Thermal impact of street canyon microclimate on the energy performance of courtyard under Mediterranean climate




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In order to improve the prediction of the building's energy performance, it has become necessary to evaluate their interactions with the urban microclimate. Currently, there are few tools allowing to simulate the buildings energy consumption taking into account the impact of the urban microclimate with a satisfactory precision and acceptable computing time. In this study, the topic is addressed by investigating the effects of the local microclimate on the energy performance of courtyard buildings. To achieve this, an integrated approach in the TRNSYS software validated in previous studies was used. The analysis was conducted for 8 Mediterranean cities. The obtained results highlight potentially large discrepancies between the usual practice of building energy simulation, and the advanced simulation which takes into account local urban effects. This approach would improve to adapt HVAC system choices, especially by considering the urban morphology. Significant heating and cooling need variation were observed for high aspect ratio of courtyards within several Mediterranean cities.

In architectural design history, the courtyard represents one of the major building models whose characteristics depend on the environment and culture of the region [1]. Courtyards are still widely used worldwide, as a traditional urban pattern in Asia, Middle East, South America and specifically in Mediterranean countries [2]. This type of building creates local microclimate conditions, which may improve thermal comfort conditions [3]. Actually, this is an effective sustainable strategy to control the microclimate and the energy consumption of buildings. However, the complex interactions between the microclimatic and thermal functions of the courtyard make simultaneous simulation of indoor and outdoor thermal conditions an unavoidable requirement.

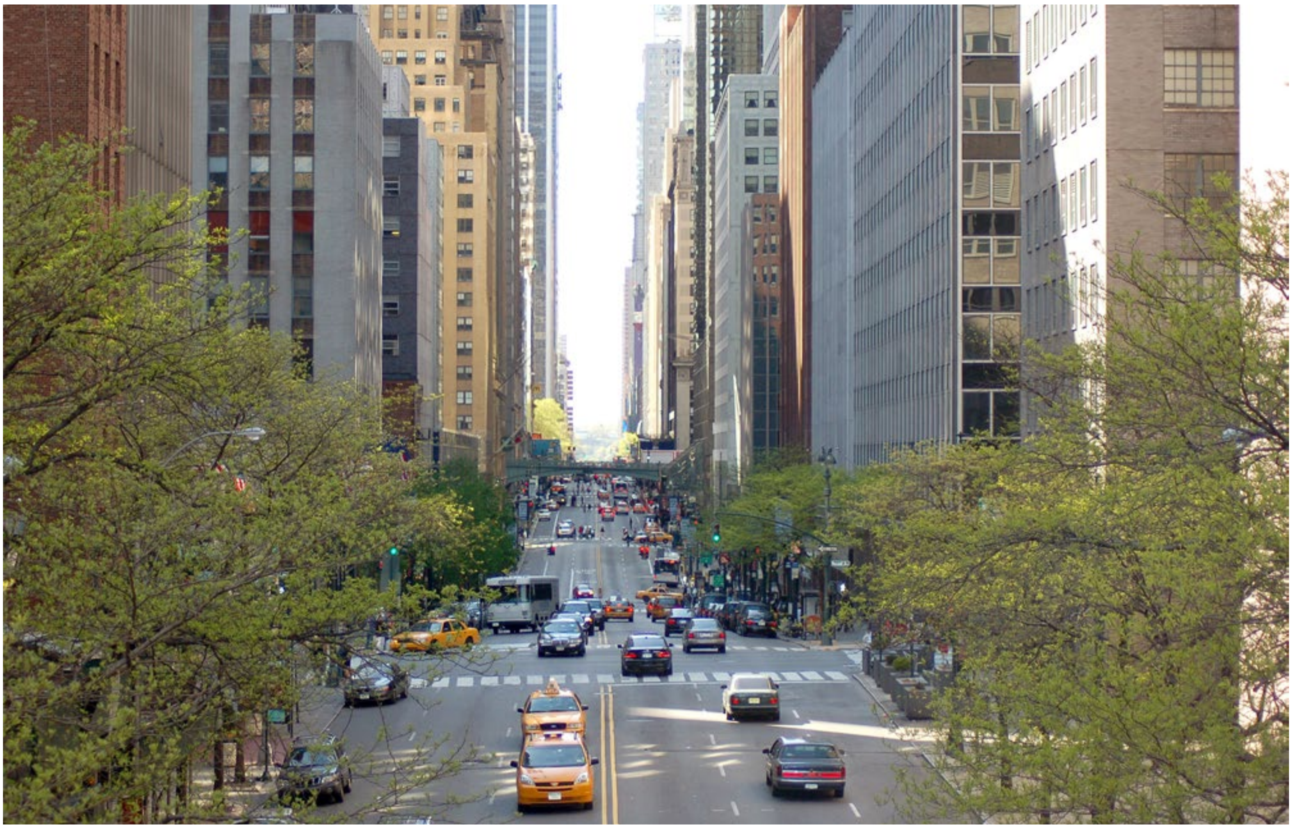
In this context, a review of the related literature showed that seventeen percent of studies focused on the thermal function of the courtyard, while sixty-three percent of studies focused on the microclimatic function of the courtyard, and only one-fifth considered the thermal and microclimatic function of courtyards simultaneously [4]. Furthermore, there are limitations to understanding the complex interactions between indoor and outdoor thermal conditions. One of them is the lack of suitable simulation programs. To this end, it appears advantageous to develop a more complete approach to evaluate the thermal and microclimatic (indoor and outdoor) performance of courtyard and their energy consumption.

