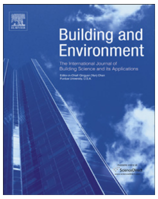
Building and Environment 94 (2015) 68–81

Contents lists available at ScienceDirect

Building and Environment

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



Constructing Markov matrices for real-time transient contaminant transport analysis for indoor environments

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
23 June 2015
Accepted 20 July 2015
Available online 22 July 2015

Keywords:
Markov matrix
Scalar transport
Contaminant dispersion
Real-time prediction
Infectious disease control
Indoor air quality estimation

ABSTRACT

Predicting the movement of contaminants in the indoor environment has applications in tracking airborne infectious disease, ventilation of gaseous contaminants, and the isolation of spaces during biological attacks. Markov matrices provide a convenient way to perform contaminant transport analysis. However, no standardized method exists for calculating these matrices. A methodology based on set theory is developed for calculating contaminant transport in real-time utilizing Markov matrices from CFD flow data (or discrete flow field data). The methodology provides a rigorous yet simple strategy for determining the number and size of the Markov states, the time step associated with the Markov matrix, and calculation of individual entries of the Markov matrix. The procedure is benchmarked against scalar transport of validated airflow fields in enclosed and ventilated spaces. The approach can be applied to any general airflow field, and is shown to calculate contaminant transport over 3000 times faster than solving the corresponding scalar transport partial differential equation. This near real-time methodology allows for the development of more robust sensing and control procedures of critical care environments (clean rooms and hospital wards), small enclosed spaces (like airplane cabins) and high traffic public areas (train stations and airports).

1. Introduction

High indoor air quality (IAQ) is essential for safety and comfort within the indoor built environment. Poor IAQ may lead to a loss in productive work time in commercial environments, expensive mechanical systems maintenance, and even litigation [2]. Gasses (carbon dioxide, volatile organic compounds, carbon monoxide, and radon) and airborne particulates (mold, atmospheric particulate matter, and microbial contaminants) are generally known to negatively affect IAQ. Control of these contaminants is critical in healthcare environments, clean rooms, and confined spaces.

For instance, incidence of burn wound infections remains a high-risk proposition even today when the burn area covers a substantial portion of the patient's body. Controlling airborne contamination is of major importance in these cases. The susceptibility of patients is partially due to infections (from the large amount of exposed area) and the unique environmental conditions (the required elevated temperatures and humidity in the patient room) that such rooms operate under. Furthermore, the biological quality of air in hospital environments is of particular concern as patients may serve as a source of pathogenic microorganism to staff and hospital visitors in addition to other admitted patients. A classic example of this problem is the tuberculosis outbreak in 2000 [25].

Outside of healthcare facilities, confined spaces are also susceptible to the transmission of infectious diseases. Public transportation (especially aircraft and underground subway systems), schools classrooms, and close office quarters provide an environment where a single infected individual can potentially infect a large number of people. Examples include the spread of influenza [26] and severe acute respiratory syndrome (SARS) [30] that have been reported in aircraft travel. Other examples include the gas attack on the Tokyo subway system in 1995 [31], and the measles outbreak in office spaces in 1985 [7]. In US schools, students miss approximately 38 million school days each year due to the influenza virus [8].

Motivated by these issues, it is clear that methods for prediction and control of these contaminants in indoor environments are

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http://dx.doi.org/10.1016/j.buildenv.2015.07.020

needed. In this context, Computational Fluid Dynamics (CFD) simulations have been used extensively for determining airflow in indoor environments. The earliest reference to CFD being used for this purpose was the study of the velocity characteristics of ventilated rooms by P.V. Nielsen et al., in 1978 [27]. Since then the popularity of running CFD simulations for predicting air flow in indoor spaces has increased rapidly. ASHRAE has taken efforts to standardize CFD simulation procedures, i.e. to setup, simulate, and perform both verification and validation [1]. CFD simulations have also been integrated into building simulation programs like EnergyPlus [37] and ESP-r [16] for establishing boundary conditions of buoyancy based fluid flow. CFD flow fields have also been used for developing methods for scalar-transport in indoor environments. Validation for multi-zone CFD simulations with contaminant transport has been performed by building researchers [35,40]. Other validations of scalar contaminant transport has been performed for ventilation efficiency [3], personal ventilation [22], occupant exposure [23] and dispersion [21] of toxic contaminants, and dispersion of contaminants in hospital wards [15]. The application of contaminant dispersion in the indoor environment applied to emergency situations was investigated by L. Wang et al. [41]. Many other application of contaminant transport in the indoor environment can also be found in scientific literature. A few examples include identification of sources using an inverse CFD approach [44], removal of contaminants using different ventilation strategies [17], and contaminant transport in an airliner by moving bodies [32].

