wave of urban growth in history (Marshall et al., 2007). Currently, about 54% of the world's population lives in urban areas. This number is expected to increase dramatically and reach 66% worldwide by 2050 (United Nations, 2014). This is especially the case in European countries where the urban and peri-urban population are expected to exceed 80% by the end of 2020 (European Council, 2013). In addition, climate change is likely to present a number of challenges for the built environment. For example, the Urban Heat Island (UHI) effect and heat waves are anticipated to become more severe, with dramatic consequences for the urban population (Emmanuel and Krüger, 2012; Mirzaei and Haghighat, 2010; Sarrat et al., 2006).

The increased temperatures in urban areas and the associated heat stress can lead to additional building energy consumption for cooling in summers, and to increased levels of human morbidity and mortality ("ClimateCOST," The climatecost project, 2011; Garssen et al., 2005; Haines et al., 2006; Xu et al., 2012). If extensive indoor cooling is provided by air conditioning systems, this will cause a net increase of the outdoor air temperature, which in turn will increase the need for cooling indoors – a vicious circle. If no extensive indoor cooling is provided, the air temperature inside can even be higher than that outside, especially during night-time. Given the fact that people spend a lot of time inside, especially during night when their body should be recovering from a heat-wave day, high temperatures inside can be the direct cause of excess morbidity and mortality. As an example, Fig. 1 shows the relation between the average weekly maximum outdoor air temperature and the number of deaths in the Netherlands during the heat wave of 2003. A very strong correlation is observed where higher average weekly maximum temperatures result in a higher number of deaths.

Urban thermal microclimate and heat stress can be studied by numerical simulations with Computational Fluid Dynamics (CFD). CFD is increasingly used for a wide range of urban microclimate studies (Lai et al., 2019; Toparlar et al., 2017) focusing on wind flow around buildings (Gousseau et al., 2013; Kikumoto et al., 2018; Li et al., 2015; Stathopoulos and Tominaga, 2007), pedestrian thermal comfort (Blocken, 2014; Gao et al., 2018; Montazeri et al., 2017; Neophytou et al., 2011; Tominaga et al., 2015; Toparlar et al., 2015), pollutant dispersion (Buccolieri et al., 2010; Hang et al., 2012; He et al., 2017; Kubilay et al., 2017; Panagiotou et al., 2013; Tominaga and Stathopoulos, 2011), etc. CFD provides whole flow-field data of the target parameters in the area of interest, and offers the advantage that the individual and combined impacts of different physical processes can be assessed. CFD also allows full control of boundary conditions. In

addition, using CFD, parametric studies can be performed efficiently. Nevertheless, given the complexity involved in urban microclimate studies, several simplifications need to be applied that might compromise the accuracy and reliability of the simulation results. These are mainly related to simplifications in terms of geometry, material characteristics, surface land use, boundary conditions, physical processes, etc. This is especially the case for complex real urban areas. Therefore, careful validation of the simulation results is imperative.

A detailed review of CFD studies of urban microclimate performed by Toparlar et al. (2017) indicates that more than half of such CFD studies did not include a validation study. A proper validation for real urban areas requires the availability of high-quality experimental data. These data can be obtained from either on-site measurements, thermal remote sensing or reduced-scale modeling. On-site measurements offer the advantage that the real situations can be investigated and that the full complexity of the problem is taken into account. This approach, however, is rather expensive and time-consuming, while the measurements are often obtained at only a limited number of points in space. In addition, there is no, or very limited control on the boundary conditions that makes the repetition of the same measuring conditions very difficult or even impossible. In on-site measurements of urban microclimate in complex urban areas, air temperature (Yokoyama et al., 2018), relative humidity (Tominaga et al., 2015), wind speed and direction (Al-quraan et al., 2016), short-wave and long-wave radiation (Kambezidis, 2018), surface temperatures (Shahrestani et al., 2015) etc. are often measured. Gao et al. (2018) used on-site measurements of air temperature, wind flow and pollution concentration to validate CFD results for a real urban area in Toulouse. The focus in that study was on local air pollution. Validation was performed at only a single point inside the area of interest, showing good agreement for air temperature, wind speed and air pollution, while large deviations were observed between measured and simulated wind direction. Athamena et al. (2018a, 2018b) compared CFD simulations and on-site measurements of wind velocity, air temperature, surface temperature and turbulent kinetic energy in an urban canyon for a period of one week. The measurements were performed at different locations inside the urban canyon represented by two lines of empty steel containers, where data were collected every 15 minutes. Satisfactory agreement between experimental and numerical results was achieved for all the evaluated parameters, except for the turbulent kinetic energy where relatively large deviations were observed.

The use of thermal remote sensing for collecting validation data for CFD simulations has gained attention in recent years (Chui et al., 2018; Coutts et al., 2016; Gulten et al., 2016). This can be explained due to the substantial improvements in the underlying technology, offering higher resolution and better accuracy at considerably lower cost. Nevertheless, caution is required as many parameters may affect the results, such as material surface reflections, airborne particles, the angle of perspective, etc. Remote sensing has been used to collect surface temperature data, by satellite images (Bechtel et al., 2017) and aerial and on-ground thermographic images (Alchapar et al., 2014). Toparlar et al. (2015) used satellite thermographic images provided by Klok et al. (2012) to validate simulated surface temperatures for the area of Bergpolder Zuid, Rotterdam, for five consequent days. The results showed a good agreement with an average deviation of 7.9%. However, due to the low resolution of the provided results, the surface temperatures were spatially averaged for almost the whole area of interest.