For this purpose, the aim of this study is to quantify the influence of the street canyon microclimate on building courtyard energy performance, considering the case of the Mediterranean cities. For that, a simplified approach that we have developed and integrated in the TRNSYS 18 software is used [5–7]. This approach allows the description of thermal as well as aeraulic and radiative phenomena not only in the building's, but also at the microclimatic scale.

Methodology

Numerical model

In this research work, the TRNSYS 18 software was used for the energy simulation knowing that this software does not include urban modelling. Indeed, we developed a model integrated in this software in order to achieve the microclimatic simulation. The transfer function method of Mitalas and Stephenson [8] is used to express heat conduction through the walls. The heat transfer coefficient value of building façades is assumed to be constant on the inside surfaces of the building (6.1W/m²K for the ceiling, 1.6 W/m²K for the floor and 4.1 W/m²K for the vertical walls [9]). For the outside surfaces, the heat transfer coefficient by convection was evaluated using the Hagishima and Tanimoto correlation [10]. The modelling of ground heat transfers is based on standard EN ISO 13370 "Thermal performance of buildings -Heat transfer via the ground - Calculation methods" and Type 77 of TRNSYS [11]. This represents the sinusoidal evolution of the temperature over the year.



A street canyon in Manhattan, New York City, USA. [Wikimedia commons / David Brooks. (CC BY 2.0)]

For radiative exchanges, TRNSYS distinguishes between short-wavelength and long-wavelength exchanges. These are modelled differently for indoor and outdoor surfaces. More specifically, solar irradiation on outdoor surfaces is considered as a gain while the longwave radiation is treated as a heat loss to the cold sky. A 3D radiation model that takes account of multiple reflections is provided only on interior zones. The street canyon building and the courtyard are modelled as an outdoor environment, which the radiative model does not consider either the shortwave or the longwave inter-reflections between the façades of street canyon buildings.

As the ultimate aim of this study is to investigate the influence of microclimatic phenomena generated by the street canyon and the courtyard on the energy needs of a building. The street canyon and the courtyard are modelled by a simplified approach developed and validated in previous studies [5–7]. In this approach, the radiative model is based on the Gebhart factor [13] to calculate radiative exchanges and inter-reflections as well as the solar radiation distribution coefficients. While the aeraulic model is based on the Harman model [14] and the Soulhac model [15] which allows to take into account the effects of dominant winds. The originality of the method is its capacity to model the microclimatic phenomena generated by the street canyon and the courtyard (**Figure 1**), using dynamic thermal simulation software.

Description of the case study: Courtyard energy simulation model

In order to analyse the studied courtyard heating and cooling demand, an energy modelling was carried out for three different cases: a stand-alone courtyard in an open field by using TRNSYS software only, the same courtyard by using the developed approach (SACM) and the same courtyard located in an urban environment with a street canyon in front and behind the considered building. A street canyon with aspect ratios of 0.5, 1 and 2 (aspect ratio *H*/*W* with *H*: height of the building, *W*: street canyon width) are considered. **Figure 2** show the studied courtyard surrounded by street canyons with an aspect ratio of 1.

