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Modelling of Egyptian low-cost-housing natural ventilation: Integration of geometry, orientation and street width optimization

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ABSTRACT

Starting from year 1995, 50 thousand low-cost housing units were been proposed to be built In Egypt by 2020 to overcome housing problems, only 60% have been already implemented. Three prototypes are amongst the most frequently built ones by the Egyptian government. In this research, these prototypes have been subject to natural ventilation modelling optimization based on three parameters which are geometry, orientation and the ratio between height and street width H/W using computational fluid dynamics (CFD) standard steady-state K-epsilon turbulence model and standard near wall function by adopting de-coupled approach. This approach indicates that the study is conducted in two levels: Firstly, the resulted pressure values on both sides of each prototype (the windward and the leeward walls) are measured numerically. Secondly, airflow rates inside buildings are calculated using Bernoulli equation. Results have been compared to each prototype's natural-ventilation requirements. In-situ measurements have been conducted to ensure adequate accuracy of calculations. Results of the study showed that further modifications have to be considered in the future configurations of these buildings.

1. Introduction

By 2020, it is estimated that 70% of the world will be living in urban areas. This gives rise to some serious environmental, social, political, economic and cultural problems (Santamouris, 2013; Bueno et al., 2014; Molla et al., 2014; Shabana et al., 2015). One of the major consequences of urbanization, is the urban heat island (UHI) which makes air temperature in the densely built-up urban areas dramatically higher than that of the rural surroundings (Bueno et al., 2013; De Ridder et al., 2015). In addition, it has a considerable impact on energy demand, human health and environmental conditions (Oke, 1987; Molla et al., 2014). Many reasons are responsible for UHI one of them is the roughness of the urban surfaces that trap wind in between buildings, and thus decreases heat dispersion (Oke, 1982; Oke, 1987; Mochida and Lun, 2008).

UHI has contributed to significant necessity to more thermal comfort energy resources to rebalance the formula especially in hot-climate regions (Crawley, 2008). A study conducted by Santamouris et al. (2001) over more than 30 urban areas indicates that UHI is responsible for doubling cooling loads and tripling electricity consumption in these areas. This problem exacerbates in the developing countries as it is monitored that citizens spend 12% of their income on energy and its services i.e. five times more than the average of developed countries (CICA, 2000; Santamouris, 2005) and 60% of foreign exchange is spent in energy imports in some developing countries (Ali et al., 2016). Furthermore, energy use by nations with emerging economies is forecasted to increase at an average of

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3.2% and to overtake that of the developed ones. Thus, a study by US Office of Technology Assessment indicates that the efficient use of energy in the developing countries could significantly halve their electricity production especially in a sector that consumes 40% of the world's energy (Der-Petrossian, 1999; Nordberg, 1999). Another study by Ali et al. (2013) demonstrates how quantitative methods for using low carbon society development contribute to mitigation of climate change in Asian developing countries.

Natural ventilation is defined as "the flow of outdoor air caused by wind and thermal pressures through intentional openings in the building's shell" (ASHRAE, 2009). The control of airflow into buildings is considered an energy efficient method for both thermal comfort and human health (Dimitroulopoulou, 2012). On one hand by controlling heat dispersion through convection and decreasing sensible heat loads. On the other hand, by the renewal of indoor air and thus removing contaminants and odours. With respect to hot arid climates like that in Egypt, natural ventilation is considered an efficient method for thermal comfort and human health (Nguyen and Reiter, 2014). Numerous researches on natural ventilation for thermal comfort and human health have been conducted based on theoretical (Awbi, 1994; Etheridge and Sandberg, 1996; Awbi, 2003), analytical (Linden, 1999; Coffey and Hunt, 2007), experimental (Straw et al., 2000) and numerical simulations such as Computational Fluid Dynamics (CFD) (Ramponi and Blocken, 2012a, 2012b; van Hooff and Blocken, 2013; Santiago et al., 2014; Yuan and Ng, 2014). Computational Fluid Dynamics (CFD) is defined as the study of fluid motion and heat transfer as well as the interaction of the fluid with solid bodies numerically by solving a number of partial differential equations i.e. continuity equation, energy conservation equations, momentum conservation equations and turbulence models by discretizing a computational domain into tiny finite elements and solving these equations at each point of these elements (Tu et al., 2012; Blazek, 2015). With regard to efficiency, time and cost, CFD is considered a suitable tool for predicting fluid behavior in and around buildings due to the increasing advancement in computers' speed, memory and advanced efficient algorithms.

One approach by the Egyptian government has been adopted to overcome housing problems and their consequences started at October 1995. This approach was to build 50,000 low-cost economic housing units with specific designs and geometries. These designs have been approved by the Egyptian Housing and Building National Research Centre HBRC. These units are distributed all over the country and only 60% of these units have been implemented the other 40% units are expected to be built in the next few years (Portal, 2016). They are existed in a number of different sizes and shapes (Portal, 2016). This paper presents a natural ventilation assessment of three of these prototypes based on their geometry, orientation and ratio between height and distance between buildings (H/W), taking into consideration the estimated number of occupants, and the local weather data using CFD.

1.1. Justification of case study selection

The selection of these three prototypes is based on the following criteria stated by Gado and Mohamed (2006):

1- These prototypes are amongst the most frequently built prototypes by the Egyptian government, that is a total number of 50,000 were prospected to be built in both old and new cities and about 60% of these housing units have been already implemented (Portal, 2016). Thus, and optimized modelling of these prototypes is justified due to their quantitative volume around the country.
2- These prototypes are meant to be economic and low-income housing. Thus, depending on optimization studies and early stages energy efficiency designs serve this objective.
3- The accessibility of climatic data in addition to safely accessing the site and positioning the measurement instruments is one major fact in choosing case studies.

1.2. Previous studies

Pressure-difference based natural ventilation has gained interest of large number of research studies e.g. a study by Asfour (2010) and Asfour and Alshawaf (2015) has investigated the pressure difference on different groups of buildings' configurations. While the study conducted by Zhang and Gu (2008) presented RNG k-epsilon numerical and wind-tunnel investigation of pressure distribution on buildings arranged in staggered way. Another study by Jiang et al. (2003) presented natural ventilation in building using LES model and wind tunnel validation. While urban built-up density i.e. height to street canyon width H\W effect on urban energy balance and thermal comfort has been studied by Wang et al. using Large-Eddie-Simulation approach (Wang et al., 2017). On the other hand, Egyptian prototype housing has been the subject of interest by many researches e.g. a study by Rizk and Henze (2010) investigated air flow around rectangular row of prototype buildings in Egypt. While the study conducted by El-Hefnawi (2000) focused on indoor thermal comfort of Egyptian youth housing without taking into consideration natural ventilation. Also the study by Gado and Osman (2009) and Osman (2011) investigated natural ventilation inside walk-up housing blocks in Egypt. The uniqueness of the current research comes from investigating different parameters of prototype housing such as (geometry, orientation, height to street width aspect ratio) to be integrated with the previous studies.

2. CFD model

2.1. Governing equations

Reynolds-Average Navier-Stokes (RANS) turbulence model has been adopted by averaging Navier-Stokes equations' components as shown in the general form:where [1] represents the local acceleration, [2] is the advection term, [3] is the diffusion and [4] is source term. While ϕ, Γ and S_ϕ are the property, diffusion coefficient and source respectively and their values change with the type of equation as follows: