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Research paper

Simulating the cooling effects of water spray systems in urban landscapes: A computational fluid dynamics study in Rotterdam, The Netherlands

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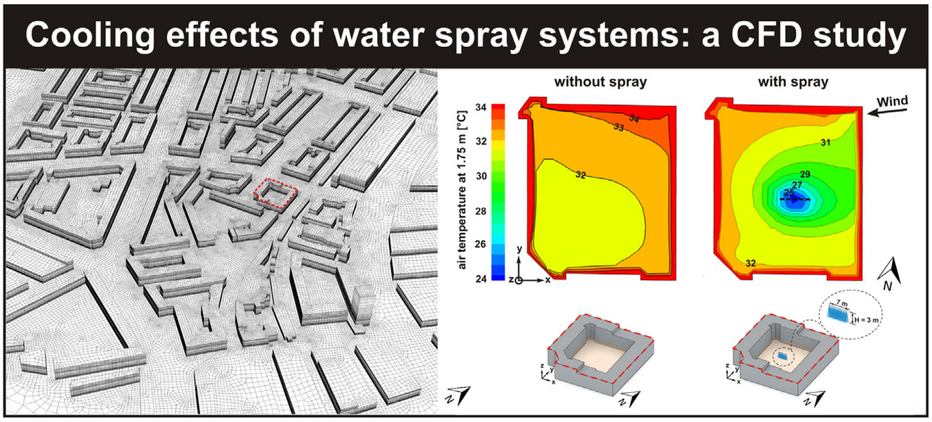
HIGHLIGHTS

- Water spraying is an effective measure for improving outdoor thermal comfort.
- Maximum air temperature reduction and UTCI reduction are 5 and 7 °C at 1.75 m height.
- Thermal comfort at pedestrian height is improved up to 5 m away from spray system.
- Water flow rate and spray height strongly affect cooling potential of spray systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Heat waves and the related heat stress can increase human morbidity and mortality, decrease human productivity and increase building energy consumption for cooling. There is a need for sustainable systems to reduce heat stress in urban areas. Evaporative cooling by water spray systems is increasingly used for this purpose. However, the evaluation of the cooling potential of such systems is difficult. To our knowledge, a systematic investigation of the cooling potential of such a system in an actual urban area has not yet been performed. This paper presents high-resolution Computational Fluid Dynamics (CFD) simulations based on the 3D unsteady Reynolds-Averaged Navier-Stokes equations to assess the cooling potential by a water spray system with 15 hollow-cone nozzles. The system is numerically implemented for a courtyard in the Bergpolder Zuid region of Rotterdam, the Netherlands and operated during the heat wave period of July 2006. The simulations are validated based on wind-tunnel measurements of an evaporative cooling process and satellite imagery data during the heat wave period. The Universal Thermal Climate Index (UTCI) is used to assess the heat stress reduction due to evaporative cooling. The results show that for given values of injected water flow rate ($\dot{m}_w = 9.0$ l/min) and height of the spray system (H = 3 m), a maximum temperature reduction and UTCI reduction of about 7 and 5 °C are achieved

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at pedestrian height. In addition, a thermal comfort improvement from strong heat stress (without spray system) to moderate heat stress up to a distance of 5 m from the spray line is obtained.

1. Introduction

Climate change is expected to increase the frequency and the intensity of heat waves (Kovats & Hajat, 2008). Major heat waves, such as the European heat waves of 2003 and 2006, might occur more frequently and could become common events by 2040 (Kovats & Hajat, 2008; Stott, Stone, & Allen, 2004). Increased heat waves and heat stress will cause increased heat-related morbidity and mortality, as illustrated for the hot summers of 2003 and 2006 (Fischer, Brunekreef, & Lebret, 2004; Haines, Kovats, Campbell-Lendrum, & Corvalán, 2006). During the summer of 2003, more than 70,000 heat-related deaths were reported in Europe (Robine et al., 2008). Due to increased intensity and frequency of heat waves, cooling energy demand in summer is expected to increase by 72% worldwide by 2100 (Isaac & van Vuuren, 2009). These problems are potentially aggravated by the urban heat island effect (UHI) (Allegrini, Dorer, & Carmeliet, 2012; Grimmond & Oke, 1991; Heusinkveld, Steeneveld, Hove, & Jacobs, 2013; Mirzaei & Haghighat, 2010; Oke, 1982).