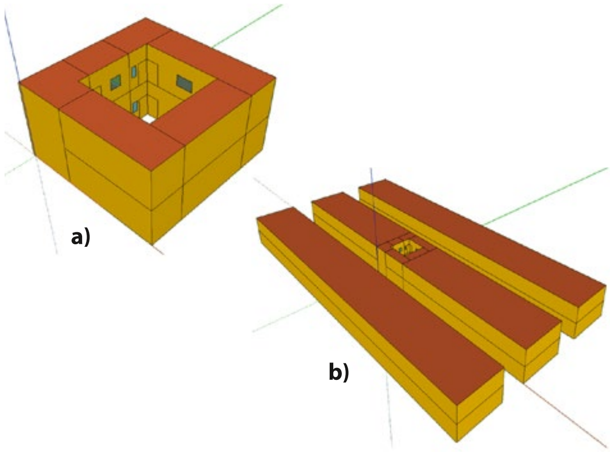


Figure 2. Overview 3d of the courtyard building (a) and the street canyon (b).

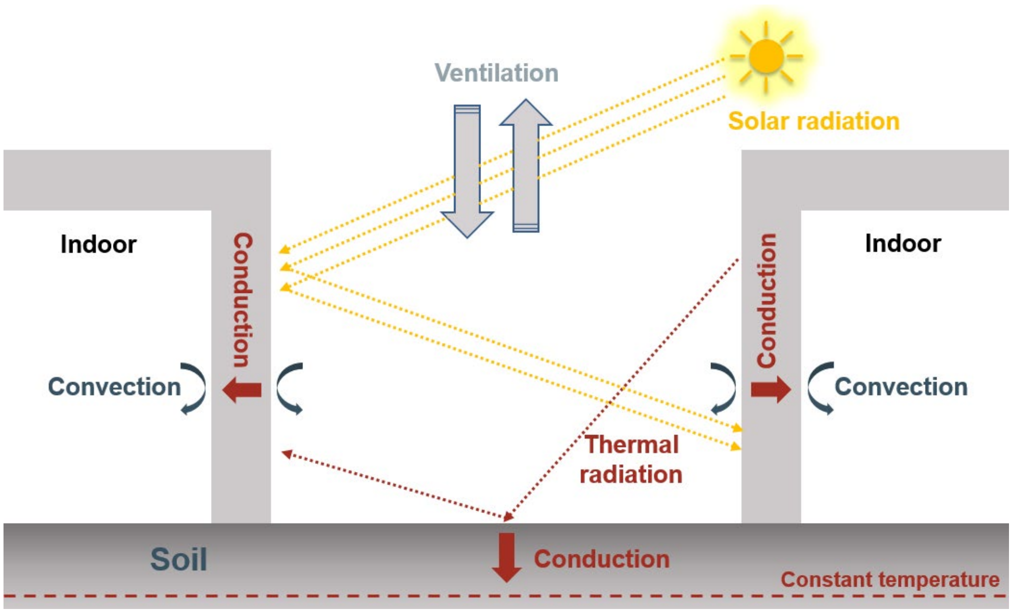


Figure 1. Illustration of the heat and aeraulic exchange processes in the courtyard or in the street canyon.

The considered courtyard has a total area of 169 m² (13 m of width and 13 m of length) and the height is of 3.5 m, with 10% of this area occupied by the courtyard. The total area of the window is 12.2 m². **Figure 3** and **Table 1** give the description of the courtyard model used as a case study.

The **Table 2** shows the glazing characteristics used.