Laboratory reduced-scale measurements, unlike on-site measurements, offer the advantage of full control on boundary conditions. However, through this approach due to the reduced scale, similarity issues may arise. Reduced-scale experiments of urban microclimate for complex urban areas are generally measured in atmospheric boundary layer wind tunnels and usually focus on wind speed and direction (Ricci et al., 2019; Stathopoulos, 2006), wind pressure (Baik and Kim, 2002), pollution concentrations (Mu et al., 2017; Stathopoulos et al.,

Fig. 1. Mortality and average maximum temperature per week in the Netherlands during June–September 2003 (modified from Ref. (Garssen et al., 2005)).

2004; Yu et al., 2017), surface temperatures (Allegrini, 2018; Allegrini et al., 2013) etc.

A high-quality CFD validation with experimental data should include at least the main target parameters (depending on the focus of the study), measured with an adequate temporal and spatial resolution. For urban microclimate studies, however, high-quality high-resolution experimental data are not readily available or easily obtained. Therefore, in most CFD studies of real urban microclimate including validation, the validation usually does not cover the full set of target parameters (Gracik et al., 2015; Tang et al., 2014), and low to medium spatial resolution is used (Tang et al., 2014; Toparlar et al., 2015). The aim of the present study is to contribute to the validation of CFD urban microclimate simulations by employing a more extensive experimental dataset. This is important because performance indicators used in urban microclimate research in most cases largely depend on the complex interplay between different climatic variables. Therefore, on-site measurement data of air temperature, surface temperature and wind speed inside a real complex urban area under the TOPEUM project (Neophytou et al., 2011, 2013) are adopted. These data were obtained during an extended period by a number of different field measurement campaigns and activities. The CFD simulations to be validated are performed using the 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations in combination with the realizable $k - \varepsilon$ turbulence model.

Details regarding the case study area are presented in Section 2 and field measurements are described in Section 3. Section 4 presents the computational settings and parameters for the CFD simulations and in Section 5 the CFD results compared with field measurements are described. Conclusions and discussion are presented in Section 6.

2. Case study area

The area of interest is located in the old historical part of Nicosia (Fig. 2), representing a typical eastern Mediterranean city center. It covers a total surface area of about 0.247 km². The area is mainly composed of low-rise and medium-rise buildings corresponding to Local Climate Zone 3 (compact low-rise buildings) based on the classification made by Stewart and Oke (2012). The average and maximum building height is about 8.1 m and 45.5 m (Shakolas Tower), respectively. The plan area density λ_p is about 0.40 (Mouzourides et al., 2014; Neophytou et al., 2011). The width of the streets ranges from 6 m to 10 m, where the aspect ratio of the street canyons (width to height) ranges from 0.5 to 1. Streets are covered with pavement and buildings are mainly constructed of concrete and brick. The vegetation levels of the area are low, trees are mostly located in a few small courtyards and long main streets. The general climatic conditions can be characterized by a hot-summer Mediterranean climate based on the Köppen-Geiger classification (Strahler and Strahler, 1984). The prevailing wind direction in the summer period is west – south-west during the daytime and east at night.

3. Field measurements

A series of on-site measurements was conducted in July 2010 inside the area of interest, within the framework of the TOPEUM project (Neophytou et al., 2011). Through an extensive multi-scale and multi-themed measurement campaign, data of air temperature, wind speed and surface temperature were collected at different locations inside the case study area for a period of 19 days. The measurements used for the purpose of the validation study in the present paper were taken during an intensive observation period covering four consecutive days, between the 9th and 12th of July 2010. The complete set of field measurements is documented in Neophytou et al. (2013). Table 1 presents some information about the measurement locations, the number of measurement points for each location, equipment characteristics, and the measurement period. More relevant details are provided in

Subsections 3.1 to 3.3 to enable an insightful evaluation of the comparisons between the measurements and the simulated data discussed later in the paper.

3.1. Air temperature

Air temperature was measured at four locations (points labeled as “S1”, “S2”, “S3” and “S4” in Fig. 3.) The measurement points “S1” and “S4” were positioned in the center of narrow streets of approximately 6 m width, both at 5 m height above the ground level, while the measurement location point labeled “S2” was placed on the roof of the second highest building in the area at the height of 26.8 m above the ground level and 5 m above the building roof. The point “S3” was positioned inside a street canyon of 10 m width, at 5 m above the ground and 3 m from the west façade (Fig. 3c). For “S1” and “S2”, the air temperature was measured between the 9th and 12th of July. For “S3” and “S4”, the measurements were performed between the 10th and 12th of July. All measurements were taken using an AT2 sensor, with an accuracy of ± 0.1 °C (in the range of 0 to 70 °C). The data were collected every minute. More detailed information about the air temperature measurements is provided in Table 1.

