Science of the Total Environment 626 (2018) 134–146

Contents lists available at ScienceDirect

Science of the Total Environment

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

WRF modeling of $PM_{2.5}$ remediation by SALSCS and its clean air flow over Beijing terrain

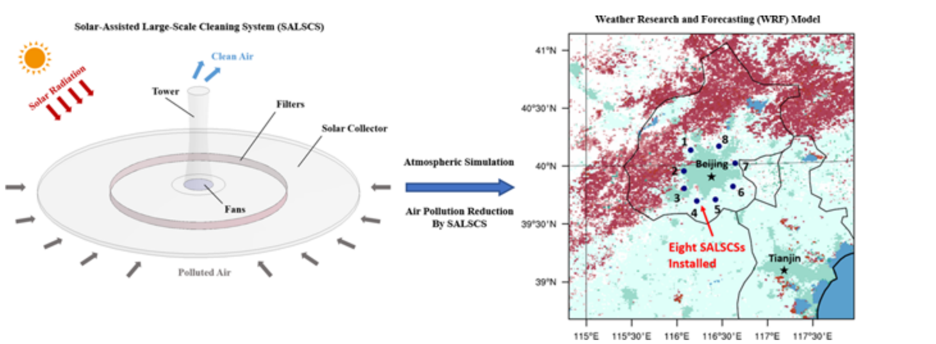
Qingfeng Cao, Lian Shen, Sheng-Chieh Chen, David Y.H. Pui *

Department of Mechanical Engineering, University of Minnesota, 111 Church Street SE, Minneapolis, MN 55455, USA

HIGHLIGHTS

- SALSCS is a large-scale cleaning system proposed for urban air pollution reduction.
- WRF simulations were conducted to evaluate SALSCS over the Beijing terrain.
- Passive tracer scalars were used to simulate $PM_{2.5}$ pollutant and SALSCS clean air.
- Air pollution reduction percentages of SALSCS over the urban region were obtained.
- Clean air plumes of SALSCS were visualized.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 October 2017
Received in revised form 7 January 2018
Accepted 7 January 2018
Available online xxxx

Editor: Xuexi Tie

Keywords:
SALSCS
Air pollution reduction
WRF
Atmospheric simulation
Clean air

ABSTRACT

Atmospheric simulations were carried out over the terrain of entire Beijing, China, to investigate the effectiveness of an air-pollution cleaning system named Solar-Assisted Large-Scale Cleaning System (SALSCS) for $PM_{2.5}$ mitigation by using the Weather Research and Forecasting (WRF) model. SALSCS was proposed to utilize solar energy to generate airflow therefrom the airborne particulate pollution of atmosphere was separated by filtration elements. Our model used a derived tendency term in the potential temperature equation to simulate the buoyancy effect of SALSCS created with solar radiation on its nearby atmosphere. $PM_{2.5}$ pollutant and SALSCS clean air were simulated in the model domain by passive tracer scalars. Simulation conditions with two system flow rates of 2.64×10^5 m^3/s and 3.80×10^5 m^3/s were tested for seven air pollution episodes of Beijing during the winters of 2015–2017. The numerical results showed that with eight SALSCSs installed along the 6th Ring Road of the city, 11.2% and 14.6% of $PM_{2.5}$ concentrations were reduced under the two flow-rate simulation conditions, respectively.

1. Introduction

Many urban areas in the world are currently experiencing severe air pollution problems, adversely affecting the health and living quality of the city population (Seaton et al., 1995; Kampa and Castanas, 2008; Shah et al., 2013; Chen Y. et al., 2013). For instance, Beijing, the capital city of China, has been facing high concentrations of $PM_{2.5}$ (fine particulate matter <2.5 μm) and gaseous pollutions over the last two decades (Tang et al., 2017; Zhang et al., 2016; Sun et al., 2016; Hao et al., 2007). Most of the strategies for air pollution mitigation are targeted on cutting the pollutant emissions from the sources (Pui et al., 2014; Wang et al., 2016a; Wang et al., 2016b; Shi et al., 2016; Mao et al., 2014; Wang et al., 2017), but not reducing the air pollutions after their emission and dispersion into the atmosphere. Recently, a Solar-Assisted Large-Scale Cleaning System (SALSCS) was proposed by Cao et al. (2015) as a

* Corresponding author.
E-mail address: dyhpui@umn.edu (D.Y.H. Pui).

https://doi.org/10.1016/j.scitotenv.2018.01.062
0048-9697/

novel strategy aimed at generating airflow in large quantities to facilitate the separation of $PM_{2.5}$ from polluted atmospheric air for urban areas.