Table 2. *Windows characteristics.*

Envelope element	Material	U-value [W/m².K]	G-value	ε
Windows	Glass	1.4	0.6	0.84

Table 1. *Thermophysical properties of courtyard and soil materials [16].*

Envelope element	Materials	Thickness [cm]	λ [W/m².K]	C_p [J/Kg.K]	ρ [kg/m³]
Outside Wall	Cement	1.5	1.15	1000	1700
	Brick	7	0.3	741	1200
	Air	10	–	1000	1.25
	Brick	7	0.3	741	1200
	Cement	1.5	1.15	1000	1700
Adjacent Wall	Cement	1.5	1.15	1000	1700
	Brick	7	0.3	741	1200
	Cement	1.5	1.15	1000	1700
Roof and ceiling	Tile	0.7	1.4	1000	2500
	Screed	5	0.42	1000	1800
	Concrete	4	2.3	1000	2350
	Hollow block	16	0.6	880	1000
	Cement	1.5	1.15	1000	1700
Ground floor	Tile	0.7	1.4	1000	2500
	Screed	5	0.42	1000	1800
	Concrete	20	2.5	1000	2350
Sidewalk	Ceramics	0.7	1.4	1000	2500
	Concrete	10	0.04	1000	2350

Where λ is the conductivity, C_p is the heat capacity and ρ is the density.

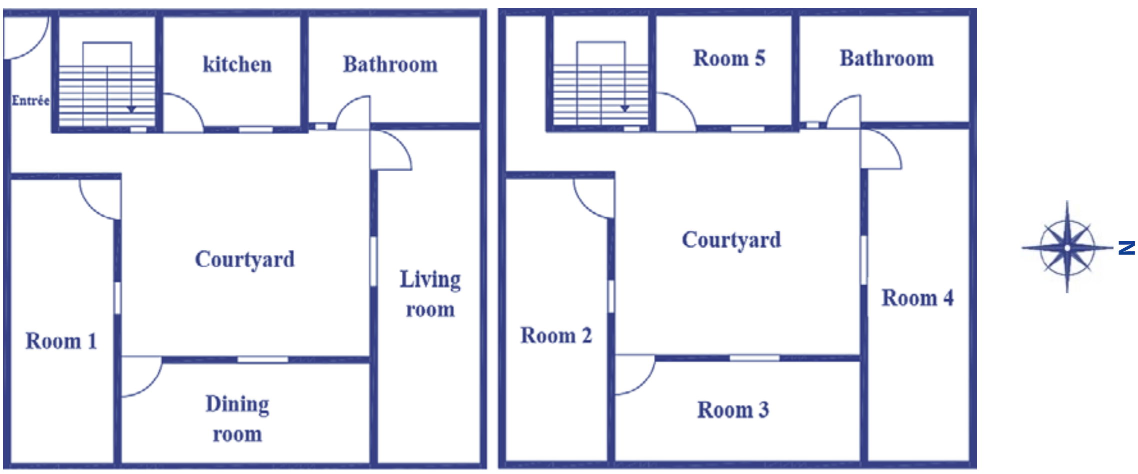


Figure 3. Ground floor (left) and first floor (right) plans.

During the modelling, we supposed that the courtyard is occupied by five people. The rooms are occupied every day from 22h to 7h 30 min. The living room is used for relaxing during the day. It is occupied from 7h30 to 8h, from 13h to 18h and from 20h to 22h. The kitchen is occupied from 7h to 7h30, from 12h30 to 12h and from 18h to 19h.

The internal gains due to the lighting system are 5 W/m² (incandescent lamp). The other appliances that produce the internal loads in the building are presented in **Table 3**.

Table 3. *Specific values of internal gains.*

Appliance	Area	Operating time	Power [W]
Refrigerator	Kitchen	24/24	125
TV	Living room	In occupation	75
Cooking appliances	Kitchen	In occupation	200
Computer	Bed-room	In occupation	100

The ventilation rate is 0.5 vol/h while the envelope infiltration rate is assumed to be 0.2 vol/h. The cooling and heating temperature set point are respectively 26°C and 20°C. The climatic data taken into account are those of the Mediterranean cities: Tangier (Morocco), Algiers (Algeria), Nice (France), Tripoli (Libya), Athens (Greece), Rome (Italy) Tunis (Tunis) and Barcelona (Spain).

Results and discussion

Figures 4 and 5 show the cooling and heating energy needs of courtyard building in different urban contexts. The results were given according to the aspect ratio of street canyons for the different Mediterranean cities.