3.2. Surface temperatures

Surface temperatures were measured by infrared thermography while local temperatures at specific points were captured using thermocouples. The thermal images were taken both from air and from the ground. The aerial thermal images were taken from a helicopter using a FLIR-P640 thermal camera with an accuracy of $\pm 2\%$ (± 2 °C). Thermocouples were used to measure local surface temperatures on the exterior facades of four different buildings, and on the interior façade of one of the four buildings (Building B1). The location of the four buildings is shown in Fig. 4 while the position of the thermocouples on a relevant building façade (Building B1) is shown in Fig. 5. Specifically, for each building, three thermocouples were installed at different heights along a vertical line (0.40 m, 1.2 m, and 2 m). The data were collected every 10 minutes using a Mitec-AT40 universal recorder, with an accuracy of ± 0.4 °C. The measurements were performed between the 10th and 12th of July. In addition, a FLIR – T335 thermal camera was used to measure the surface temperatures of the same façade of building B1 where thermocouples were placed (Fig. 5). The accuracy of the measurements is about $\pm 2\%$ (± 2 °C); the data were collected every 2 hours between the 10th and 12th of July (Table 1).

3.3. Wind speed

Four ultrasonic anemometers were placed at the same locations as the air temperature sensors, shown in Fig. 3. The measurements were performed between the 9th and 12th of July (Table 1) with data collected every minute. The Metek ultrasonic anemometers, with an accuracy of ± 0.1 m/s (i.e. 2%) were used at locations S1 and S2 while the Young 81,000 ultrasonic anemometers with an accuracy of ± 0.05 m/s (i.e. 1%) were used at locations S3 and S4. Wind speed and wind direction were also recorded from the national meteorological station of Athalassa, located about 5 km away from the area of interest, every hour.

4. CFD simulations

4.1. Computational domain and grid

The dimensions of the computational domain are selected based on the relevant best practice guidelines (Franke et al., 2007; Tominaga et al., 2008), where the height of the domain is 270 m corresponding to 6 times the maximum building height and the distance between the area with the explicitly modeled buildings and the boundaries of

Fig. 2. Case study area and surroundings: (a) Top view, (b) View from South to North taken from a high rise building South of the case study area, (c) aerial view from South to North direction (d) Street view of Ledras street taken from point 1 on Fig. 2a from North to South direction. (e) Aerial view of the case study area and surroundings from South East to North West. The black line in Fig. 2a and e indicates the border of the case study area and point 2 indicates the location of Shiakolas tower.

Table 1
Details of the field measurements.

Location	Measured parameter	No. of measuring points (location)	Equipment	Averaging interval (min)	Period	Accuracy
Street canyons (Fig. 3)	AT	4 (S1 – S4)	AT2	10	S1 and S2: 00:00 of 9th – 23:59 of 12th July S3 18:00 of 10th – 23:59 of 12th July S4 00:00 of 11th – 23:59 of 12th July	± 0.1 °C (0–70 °C)
Outdoor building walls (Fig. 4)	ST	12 (B1 – B4)	Mitec-AT40	10	10th – 12th July	± 0.4 °C
Indoor building wall	ST	3 (B1)	Mitec-AT40	10	10th – 12th July	± 0.4 °C
Building wall (Fig. 5)	ST	^a (B1)	FLIR – T335	120	05:48 of 10th to 21:45 of 12th of July	$\pm 2\%$ (± 2 °C)
Case study area (Fig. 2e)	ST	^b	FLIR-P640	^c	15:00 12th July	$\pm 2\%$ (± 2 °C)
Street canyons (Fig. 3)	WS	2 (S1, S2)	Metek GmbH ultrasonic-3	1	00:00 of 9th – 23:59 of 12th July	$\pm 2\%$ (± 0.1 m/s)
Street canyons (Fig. 3)	WS	4 (S3, S4)	Young 81,000 ultrasonic	1	S3 18:00 of 10th – 23:59 of 12th July S4 00:00 of 11th – 23:59 of 12th July	$\pm 1\%$ (± 0.05 m/s)

AT: air temperature; ST: surface temperature; WS: wind speed (velocity magnitude).

^a Data are collected for building facade.

^b Data are collected for whole case study area.

^c Data are collected for one moment.

Fig. 3. Plan view of the area and location of measurement points: (a) Top view (Source: Google Earth), (b-d) Location of air temperature sensors and sonic anemometers S1, S2, S3 and S4 (Source: TOPEUM project).

Fig. 4. Plan view of the area and location of four buildings: (a) Top view (Source: Google Earth), (b-d) the position of thermocouples on building walls (Source: TOPEUM project).

Fig. 5. (a) Photo of building B1 (Fig. 4). Markings show the location of thermocouples.

the domain, is kept to a minimum distance of 675 m corresponding to 15 times the maximum building height (Fig. 6). Note that 15H instead of 5H is used to take into account varying approach-flow wind directions. The computational grid is created using the surface-grid extrusion technique by van Hooff and Blocken (2010). The procedure is executed with the aid of the pre-processor Gambit 2.4.6, resulting in a grid with 14,670,517 hexahedral cells. Based on the best practice guidelines

Fig. 6. Perspective view of computational domain with indication of main dimensions.