The idea of SALSCS utilizing solar energy to generate updraft airflow originated from the configuration of solar chimney power plant first described by a Spanish artillery colonel, Isidoro Cabanyes, in 1903 (Al-Kayiem and Aja, 2016; Kasaeian et al., 2017). The system was proven to work after a pilot plant was constructed and tested in Manzanares, Spain (Haaf et al., 1983; Haaf, 1984). Many seminal works have been done over the last 30 years, demonstrating the system's capability of creating airflow (Pasumarthi and Sherif, 1998a; Pasumarthi and Sherif, 1998b; Pastohr et al., 2004; Schlaich et al., 2005; Pretorius and Kröger, 2006; Ming et al., 2008; Fasel et al., 2013). A schematic configuration was presented as an initial design of a full-scale system as shown in Fig. 1. The SALSCS is composed of four basic elements: (1) a solar collector, (2) a tower, (3) filtration elements and (4) fans for creating more airflow if necessary. The system generates updraft airflow based on the principle of buoyancy effect with solar energy. After heated by the sunlight, the warmer air inside the system has a lower density than the air in the ambient environment, so that buoyancy-driven flow is induced. Fans can also be employed to generate higher flow rate. Atmospheric polluted air is pulled into the system at the solar collector aperture, flows over the warm ground heated by solar radiation under the collector shed, and passes through the filtration elements for the removal of $PM_{2.5}$. It is to be mentioned that, in addition to $PM_{2.5}$, gaseous pollutants can also be mitigated if selected chemical filters are applied. However, $PM_{2.5}$ is the concerned air pollutant in this study. The filtered and cleaned air with low $PM_{2.5}$ concentration then enters the tower and is delivered back into the atmosphere.

Cao et al. (2015) conducted a numerical calculation and estimated the total flow rate of the full-scale SALSCS to be 2.64×10^5 m^3/s with a filter bank installed in the system, where Reynolds-Averaged Navier-Stokes (RANS) equations were solved together with the standard k-ε 2-equation turbulent model using the ANSYS Fluent software. As a validation of the calculated system flow rate, a demonstration unit of SALSCS was constructed in the city of Xi'an, China, during the summer of 2016. Experimental measurements were conducted to evaluate the system performance. The obtained measurement data showed a good agreement with the numerical results calculated from the same ANSYS Fluent solver. Comparisons between the experimental data and numerical results are given in the Supporting Information of this paper, and detailed descriptions of this validation study will be published in the near future.

Given the high flow rate of SALSCS according to the calculation of Cao et al. (2015), it is interesting to find out how much of air quality can be improved over urban areas by implementing an array of SALSCSs. Thus, atmospheric simulations at meteorological scale over the terrain of certain urban areas were conducted. A computer program named Weather Research and Forecasting (WRF) model was utilized for the purpose of this study.

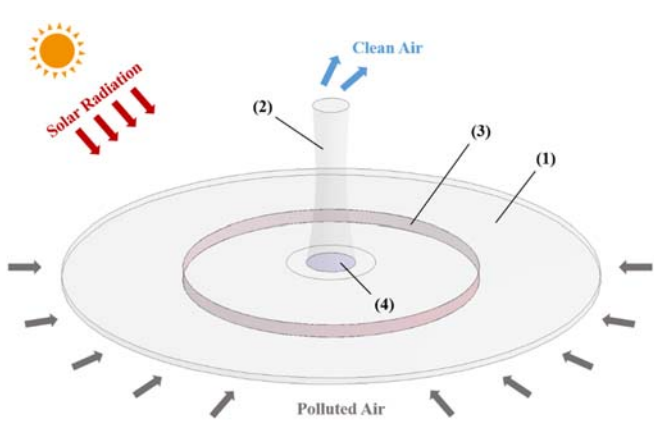


Fig. 1. Schematic diagram of the SALSCS with (1) solar collector, (2) tower, (3) filtration elements, and (4) fans (optional).