First, based on the comparison between different simulation results obtained, we can see that the cooling energy needs estimated using TRNSYS 18 only are underestimated by about 70% compared to those of SACM, and the heating energy needs generated by TRNSYS 18 are about 10% higher than those obtained by our models (SACM). This is due to the fact that the courtyards generate microclimatic phenomena such as radiative trapping and inter-reflections of solar radiation, which have the effect of increasing the building's external surface temperature and consequently increasing the cooling energy needs. Moreover, TRNSYS 18 software does not allow to model the courtyards microclimate and therefore the shading effect as well as the thermoaeraulic exchange between the courtyard and the outside environment is not modelled. On the other hand, the radiative exchanges between the surfaces of the courtyard are not modelled if TRNSYS is used only.

For the impact of the street canyon microclimate on the energy needs of buildings in different Mediterranean cities under summer period (**Figure 4**), the cooling

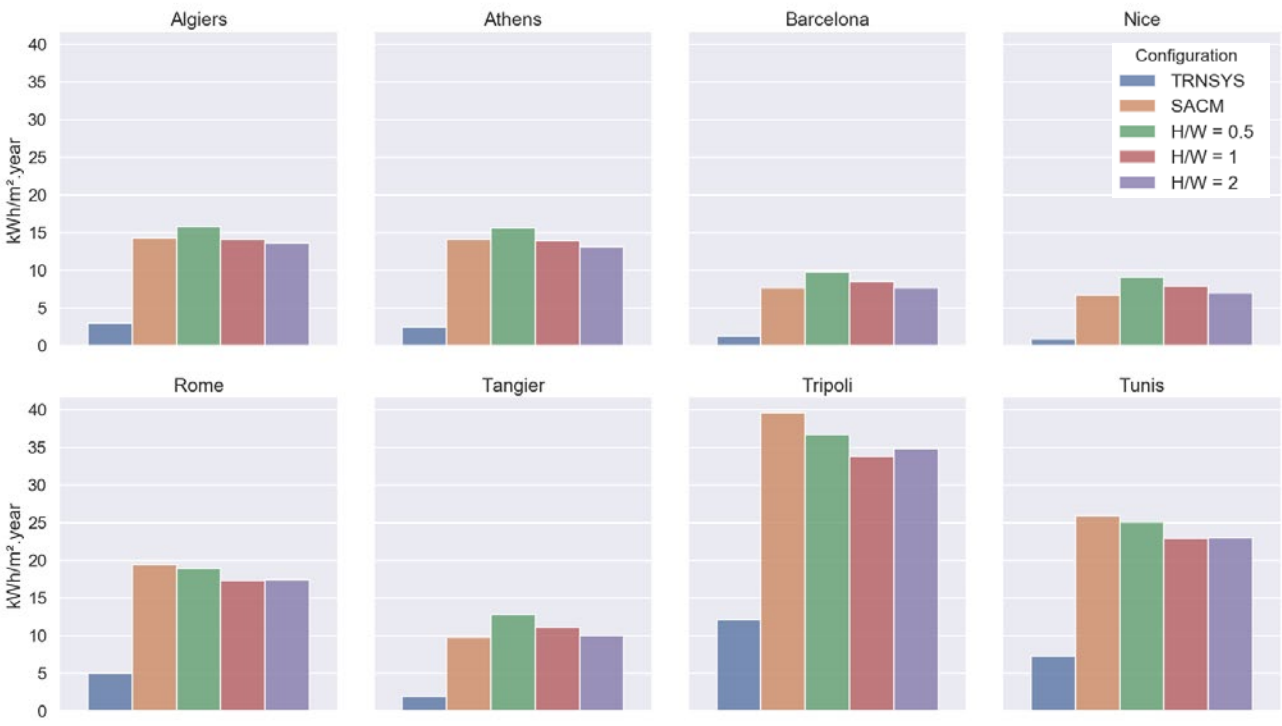


Figure 4. Cooling energy needs.

demand for courtyard building in wide canyon street is higher than the building in narrow canyon street configuration (and even more than a stand-alone courtyard building). Since more solar radiation can penetrate the wide canyon street and be trapped inside this canyon.

The lowest space cooling energy needs is associated with the *H/W* = 2 configuration. In fact, in this case, the building is flanked by narrower canyons, being therefore more sheltered from direct solar radiation. In addition, the shading effect is greater for narrow canyon than the wide one. Consequently, the narrow canyon, preventing the entry of solar radiation, offers energy advantages during the summer period, while it has the opposite effect in winter.