(Franke et al., 2007; Tominaga et al., 2008), at least 10 cells are used on the building edges, but also across each street width. The high-resolution grid is generated with a minimum near-wall cell size of 0.3 m.

In order to reduce the computational cost, the geometry of the explicitly modeled urban area is simplified with an accuracy of 1 meter, while details on building facades such as balconies and shading components are neglected. The computational grid is generated in line with the recommendations of the best practice guidelines (Blocken, 2015; Casey and Wintergerste, 2000; Franke et al., 2007; Tominaga et al., 2008; Tucker and Mosquera, 2001), as shown in Fig. 7.

4.2. Boundary conditions

For the outer faces of the domain, either a velocity inlet or a pressure outlet boundary condition is imposed depending on the hourly wind direction. At the inlets, the vertical profiles for mean wind speed (Eq. (1)), turbulence kinetic energy (k) (Eq. (2)) and turbulence dissipation rate (ε) (Eq. (3)) by Richards and Hoxey (1993) are imposed for each time step, based on the hourly meteorological data obtained from the national meteorological station of Athalassa, which is located approximately 5 km away from the area of interest (see Fig. 8).

$$U(z) = \frac{u_{ABL}^*}{k} \ln \left(\frac{z + z_0}{z_0} \right) \quad (1)$$

$$k = \frac{u_{ABL}^{*2}}{\sqrt{C_\mu}} \quad (2)$$

$$\varepsilon(z) = \frac{u_{ABL}^{*3}}{\kappa(z + z_0)} \quad (3)$$

In these equations, z_0 is the aerodynamic roughness length that varies from 0.25 m to 0.4 m, depending on the wind direction, as shown in Fig. 8. In Eqs. (1)–(3), z is the height (m), u_{ABL}^* is the atmospheric boundary layer friction velocity (m/s) and κ is the von Karman constant ($= 0.42$). Fig. 9 presents the hourly meteorological data of air temperature, wind speed and wind direction for the four days under study.

The standard wall functions by Launder and Spalding (1974) are used at the wall boundaries with roughness modifications by Cebeci and Bradshaw (1977). The values of the roughness parameters, i.e. the sand-grain roughness height (k_s) and the roughness constant (C_s) are determined using their consistency relationship with the aerodynamic roughness length z_0 introduced by Blocken et al. (2007):

$$k_s = \frac{9.793z_0}{C_s} \quad (4)$$

Note that up to the version 16.0 of ANSYS/Fluent, the k_s value cannot be larger than y_p (distance between the center point of the wall-adjacent cell and the wall). Therefore, C_s is increased instead, chosen to satisfy Eq. (4). The ground plane of the subdomain with the explicitly modeled buildings is modeled with $k_s = 0$ m. For the rest of the ground plane, $k_s = 0.15$ m ($=y_p$). In combination with Eq. (4) and z_0 values presented in Fig. 8, this yields: $C_s = 26$ for $z_0 = 0.4$ m, $C_s = 22$ for $z_0 = 0.35$ m, $C_s = 20$ for $z_0 = 0.3$ m and $C_s = 16$ for $z_0 = 0.25$ m. Note that in Ansys/Fluent 16.0, a high input value of C_s can lead to numerical instabilities. Therefore, in this study $C_s = 16$ is used for all the simulations. The simulations are performed for five consecutive days between the 8th and 12th of July 2010, while the validation study is performed for the last four days of this period. Unsteady simulations are performed with a time step of 1 hour and with 4000 iterations per time step. 1-hour time steps are used because only hourly meteorological data are available. The number of iterations per time step is selected based on a sensitivity analysis, where additional simulations are performed for different numbers of iterations per time step: 500, 1000, 2000, 4000

and 5000. The results show that by increasing the number of iteration per time step from 500 to 1000, the mean surface-averaged temperature for the entire domain changes by about 2.64 °C. This is about 1.88 °C and 1.32 °C when this increases from 1000 to 2000, and from 2000 to 4000, respectively. This deviation, however, reduces to about 0.61 °C when increasing from 4000 to 5000 iterations per time step. Symmetry conditions are applied at the top of the domain. At the outlets, zero static gauge pressure is imposed. The ground and the building surfaces are set as walls. The internal surface temperature for all buildings is assumed to be 28 °C based on the indoor surface temperature measurements of building B1 (Fig. 4) representing a typical building of the case study area. The results of these measurements are presented in Section 5. The heat flux from fluid cells to adjacent walls is calculated based on Eq. (5) where, T_w is the wall surface temperature, T_f is the local fluid temperature, q_{rad} is the radiative heat flux and h_f is the fluid-side local heat transfer coefficient, which is computed based on the local flow field conditions (average velocity, temperature and turbulence level) (ANSYS Inc, 2013). For simplification reasons, building walls, building roofs and ground are modeled as zero-thickness walls, where conduction was calculated using the shell conduction model (ANSYS Inc, 2013). Three main materials are used to model the thermal properties of building walls, roofs and ground (see Table 2). Note that the material selection is based on the most typical materials used in the area resulting from a material analysis in this area. The building walls are modeled implicitly, i.e. using the shell conduction model, as layers of brick with a 0.25 m thickness. The ground plane is modeled implicitly as a 10 m thick layer composed of a layer of concrete with 0.35 m thickness on top and a layer of earth underneath with 9.65 m thickness with a constant temperature of 10 °C at 10 m below ground. The roofs of the buildings are modeled as layers of concrete with 0.25 m thickness. Since surfaces with transparency like glazing in windows are not modeled, the shortwave reflectivity of the surfaces is given by the relationship “reflectivity = 1 – absorptivity”.