In the previous discussed work, contaminant transport simulations by solving the scalar transport equations have been shown to produce accurate results, but many limitations exist to utilizing these methods for real-time prediction and control of indoor environments. Solving the scalar transport equations involves loading a potentially large CFD data and mesh into a computer's memory, and then solving a partial differential equation (PDE) for the transient contaminant transport. Buildings with a complex geometry could require specialized hardware simply to load the CFD data and mesh into memory. Specialized software packages or commercial software may also be needed to perform the transient contaminant transport simulation. The computational time and memory requirements are too much for wireless sensors designed for a long battery life to manage for real-time decisions.

There have been some promising advances that enable simulating fluid behavior in real time. These include Fast fluid dynamics, lattice Boltzmann methods, and Markov methods. Fast fluid dynamics (FFD) [36] uses a set of low order schemes and a semi-lagrangian approach for advection to reduce computing cost. Comparisons of FFD and CFD along with implementation of FFD on graphical hardware with promising results have been recently accomplished by Zuo et al. [45,46]. The lattice Boltzmann method uses kinetic theory to incorporate physics of micro/mesoscopic processes on the behavior macroscopic modules [9]. Lattice Boltzmann methods have been popular due to their ability for parallelization and implementation on graphical processing units (GPU)s [4,42]. The third alternative is Markov matrices methods that are the focus of the current work.

Markov matrices provide an efficient and elegant approach to modeling the contaminant transport problem. This was explored in the recent seminal work by Chen and co-workers for CFD data [10,11] and Nicas for a multi-zone model [20]. These methodologies use either Lagrangian particle tracking or a contaminant flux to calculate entries of the Markov matrix. The Markov matrix is used to propagate concentrations of contaminants through time. The simulation results using the Markov method compared well with experiments and CFD simulations [10,11]. The Markov method is extremely fast compared to Eulerian transport, as only a single matrix-vector multiplication is needed to perform the transient contaminant transport. Due to the speed of this method, real-time inference of the contaminant field can be performed. Furthermore, by utilizing sparse matrix storage this method drastically reduces the memory requirements needed to perform the analysis.

Analyzing the transport of contaminants using Markov matrices has some additional benefits over other fast simulation techniques. Not only can Markov matrices be used for forward propagation of contaminants, but they can also be used for inferring the positions of the contaminants at previous times. The Markov matrix can be used to develop systematic optimization-based procedure for the optimal locations of actuators and sensors for the sensing and control of contaminants [34,39]. Furthermore, the linear property of a Markov matrix can also be used to develop a systematic procedure using linear system theory for the optimal control and estimation of contaminant [33,38]. Besides control and estimation applications, the spectral properties of the Markov matrix provides information about the long-term concentration profiles of contaminants in the space and the amount of time contaminants stay at a given position. Thus, utilization of the Markov matrix for flow field analysis and contaminant transport can be used to get more insight than the standard scalar transport methodology. An approach dual to the Markov approach using finite dimension approximation of Koopman operator is proposed by M. Georgescu et al. [14] for reducing order modeling in building system.

While the Markov method is very promising, some aspects of the procedure to calculate the Markov matrix are still unclear. The Markov matrix is based on a time step that allows scalar density evolution in a flow field, Fig. 1. While previous work Chen et al. [10] emphasizes the importance of the time step, Δt, associated with the Markov matrix, there are no rigorous rules available for determining this time step. Other open parameters are the size of the Markov states, h in Fig. 1, and the number of streamlines needed to construct an accurate Markov matrix. Establishing guidelines for determining these parameters can help bring the utility of Markov matrices closer to practice. A standard methodology will provide engineers and researchers an enabling framework for real-time prediction of transient contaminant transport in indoor environments.

In this paper, we develop a rigorous framework for estimating the parameters involved in the construction of the Markov matrix from CFD data. We present a data driven approach to determine the size of the Markov states. We then give simple formulas that provide bounds for the time step associated with the Markov matrix,

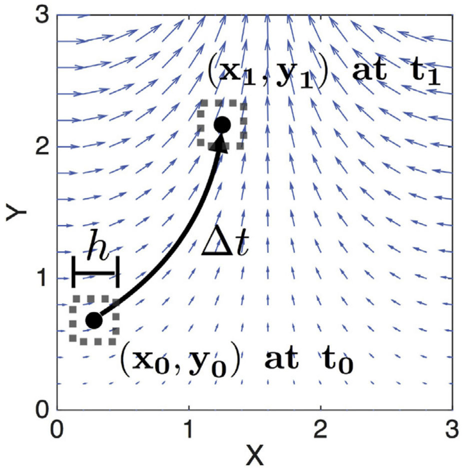

Fig. 1. Motion of a particle and a discrete volume in an airflow field.