For the stand-alone courtyard building (SACM), the simulation results show that the cooling energy needs are very low compared to other configurations while the heating energy needs are high. During the summer, this is expected as the courtyard's openings are shaded and located in a controlled microclimate of the courtyard space. However, in winter, this is due to the fact that solar radiation is the engine of energy demand trends. If more solar radiation reaches the building envelope, the heating system requires less energy demand.

Finally, these results show the importance of considering the urban microclimate in the simulations carried out at the design stage, given its effects on energy needs and consequently on the decisions and choices adopted by deciders. It is therefore necessary to confirm the drastic effect of considering the urban microclimate in the building energy simulations. This leads to a significant error to dimensioning the HVAC systems.

Conclusion

Most neighbourhoods in Mediterranean cities are traditionally designed with street canyons, and enclosed courtyards between buildings. These courtyards had several spiritual, organizational, climate and social roles, as well as practical functions such as daylighting and building ventilation. The obtained results demonstrated the variety of courtyard effects, depending on its characteristics and locations.

The results for 8 Mediterranean cities confirmed that any changes in the microclimate affect the building energy needs in urban context, but their relative impact depends on the climate of the region. Moreover, the results obtained show that the use of regional climate data is not representative enough of the specificities of urban sites, which might lead to incorrect HVAC sizing.

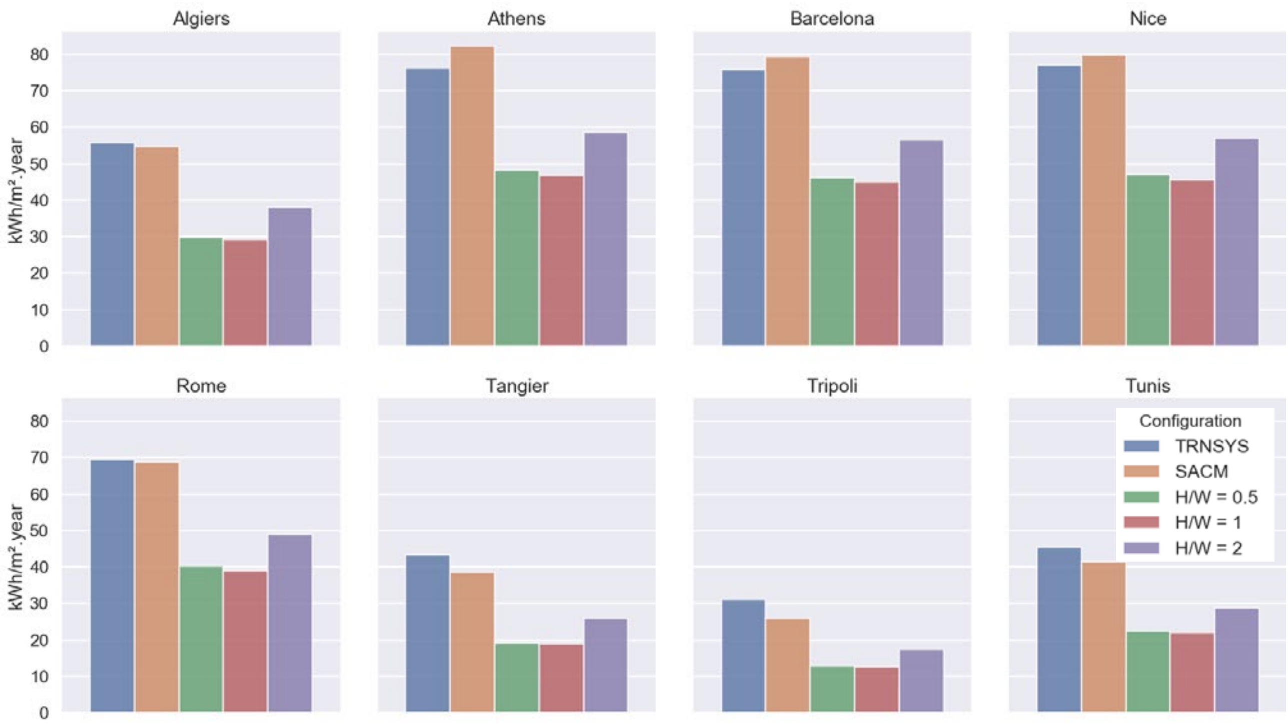


Figure 5. Heating energy needs.

