Building and Environment 121 (2017) 247–261

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Optimization procedures for enhancement of city breathability using arcade design in a realistic high-rise urban area

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ARTICLE INFO

Article history:
Received 23 February 2017
Received in revised form
28 April 2017
Accepted 24 May 2017
Available online 28 May 2017

Keywords:
City breathability
Urban street canyons
Half open spaces
Arcade design
Computational fluid dynamics
Optimization procedure

ABSTRACT

Concern of city breathability has increased in recent project planning activities. Most previous studies in the literature have demonstrated that it is possible to improve urban ventilation efficiency by manipulating the arrangement of buildings with the integration of half open spaces into building configurations. In considering the arcade design which is a conventional type of half open space, this paper first focuses on examining the ventilation performance in a realistic high-rise urban area and its associated city breathability in terms of the ACH^* (defined as the ratio of the ACH to a characteristic frequency, determined by the reference velocity of the far upstream free flow divided by the reference building height) with or without incorporating an arcade into the object buildings. On-site measurements are conducted to validate the computational model. Then, the optimization procedures are presented, in which correlations from multivariable regression from our earlier study on generic urban street canyons are applied as the design guidelines for the arcade to maximize the ACH^*. Computational fluid dynamics simulations are extended to take into consideration buildings with an arcade of optimum height and width in actual urban canyons to determine the effectiveness of the optimization procedures used to design arcade buildings for enhancing city breathability.

1. Introduction

Global urbanization which entails the rapid growth of high-rise buildings continue to cause concerns about city breathability and is associated with microclimate variations in the main urban districts of densely-populated cities. The issue of city breathability and ventilation in street canyons has been evaluated with various indices, including ventilation indices such as the volumetric flow rate [1,2], air change rate per hour (*ACH*) [3–8] and ventilation efficiency [9–11], as well as pollutant indices such as the purging flow rate (PFR) [6,12–14], age of air [1,15,16] and exchange velocity [6,14,16–18]. Therefore, good design practices and implementation of architectural features are important as possible options in design strategies to enhance city breathability in a specific urban space. Since urban planning has essentially affected low-level airflow, optimization of urban design plans that would enhance natural ventilation in high-density urban areas has become the focus of city planners and architects. Design concepts that have inspired present-day architecture include increasingly detailed arrangement of buildings in the urban canopy layer (UCL) as a climatic control strategy. Most studies have demonstrated that it is possible to improve urban air ventilation and urban climate by manipulating the building configurations during the early stages of planning. This is due to the effects from urban heat islands (UHIs), which are urban areas with warmer temperatures than the rural areas that surround them. Therefore, a possible solution is address the problem of UHIs is to manipulate the arrangement of buildings by integrating half open spaces into the building designs.

Recently, computational fluid dynamics (CFD) calculations coupled with wind tunnel or field experiments have become very popular for pre-evaluations and design simulations that evaluate urban ventilation and city breathability at the urban neighborhood scale [19,20]. CFD has some clear advantages; full control can be established over the initial and boundary conditions to obtain the flow field data and relevant parameters in the whole computational domain, thus allowing for variations in the design parameters which will allow evaluation of alternative geometric

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http://dx.doi.org/10.1016/j.buildenv.2017.05.035
0360-1323/

configurations. CFD can be also used to quantitatively assess the design strategies for conceptual architectural layouts in urban planning. This is particularly important as on-site experiments are not an option in the design stage, when the buildings under study have not yet been constructed. Nevertheless, the accuracy and reliability of CFD simulations are crucial concerns and need to be validated with field measurements.