$$q = h_f(T_w - T_f) + q_{rad} \quad (5)$$

4.3. Solver settings

The commercial CFD code ANSYS/Fluent 16.0 is used to perform the simulations. The 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations are solved in combination with the realizable $k - \varepsilon$ turbulence model by Shih et al. (1995). The following equations are the governing equations for continuity (Eq. (6)), momentum (Eqs. (7)–(9)) and turbulent quantities (Eqs. (10)–(11)):

$$\text{div} \vec{V} = 0 \quad (6)$$

$$\rho \frac{\partial U}{\partial t} + \rho \text{div}(\vec{U} \vec{V}) = -\frac{\partial P}{\partial x} + \text{div}(\mu \text{grad } U) + \left[-\frac{\partial \rho \overline{u'^2}}{\partial x} - \frac{\partial \rho \overline{u'v'}}{\partial y} - \frac{\partial \rho \overline{u'w'}}{\partial z} \right] \quad (7)$$

$$\rho \frac{\partial V}{\partial t} + \rho \text{div}(\vec{V} \vec{V}) = -\frac{\partial P}{\partial y} + \text{div}(\mu \text{grad } V) + \left[-\frac{\partial \rho \overline{u'v'}}{\partial x} - \frac{\partial \rho \overline{v'^2}}{\partial y} - \frac{\partial \rho \overline{v'w'}}{\partial z} \right] \quad (8)$$

$$\rho \frac{\partial W}{\partial t} + \rho \text{div}(\vec{W} \vec{V}) = -\frac{\partial P}{\partial z} + \text{div}(\mu \text{grad } W) + \left[-\frac{\partial \rho \overline{u'w'}}{\partial x} - \frac{\partial \rho \overline{v'w'}}{\partial y} - \frac{\partial \rho \overline{w'^2}}{\partial z} \right] \quad (9)$$

Fig. 7. (a) Aerial view of the case study area and surrounding buildings, (b,c) Corresponding views of the computational grid (14,670,517 cells).

Fig. 8. Surface use map of the broader area. Black rectangle indicates the computational domain. Dots indicate meteorological stations at University of Cyprus (UCY) and Athalassa.

$$\rho \frac{\partial k}{\partial t} + \rho \operatorname{div}(k \vec{U}) = \operatorname{div}\left(\frac{\mu_t}{\sigma_k} \operatorname{grad} k\right) + 2\mu_t S_{ij} S_{ij} - \rho \epsilon \quad (10)$$

$$\rho \frac{\partial \epsilon}{\partial t} + \rho \operatorname{div}(\epsilon \vec{U}) = \operatorname{div}\left(\frac{\mu_t}{\sigma_\epsilon} \operatorname{grad} \epsilon\right) + \rho C_{1\epsilon} \sqrt{2S_{ij} S_{ij}} \epsilon - \rho C_{2\epsilon} \frac{\epsilon^2}{k + \sqrt{u\epsilon}} \quad (11)$$

where $\vec{V}$ is the mean (ensemble-averaged) velocity vector, U , V and W are the mean wind speed in x , y , and z direction, respectively, P is the mean pressure, μ is the dynamic viscosity, ρ is the density of the fluid, μ_t is the turbulent viscosity, S_{ij} is the mean strain rate, k is the turbulent kinetic energy, ϵ is the turbulence dissipation rate and the model constants are $C_{2\epsilon} = 1.9$; $\sigma_k = 1.0$; $\sigma_\epsilon = 1.2$. In these equations “ div ” is the divergence operator and “ grad ” is the gradient operator. For all the variables $\Phi(x, t)$, $\bar{\Phi}(x)$ is the mean (ensemble-averaged) component and $\Phi'(x, t)$ is the fluctuating component.

The total solar radiation, the diffused solar radiation and the solar radiation vector are calculated with the solar calculator included in ANSYS/Fluent 16.0. The P1 radiation model is used to solve the radiative heat transfer (Siegel and Howell, 1992), which is considered less demanding in terms of computational power and has been used in previous case studies (Barbason and Reiter, 2014; Buratti et al., 2018; Gromke et al., 2015; Montazeri et al., 2017; Toparlar et al., 2015). This radiation model includes the effect of scattering and can be easily applied to complicated geometries (ANSYS Inc, 2013). However, there are limitations in the capacities of this model, which are further discussed in Section 6. Buoyancy is calculated using the Boussinesq approximation, which assumes uniform fluid density except for the body force term in the momentum equation along the direction of gravity, which is suggested for natural convection problems (ANSYS Inc, 2013). Pressure-velocity coupling is performed with the SIMPLE

algorithm. Conduction, convection and radiation are considered in the simulations, fully coupled with the wind flow. For wall surfaces, conduction is calculated only in the direction normal to the wall, while the thin wall approach in combination with shell conduction is used for calculating heat transfer through the different layers of wall surfaces (ANSYS Inc, 2013). In this approach, the effect of the wall thermal resistance is modeled based on parameters such as the thickness of the wall and material specifications. It should be noted that the ground plane and building walls are modeled implicitly, i.e. using zero-thickness walls and the shell conduction model, to reduce the total number of cells in the domain.