Finally, the simulation methodology used in this study can be applied to similar urban contexts and to other building typologies. Moreover, it can be used by architects, planners and modelers to better understand the relationship between urban morphology, urban microclimate and the energy performance of urban buildings in order to improve thermal comfort and energy efficiency. ■

References

[1] B. Edwards, M. Sibley, P. Land, M. Hakmi, Courtyard Housing: Past, Present and Future, 2006.

[2] X. Xu, F. Luo, W. Wang, T. Hong, X. Fu, Performance-Based Evaluation of Courtyard Design in China's Cold-Winter Hot-Summer Climate Regions, (2018) 1–19. https://doi.org/10.3390/su10113950.

[3] R. Saxon, Atrium buildings: development and design, LONDON Archit. Press. 182 PP. ISBN 0-85139-849-9. 182 ILLUS. BIBLIOG. (General). (1983).

[4] Z. Zamani, S. Heidari, P. Hanachi, Reviewing the thermal and microclimatic function of courtyards, Renew. Sustain. Energy Rev. 93 (2018) 580–595. https://doi.org/10.1016/j.rser.2018.05.055.

[5] A. M'Saouri El Bat, Z. Romani, E. Bozonnet, A. Draoui, Impact Of Urban Microclimate On The Energy Performance Of Riad-type Buildings, in: Proc. Build. Simul. 2019 16th Conf. IBPSA, 2020: pp. 3771–3778. https://doi.org/10.26868/25222708.2019.211272.

[6] A. M'Saouri El Bat, Z. Romani, E. Bozonnet, A. Draoui, Integration of a practical model to assess the local urban interactions in building energy simulation with a street canyon, J. Build. Perform. Simul. 13 (2020) 720–739. https://doi.org/10.1080/19401493.2020.1818829.

[7] A. M'Saouri El Bat, Z. Romani, E. Bozonnet, A. Draoui, Thermal impact of street canyon microclimate on building energy needs using TRNSYS: A case study of the city of Tangier in Morocco, Case Stud. Therm. Eng. 24 (2021) 100834. https://doi.org/https://doi.org/10.1016/j.csite.2020.100834.

[8] G. Stephenson, DG ; Mitalas, Calculation of heat conduction transfer functions for multi-layers slabs, Air Cond. Engrs. Trans; (United States). (1970).

[9] A. Rodler, S. Guernouti, M. Musy, J. Bouyer, Energy & Buildings Thermal behaviour of a building in its environment : Modelling , experimentation , and comparison, Energy Build. 168 (2018) 19–34. https://doi.org/10.1016/j.enbuild.2018.03.008.

[10] A. Hagishima, J. Tanimoto, Field measurements for estimating the convective heat transfer coe cient at building surfaces, 38 (2003) 873–881. https://doi.org/10.1016/S0360-1323(03)00033-7.

[11] S.A. Klein, TRNSYS 17: A Transient System Simulation Program, Sol. Energy Lab. Univ. Wisconsin, Madison, USA. 1 (2010) 1–5. http://www.trnsys.com/.

[12] T. Kusuda, P.R. Achenbach, Earth Temperatures and Thermal Diffusivity at Selected Stations in the United States, ASHRAE Trans. (1965) 61–74. http://www.dtic.mil/dtic/tr/fulltext/u2/472916.pdf.

[13] B. Gebhart, Surface temperature calculations in radiant surroundings ofarbitrary complexity –for gray, diffuse radiation, Int. J. Heat Mass Transf. 3 (1961) 341–346.

[14] I.N. Harman, J.F. Barlow, S.E. Belcher, Scalar fluxes from urban street canyons. Part II: Model, Boundary-Layer Meteorol. 113 (2004) 387–409. https://doi.org/10.1023/B:BOUN.0000045526.07270.a3.

[15] L. Soulhac, R.J. Perkins, P. Salizzoni, Flow in a Street Canyon for any External Wind Direction, (2008) 365–388. https://doi.org/10.1007/s10546-007-9238-x.

[16] Z. Romani, A. Draoui, F. Allard, Metamodeling the heating and cooling energy needs and simultaneous building envelope optimization for low energy building design in Morocco, Energy Build. 102 (2015) 139–148. https://doi.org/10.1016/j.enbuild.2015.04.014.