Table 1 provides an overview of recent CFD studies on the arrangement of buildings with the integration of half open spaces in order to enhance city breathability and ventilation performance. Hang et al. [17] studied the natural aeration characteristics of arcade roof designs in typical open and half open urban environments. Different wind directions were taken into account to determine the ventilation in the UCL. Kim et al. [21] conducted wind tunnel tests and CFD calculations for eleven alternative designs of arcade-type markets, and found that the height of the surrounding buildings as well as the type of roof, height and ventilation opening of the arcade could noticeably influence the air-exchange rate of markets. Fiala and Lomas [22] carried out a computational analysis of semi-transparent roofing materials of the ANZ Stadium in Australia for the 2000 Olympics, and found that the risk of heat strokes in the shaded upper tier of seating is greater than that in the open unshaded seating area owing to the reduced ventilation and increased radiant heat. Nguyen et al. [23] reported that side corridors have a notable role of inducing more wind into a courtyard in a wind tunnel experiment. Carrilho da Graça et al. [24] carried out experiments and CFD simulations to explore the ventilation performance of a big shopping mall with a corridor design, which included the problems of thermal comfort and energy consumption due to excessive cold airflow. Liu et al. [25] first compared their CFD simulation results with wind tunnel measurement data in terms of the wind velocities and physiological equivalent temperature (PET) around a single building both with and without an elevated design. Functioning as a well shaded corridor for wind, the elevated design (also called a lift up design) is a typical designed half open space in buildings in southern China and southeastern Asia. Fan et al. [26] evaluated the air quality and wind comfort induced by building openings with various sizes and shapes at different locations of buildings. Thus, the aforementioned studies suggest the use of half open spaces to augment the natural ventilation of the UCL over urban areas. In countries and cities with a humid subtropical climate, including Japan, Malaysia, Singapore, Taiwan, and Fujian, Guangdong and Hainan in China, the arcade design is one of the primary shape of half open spaces and a unique architectural form that adapts to local climatic patterns of subtropical regions with high temperatures, humidity, and precipitation by using colonnades or sidewalk arcades that are retained on the ground floor of buildings. Essentially, arcades provide a comfortable passageway space for pedestrians and better urban ventilation as well as space that shades solar radiation, keeps out the rain and maintains an environment of adequate air-circulation. They are also crucial to sustainable cities because arcades allow various outdoor activities and contribute to pedestrian comfort for urban livability and vitality [27].

Although the aforementioned studies have suggested the use of half open spaces to augment the ventilation performance of UCLs, the majority of their applied numerical models generally only consider generic urban configurations in ideal types of urban street canyons [17,26,28,29] or utilize a simplified design geometry [21–25,30–32]. However, both model experiments and numerical simulations use generic cubical buildings or simplified urban configurations, which cannot take into account the influence of all the environmental parameters and the intricate geometry around the studied site. The ideal model of a street canyon normally only provides a convenient but crude estimate for urban planning applications, whereas analytical models increase the understanding of the urban physics but are limited to simple flow problems. In effect, the local wind characteristics in real urban configurations are indeed highly complex. They are strongly influenced by the wind speed and direction, which in turn are affected by the urban morphology. Most previous studies have considered three different models, including generic cubical buildings, simplified street canyons or intricate geometries in practical urban configurations to investigate the effects of environmental parameters on microclimates. Research with the use of the current findings in terms of designing a formula from ideal street canyons to improve the airing effect in real urban patterns has not been done before. As opposed to previous studies, this paper focuses on examining the optimization of arcade buildings in realistic urban environments by applying findings from our previous study as arcade design guidelines for ideal urban street canyons that increase city breathability [33].

In our previous study which investigated urban ventilation in ideal urban street canyons [33], the simulated results revealed that there is an evident increase and enhancement of ventilation efficiency in the UCL with the addition of an arcade design. Moreover, there is a 60% increase of the *ACH* in the pedestrian pathway layer (PPL) after incorporating an arcade design into the same street canyon arrangements. The integrated use of a ventilation index of the *ACH* and CFD numerical modeling was confirmed to be effective for quantitatively examining the various design impacts of the arcade layout on UCL ventilation. The simulation results were further

Table 1
Overview of recent CFD studies on arrangement of buildings with integration of half open spaces into building configurations to enhance city breathability and ventilation performance.

Publication	Ref.	Model type	Configuration with half open spaces	Validation	Discussion
Fiala and Lomas (1999)	[22]	Simplified	3D/semi-transparent roofing materials of ANZ Stadium in Australia	Wind tunnel	Air flow
Kim et al. (2010)	[21]	Simplified	3D/a market structure and enclosed-arcade form	Wind tunnel	Concentration, velocity and *ACH*
Nguyen et al. (2011)	[23]	Simplified	3D/buildings with side corridor open or closed	No	Natural ventilation conditions
Carrilho da Graça et al. (2012)	[24]	Simplified	3D/a shopping mall with corridor design	No	Airflow simulation
Hang et al. (2013)	[17]	Generic	3D/two idealized urban models consisting of 4 or 16 buildings with semi-open street roofs	Wind tunnel	Natural ventilation and age of air
Liu et al. (2016)	[25]	Simplified	3D/a single building with and without elevated design	Wind tunnel	Velocity
Fan et al. (2017)	[26]	Generic	3D/two identical building blocks with or without openings of different sizes and shapes in different locations to buildings	Wind tunnel	Air quality and wind comfort