5. Results

Fig. 10 presents the comparison between the measured and simulated hourly air temperatures for the four measuring points (S1, S3 and S4 within street canyons and S2 above roof top level) as shown in Fig. 3. The diurnal variation is fairly well captured at all points. The average deviation between measurements and simulations is 7.0%, 4.8%, 3.4% and 3.8% for points S1, S2, S3 and S4, respectively. The average deviation for all four points is 4.8% (1.35 °C in absolute difference), while the maximum deviation is 14.3% (4 °C in absolute difference), which occurs at point S1. The simulations overestimate the maximum daily average air temperature for measuring locations S1, S2 and S3. The highest deviation is observed during peak hours, especially at the measuring location S1. Generally, it can be seen that 3D URANS can predict the air temperatures in real urban environments with a fairly good agreement. This is in line with previous similar studies in which validation was performed for mean air temperature (Athamena et al., 2018b; Tominaga et al., 2015).

Fig. 11 presents the measured and simulated hourly mean wind speed (velocity magnitude) at the same four locations. A relatively

Fig. 9. Hourly meteorological data from Athalassa meteorological station during 9th to 12th of July 2010 for (a) air temperature and (b) wind speed and (c) wind direction.

Table 2
Material properties.

Material	Density (kg/m ³)	Specific heat (kJ/kg)	Conductivity (W/mK)	Absorptivity	Emissivity
Soil	1200	0.65	0.6	0.6	0.85
Concrete	1500	0.88	0.75	0.6	0.85
Brick	1400	0.84	1	0.6	0.85

good agreement is shown between measurements and CFD simulations up to mid-day, while a general overestimation is observed in the peak hours during the afternoon, especially at measuring location S1. The average absolute difference for points S1, S2, S3 and S4 is 0.61 m/s, 0.80 m/s, 0.49 m/s and 0.40 m/s, respectively. The average absolute difference for all points is 0.57 m/s. The best agreement is observed at point S4, which is located in a street almost parallel to the main wind direction (East to West). Note that the measurement point S1 is located inside a very narrow street canyon (aspect ratio 1:4), which is

Fig. 10. Comparison of measured and simulated hourly mean air temperature at four locations S1-S4, shown in Fig. 3.

Fig. 11. Comparison of measured and simulated hourly mean wind speed (velocity magnitude) at four locations S1-S4, shown in Fig. 3.

perpendicular to the prevailing wind direction, which explains the difficulty in correctly reproducing mean wind speed at this point in the CFD simulations. In this study, the simulations are performed with boundary conditions that are updated every hour based on the available hourly meteorological data. Therefore, subhourly variations in wind speed and wind direction are not taken into account. As shown by Zhang et al. (2019), this can affect the simulation results leading to deviations between measured and simulated data.

Fig. 12 presents an aerial view of the measured and simulated surface temperatures, at 15:00 on the 12th of July when the aerial thermal images were taken (Table 1). Therefore, the comparison is performed for this specific moment. The measured surface-averaged temperature in the whole area (i.e. over all surfaces appearing in the aerial view) is 40.2 °C while the corresponding simulated surface-averaged temperature is 41.7 °C. Generally, it is

observed that CFD can predict the surface-averaged temperatures with an average deviation of 3.7%, which is in line with other similar studies (Chen et al., 2004; Toparlar et al., 2015). To better compare the results, the area of interest is divided into twelve blocks, denoted as Block A, Block B, Block C, etc. (shown in Fig. 12a), and the surface-averaged temperatures obtained by measurements and CFD are calculated for each block and shown in Fig. 12b and c, respectively. It can be observed that the deviation between the measured and simulated surface-averaged temperatures ranges from 0.6 °C (Block O) to 3.5 °C (Block G). Although the maximum block-averaged deviation is 3.5 °C, note that in certain points large overestimations (Block I in Fig. 12a) or underestimations (Block N in Fig. 12a) are observed (not shown in figure), up to about 15 °C.

To gain further insight into the performance of URANS and to better explain the deviations between the CFD results and the measured data,

Fig. 12. (a) Aerial view of the case study area. Surface temperature distributions obtained by (b) infrared thermography taken at 15:00 on 12th of July 2010 and (c) CFD simulations at the same moment. Black lines indicate different blocks and numbers represents surface-averaged temperature of each block.

Fig. 13. (a) Aerial view of the case study area. Surface temperature distributions and local surface temperatures for Shiakolas tower and locations D1, J3, N4 and I2 obtained by (b) infrared thermography taken at 15:00 on 12th of July 2010 and (c) CFD simulations at the same moment.

