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ScienceDirect

Procedia Computer Science 108C (2017) 225–234

Procedia
Computer Science

International Conference on Computational Science, ICCS 2017, 12-14 June 2017, Zurich, Switzerland

Development of a new urban heat island modeling tool: Kent Vale case study

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Abstract

Urban heat island is intensified by anthropogenic activities and heat in conjunction with the built-up urban area, which absorbs more solar radiation during daytime and releases more heat during nighttime than rural areas. Air cooling systems in Singapore, as one of the anthropogenic heat sources, reject heat into the vicinity and consequently affect urban microclimate. In this paper, a new urban heat island modeling tool is developed to simulate stack effect of split type air-conditioners on high rise buildings and solar radiation induced thermal environment. By coupling the Computational Fluid Dynamics (CFD) program with the solar radiation model and perform parallel computing of conjugate heat transfer, the tool ensures both accuracy and efficiency in simulating air temperature and air relative humidity. The annual cycle of sun pathway in Singapore is well simulated and by decreasing the absorptivity or increasing the reflectivity and thermal conductivity of the buildings, the thermal environment around buildings could be improved.

Peer-review under responsibility of the scientific committee of the International Conference on Computational Science

Keywords: Urban heat island, stack effect, sensitivity analysis, solar radiation, thermal environment

1 Introduction

Urban heat islands (UHIs), together with urban noise and urban air pollution, are three of the major environmental challenges of future more livable cities. UHIs are described as the phenomenon that the air temperature in urban area is consistently higher than its rural area (Oke, 1973). While many causes of the urban heat island such as reduced evaporation, increased heat storage, increased net radiation, reduced convection and increased anthropogenic heat have been identified as in Gartland (2008), the contribution of each component strongly depends on the individual city and its geography. In a high-density mixed-used tropical city like Singapore, the urban microclimate varies from location to location and time to time. The prevalence of the use of air-conditioning in Singapore throughout the

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* This work was financially supported by the Singapore National Research Foundation (NRF) under its Campus for Research Excellence And Technological Enterprise (CREATE) program.

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Peer-review under responsibility of the scientific committee of the International Conference on Computational Science
10.1016/j.procs.2017.05.282

year has posed heat-related stress and health issues (Kovats and Hajat, 2008; Lo and Quattrochi, 2003; Oikonomou et al., 2012), higher energy costs (Kolokotroni et al. 2012) and has downgraded urban living quality (Mavrogianni et al., 2011), as pointed out in Berger (2016). A comprehensive measurement of air temperature in earlier study (Wong and Chen, 2006) between 2001 and 2004 showed that the urban heat island in Singapore was about 4.5°C. A more recent study (Chow and Roth, 2006) found that the peak urban heat island intensity occurs approximately six hours after sunset at central business districts, high-rise residential estate, and low-rise residential area. Higher urban heat island intensities generally occur during the Southwest monsoon period of May – August, with a maximum of ~7°C observed at Orchard Road at approximately 9pm local time (Chow and Roth, 2006). A more comprehensive review of recent urban heat island studies in Singapore is conducted in Roth and Chow (2012).

In Singapore, the majority of installed air-conditioning systems on high rise residential buildings are split type air-conditioners, compact units rejecting heat from air-conditioning through a dry heat exchange. They affect and in turn exposed to the urban microclimate in their vicinity, with regard to capacity to provide cooling and the efficiency of their operation. One such microclimatic effect is the stack effect, a buoyancy-driven airflow fueled by the hot air rejected from condensing units. Stack effect of split type air-conditioners on high-rise buildings are simulated by CFD models as summarized in Bojic et al. (2008) and observed in Bruelisauer et al. (2014).

In the view of respective contributions from different aspects of anthropogenic heat and built-up area of a tropical city like Singapore, an integrated system needs to be established to identify the individual effects of major heat sources and sinks. Heat sources include air-conditioners on buildings at the small end of the scale and solar radiation at the large end of the scale. This paper discusses the development of a new urban heat island modeling tool at multiple urban scales, focusing on the stack effect induced by split type air-conditioners on high rise buildings and the effects of solar radiation on thermal environment around buildings.

2 Methods

Three universal conservation laws of mass, momentum and energy are taken into account by solving continuity equation (Equation (1)), Navier-Stokers equation (Equation (2)) and energy balance equation (Equation (3)). Conjugate heat transfer is simulated by solving heat convection (Equation (4)), conduction (Equation (5)) and radiation (Equation (6)) between fluid and solid regions. Turbulence is solved by $k-\varepsilon$ model. Solar radiation is simulated by accounting for the combined effects of the Sun primary hits, their reflective fluxes and diffusive sky radiative fluxes (Howell et al. 2010). The primary hit rays of solar radiation are calculated using a face shading algorithm. The reflected fluxes are considered diffusive and use a view factors method to deposit the energy on visible walls. The sky diffusive radiation for horizontal and vertical walls is calculated following the Fair Weather Conditions Method from the ASHRAE Handbook.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u} + p\boldsymbol{I}) = \mu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{g} \tag{2}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T \right) = \kappa \nabla^2 T + Q \tag{3}$$

$$q = h(T_a - T_\infty) \tag{4}$$

$$q = -k \nabla T \tag{5}$$

$$q = \epsilon \sigma (T_a^4 - T_b^4) \tag{6}$$