Several urban scale adaptation measures, such as vegetation, increased short-wave reflectivity of surfaces and evaporative cooling can be employed to decrease high temperatures in urban areas (Akbari, Bretz, Kum, & Hanford, 1997; Gromke et al., 2015; Rizwan, Dennis, & Chunho, 2008; Rosenfeld et al., 1995). Among the proposed measures, the use of water spray systems for evaporative cooling is becoming more popular (Huang et al., 2011; Sureshkumar, Kale, & Dhar, 2008a). Water spraying can be an effective and economical tool for improving both indoor and outdoor thermal comfort. Most available adaptation measures such as vegetation and increased short-wave reflectivity are so-called passive systems, which normally have effects all year long with little or no controllability. While they clearly can provide positive effects during warm seasons, they may lead to increased building energy consumption in the winter season. (Loonen, Trčka, Cóstola, & Hensen, 2013; Taleghani, Tenpierik, & van den Dobbelsteen, 2014; van Hooff, Blocken, Hensen, & Timmermans, 2014; van Hooff, Blocken, Timmermans, & Hensen, 2016). Water spray systems, on the other hand, are flexible in use with dynamic controls and can be easily integrated in various projects (Pearlmutter, Erell, Etzion, Meir, & Di, 1996).

The two-phase flow in water spray systems is very complex as the evaporation process depends on several physical parameters, which are not easily varied independently (Ashgriz, 2011; Lefebvre, 1989; Montazeri, Blocken, & Hensen, 2015a; Montazeri et al., 2015b). Given the complexities involved in evaluating the performance of water spray systems, most previous studies were performed using field measurements. They evaluated the influence of different physical parameters on the performance of water spray systems, such as ambient air temperature and air humidity (Huang et al., 2011; Nishimura, Nomura, Iyota, & Kimoto, 1998), solar radiation (Takahashi et al., 2010), elapsed time under influence of spray (Farnham, Emura, & Mizuno, 2015) and nozzle spray characteristics. However, field measurements are usually only performed in a limited number of points in space. In addition, there is almost no or limited control over the boundary conditions. This is, however, very important given the wide range of parameters influencing the performance of evaporative cooling systems.

Numerical simulation by Computational Fluid Dynamics (CFD) can be a useful tool to investigate the two-phase flow in spray systems. The use of CFD for the evaluation of urban meteorology and microclimate has seen a rapid growth in the past 50 years (Blocken, 2014). This growth has been strongly supported by the development of best practice guidelines for CFD applications for urban areas (Blocken, 2015; Casey & Wintergerste, 2000; Franke et al., 2007; Tominaga et al., 2008) and is illustrated by a large number of review, overview and position papers (e.g. (Blocken, 2015, 2014; Blocken & Carmeliet, 2004; Mochida & Lun, 2008; Murakami, Ooka, Mochida, Yoshida, & Kim, 1999; Murakami, 1997; Ramponi & Blocken, 2012; Stathopoulos, 2002, 1997; Tominaga & Stathopoulos, 2013; Toparlar et al., 2015)). As a result, CFD is increasingly used to evaluate the potential of sustainable and renewable energy systems (e.g. (Calautit, Hughes, Chaudhry, & Ghani, 2013; Montazeri & Azizian, 2009; Montazeri, Montazeri, Azizian, & Mostafavi, 2010; Montazeri, 2011)), including the cooling performance of water spray systems (Kang & Strand, 2013; Montazeri et al., 2015a, 2015b; Sureshkumar, Kale, & Dhar, 2008b). However, to our knowledge, a systematic investigation of the cooling potential of water spray systems in an actual urban area has not yet been performed. Therefore, the current paper presents CFD simulations on a high-resolution grid to assess the cooling potential of a water spray system with hollow-cone nozzles for a courtyard in the Bergpolder Zuid region of the Dutch city of Rotterdam, the Netherlands in July 2006, when one of the major European heat waves occurred. In addition, the impact of the injected water flow rate and the height of the spray system on its cooling performance is investigated.

In Section 2, the Bergpolder Zuid region is described. Section 3 presents the validation study for the evaporative cooling model. In Section 4, the CFD simulations for Bergpolder Zuid are outlined. Section 5 presents a parametric analysis for evaporative cooling in Bergpolder Zuid. Finally, discussion (Section 6) and conclusions (Section 7) are provided.

2. Urban area and surroundings

Following the reports of the Intergovernmental Panel on Climate Change (IPCC), more and more research organizations and consortia have started to focus on climate adaptation (Parry, Canziani, Palutikof, van der Linden, & Hanson, 2007). One of these was the Climate Proof Cities (CPC) research consortium composed of universities, research institutes, policy makers and city officials investigating the application of urban scale adaptation measures in the Netherlands (Albers et al., 2015). One of the focus areas was the Bergpolder Zuid region in Rotterdam, located in the Noord district of the city (Fig. 1).

Rotterdam is subjected to an oceanic climate influenced by the Atlantic Ocean and the North Sea, which is similar in the rest of the country. Based on the Köppen-Geiger classification (Strahler & Strahler, 1984), the climate of the Netherlands is Cfb, a climate with moderate winters and moderately warm summers, though heat waves are becoming more and more frequent.

The Bergpolder Zuid region consists of both residential and office buildings with narrow streets and surrounded by large avenues (Fig. 1d). Most of the streets in the region are narrow with

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