Fig. 13 presents the local surface temperatures at several locations in the domain at which either a very good or a rather poor agreement is obtained. A close aerial view of locations D1, I2, J3 and N4 as they appear in Fig. 13, is provided in Fig. 14. The lowest local surface temperatures are observed in green areas (Figs. 13 and 14, points D1 and I2), while the highest local surface temperatures are observed in locations with large uncovered areas (Figs. 13 and 14, point J3) and with large roofs covered by metal (Figs. 13 and 14 point N4). Note that in the CFD simulations only three materials are considered, while transparent surfaces and green areas are not taken into account. Therefore, the high deviations between the measured and simulated local surface temperatures are likely associated with these simplifications in the CFD simulations. This is especially the case for green areas where the deviations can reach up to 15.6 °C (Point I2). This could be due to the lower absorptivity

levels of trees in comparison of construction materials, and their combined effect of evapotranspiration (Gromke et al., 2015) and solar shading (Robitu et al., 2006; Shashua-Bar and Hoffman, 2000; Simpson, 2002). On the other hand, for surfaces covered by similar materials with those used in the CFD simulations, a good agreement between the measurement results and the CFD results is normally obtained. For example, for point J3 (Fig. 14c), the deviation is about 0.2 °C. In addition, it is expected that near the borders of the area with explicitly modeled buildings, extra deviations occur because the buildings outside this area are only modeled implicitly, i.e. by values of K_s and C_s assigned to flat surfaces. Research by Yoshie et al. (2007) has indicated that at least two upstream building rows are needed to cancel this effect.

Fig. 15 compares the temporal evolutions of the measured and simulated surface temperatures at the building walls, shown in Fig. 4. Note

Fig. 14. Aerial view of points D1, I2, J3 and N4, as presented in Fig. 13a.

that the measured data are averaged for the three measurement points on each building wall (Table 1), obtained from the thermocouples and the ground thermal images. The CFD results are presented as the surface-averaged temperature up to a height of 2 m on each building wall. It can be seen that the results from both thermocouples and ground-based thermal images are in good agreement with an average absolute difference of 0.3 °C. The results show that CFD can accurately predict the diurnal variation of the wall temperatures. The highest absolute difference is related to building B1 that occurs at 08:00, where CFD underestimates the results by about 7.6 °C. The absolute average difference between the measured and simulated surface temperatures for buildings B1, B2, B3, and B4 is 2.08 °C, 1.63 °C, 2.96 °C and 2.68 °C, respectively. In this case, the overall average absolute difference for all measurement points is 2.37 °C.

Based on the abovementioned discussion, the main reasons for the deviations between CFD and full-scale measurements are considered to be the following:

- Simplified specifications of construction materials: Given the complexity involved in imposing detailed material specifications for urban areas, the actual variety of construction materials in an urban area is normally not taken into account in CFD simulations of urban microclimate. This can significantly affect the results leading to large deviations between measurements and CFD. In real urban environments, material use can be different for each building and street. Therefore, imposing more detailed (realistic) specifications of construction materials can locally influence the temperature field.
- Trees and green fields: The presence of trees can have a strong impact on the urban microclimate in their vicinity (Lin et al., 2008; Ng et al., 2012; Shahidan et al., 2012) by reducing solar heat gains and the sky view factor (Robitu et al., 2006; Simpson, 2002), reducing the air temperature through the effect of evapotranspiration (Dimoudi and Nikolopoulou, 2003; Gromke et al., 2015) and its effects on wind flow (Gromke et al., 2015) and pollutant concentration (Vranckx et al., 2015). In the present study, trees were neglected. Although this is a reasonable assumption for the largest part of the studied area, the very local presence of trees and green fields can lead to locally very large deviations between the measured and simulated surface temperatures up to 15.6 °C.
- Geometrical simplifications: In this study, the simulations are performed for smooth and simple facades. However, façade geometrical details or external components attached to the facades and roofs such as balconies, canopies and shading devices, can reduce direct solar radiation on the building facades leading to lower surface

Fig. 15. Comparison of measured and simulated surface temperatures at the building walls, shown in Fig. 6, for two consequent days.

temperatures. In this study, differences between measured and simulated surface temperatures are more pronounced on the façades of the buildings and along Ledras street (Fig. 1d), where balconies and shading devices are widely used. These geometrical details can also significantly affect the airflow around buildings (Chand et al., 1998; Montazeri et al., 2013; Montazeri and Blocken, 2013; Montazeri and Montazeri, 2018; Ricci et al., 2017; Stathopoulos and Zhu, 1988). In addition, neglecting other elements such as cars and street furniture can lead to the CFD overestimation of the mean wind speed. The highest deviation between measured and simulated average wind speed inside the urban canopy, is found inside a narrow urban canyon with a rather high aspect ratio, where the façade geometry of adjacent buildings is expected to have a strong impact on wind flow.