WRF is a meteorological numerical simulation program designed for both operational weather forecasting and atmospheric research (http://www.wrf-model.org). The model can be used to simulate atmospheric processes over varied ranges of spatial and temporal scales (Skamarock et al., 2008). Many researchers employed the WRF program to study the processes of air pollution emission, generation and transportation in the atmosphere. For example, Ahmadov et al. (2015) modeled the wintertime ozone over the Unita Basin in northeastern Utah, USA, to examine the different factors for ozone formation. The study showed that there was a disproportionate contribution of aromatic VOCs to ozone formation relative to the other VOC emissions. Beck et al. (2013) carried out atmospheric simulations using WRF to study the ration of CH_4 mixing over the Amazon basin in South America. The major conclusions were that a wetland inundation map with inundated area as a function of time can improve the agreement with the observations, and improvements in representing the meteorological conditions are necessary for modeling accuracy. Chen D. et al. (2013) used WRF to simulate the effects of O_3 and NO_x species and their photochemistry on air quality in the Los Angeles basin. Results indicated NO_x-saturated O_3 production in the basin as a result of the O_3 concentration increase with modifying the NO_x emission reduction of the model. The WRF program was applied by Matsui et al. (2010) to study how individual aerosol chemical components affect the spatial and temporal variations of aerosol optical properties in the region of Beijing, China. It was found that aerosol optical parameters are related to synoptic meteorological conditions and spatial variations of elemental carbon and sulfate. Jiang et al. (2008) applied WRF simulations to study a continuous photochemical pollution episode in Hong Kong during Typhoon Nari, with the aim to understand the physical and chemical mechanisms of the air pollution episode. The authors concluded that meteorological conditions, such as high temperature, low relative humidity and stable boundary layer structure, provide major contributions to the pollution formation and maintenance. Although there are many researchers conducting atmospheric simulations to study different air pollution mechanisms, no research has been done so far to study the influence of a large-scale air pollution control system, e.g. the current SALSCS, on $PM_{2.5}$ remediation over urban regions. Because of the capability of WRF, we chose to use its modeling system to carry out atmospheric simulations to investigate the effectiveness of SALSCS on reducing urban $PM_{2.5}$. Most of the research mentioned above utilized the WRF-Chem model to simulate air pollution episodes, which is a version of WRF that can simulate trace gases and particulates simultaneously within the meteorological fields (Grell et al., 2005). Since our main focus is only on the physical transport process of the air pollution in the atmosphere and the physical mechanism of SALSCS collecting $PM_{2.5}$ and delivering clean air, chemical processes were neglected in our simulation. Hence, we employed the WRF model to carry out atmospheric simulations as an initial study of evaluating the effectiveness of SALSCS on urban air pollution remediation.

Beijing is a megacity rapidly developing in the northern China and experiences severe air pollution problems during the recent decades. Thus, our WRF simulation was chosen to be carried out over the terrain of the Beijing city and its surrounding regions. The present study is aimed to determine the air-pollution reduction by SALSCS over the city, and the amount of clean air reaching the ground level of its urban area. This paper first discusses the WRF model formulation, including the setup for the model domain and selection of the physics parameterization schemes. Then the approach of modeling the buoyancy effect created by SASLCS in the WRF model is introduced. The method for simulating $PM_{2.5}$ pollutant and SALSCS clean air is then addressed in the following sections. Numerical results on both the air pollution and clean air are presented and analyzed in the Results and discussion section. At the end of this paper, a summary of the current research work is given and possible future work is discussed.