- The use of wall functions for modeling flow parameters in the near-wall regions: earlier CFD studies have shown that the use of standard wall functions, rather than low-Reynolds number modeling (LRNM) approach, can significantly affect the surface heat flux and temperature (Blocken et al., 2009). The reason for this deficiency is that wall functions have been derived for wall attached boundary layers under so-called equilibrium conditions, i.e. small pressure gradients, local equilibrium between generation and dissipation of turbulent energy and a constant shear stress and heat flux in the near-wall region. However, this is not the case for complex flows, such as flow around buildings and in complex urban areas where the boundary layer does not remain attached to the surfaces. Note that in LRNM the whole boundary layer, down to the laminar sublayer, is resolved. Therefore, a very high-resolution computational grid would be required. This can be problematic for urban CFD simulations, when the grids will become too large and too computationally expensive (Iousef et al., 2017; Liu et al., 2015; Montazeri and Blocken, 2017, 2018).
- Deficiencies of the RANS approach: The performance of RANS has been proven satisfactory in the present study and also in similar urban microclimate studies (Montazeri et al., 2017; Toparlar et al., 2015) where CFD results showed very good agreement with measurements. However, RANS models have previously shown limited accuracy on the prediction of wind flow and turbulence levels in the wake region of buildings (Antoniou et al., 2017; Hanjalic, 2005; Murakami, 1993; Rodi, 1997; Tominaga and Stathopoulos, 2010). The deficiency of RANS in predicting turbulence levels can be more pronounced in the wake region of high-rise buildings (Antoniou et al., 2017), which might lead to possible deviations on air and surface temperatures locally. Nevertheless, RANS can be considered as a reasonable solution for such applications due to the overall good performance, the low computational cost and the existence of best practice guidelines (Blocken, 2015; Franke et al., 2007; Tominaga et al., 2008), and for these reasons it is still widely used in scientific research (Blocken, 2018).
- The use of P1 radiation model: This radiation model is a simplified model that generally overpredicts radiative fluxes from localized heat sources and sinks (ANSYS Inc, 2013). In addition, the use of this model for cases with complex geometries and with low optical thickness mediums can further reduce the accuracy of the simulation results (ANSYS Inc, 2013). Therefore, the coupling of CFD models with more sophisticated radiation models is likely to improve the prediction of surface temperatures as shown in earlier CFD studies of urban microclimate (e.g. Allegrini et al., 2015; Athamena et al., 2018a)

6. Conclusions

Heat stress in urban areas can have detrimental effects on human health, comfort and productivity. In order to mitigate heat stress, Computational Fluid Dynamics (CFD) simulations of urban microclimate are increasingly used. The validation of these simulations, however,

requires high-quality experimental data to be compared with the simulation results. In this study, CFD simulations of urban microclimate are performed for a dense highly heterogeneous district in Nicosia, Cyprus and validated using a high-resolution dataset of on-site measurements of air temperature, wind speed and surface temperature conducted for the same district area. The conclusions can be summarized as follows:

- 3D URANS on a high-resolution grid constructed according to best practice guidelines can accurately predict air temperatures, surface temperatures and wind speed in a real complex urban area. The average absolute deviation between full-scale on-site measurements is 1.35 °C for air temperature, 0.57 m/s for wind speed and 2.31 °C for surface temperatures.
- Thermal images can be a useful tool for measuring surface temperatures in the urban environment providing satisfactory agreement with data provided through other measuring techniques, however parameters like angle of perspective, high reflectance surfaces and composition of atmosphere must be considered.
- Highest discrepancies between measured and simulated surface temperatures are observed in locations with large surfaces covered with materials that have not been modeled explicitly in CFD model, such as green areas and large metal ceilings.
- The best agreement between surface temperatures taken through aerial thermal image and CFD results is observed in locations with low variation in construction materials, which have been modeled explicitly in CFD model, such as parking spaces covered with concrete.
- The prediction of wind speed by CFD can be less accurate in locations inside narrow streets and close to downwind regions of buildings.
- CFD results are generally over predicting wind speed, possibly caused by the absence of obstacles like trees, cars and building geometrical details in the CFD model, which generally reduce wind speed and increase turbulence intensity.
- The highest surface temperatures are observed in large metal ceilings and lowest surface temperatures are observed in green areas. This confirms that building materials are one of the most important parameters affecting surface temperatures.
- The most important reasons for deviations between measured and simulated results are: (1) The simplified specifications of construction materials, (2) the effect of trees and green fields that has been omitted, (3) the geometrical simplifications, (4) the use of wall functions for near wall treatment, (5) the deficiency of RANS models in predicting wind flow and turbulence levels in the wake region of buildings and (6) the radiation modeling approach.

The aim of the present study is to contribute to the validation of CFD urban microclimate simulations by employing more extensive experimental dataset. In addition, possible reasons for deviations between measured and simulated results are discussed. The focus of this study is on air temperature, wind speed, and surface temperature. Future research should focus on the impact of the level of accuracy of simulation results on performance indicators used in urban microclimate research. This is important because these performance indicators in most cases largely depend on the complex interplay between different climatic variables. For example, to evaluate the potential of different mitigation measures to enhance thermal comfort in the outdoor environment, the Universal Thermal Climate Index (UTCI) is normally used, which reflects the human physiological reaction to meteorological parameters including air temperature and humidity, wind speed and mean radiant temperature. Therefore, the accuracy of individual target variables can significantly affect the overall accuracy of performance indicators.

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