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A grey model approach to indoor air quality management in rooms based on real-time sensing of particles and volatile organic compounds

Antanas Mikuckas [a], Darius Ciuzas [b], Tadas Prasauskas [b], Irena Mikuckiene [a], Romas Lukas [a], Egidijus Kazanavicius [a], Andrius Jurelionis [c], Dainius Martuzevicius [b,*]

[a] *Centre of Real Time Computer Systems, Kaunas University of Technology, Studentu g. 50, Kaunas, Lithuania*
[b] *Department of Environmental Technology, Kaunas University of Technology, Radvilenu pl. 19, Kaunas, Lithuania*
[c] *Department of Building Energy Systems, Kaunas University of Technology, Studentu g. 48, Kaunas, Lithuania*

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ABSTRACT

The study presents an attempt to develop a model for the management of indoor air quality based on real-time sensing of particulate matter (nano and micro particles) and volatile organic compounds. The development of the model used a grey box approach where the initial data on pollutant variation was collected during the experimental phase, and further applied to the pollutant mass balance model. The pollution sources have been analyzed in a controlled environment to obtain patterns of temporal variation, which have been approximated by mathematical functions. Approximations allowed the employment of pollutant mass balance model for determining the variation of pollutant source and further to modeling variation of pollutant concentration with changing air change rate. The proposed management approach can be applied to control indoor air quality in homes, assuring optimal utilization of the air handling unit in order to achieve the acceptable indoor air quality in the lowest time span and optimal energy use.

1. Introduction

The paradigm for sustainable construction prioritizes healthy indoor environment for the residents. Healthy indoor microclimate is described by multiple parameters, including thermal comfort, sufficient lighting, low noise, and good indoor air quality (IAQ). Based on the definition by the US Environmental Protection Agency (EPA) good IAQ is represented by concentrations of pollutants and thermal (temperature and relative humidity) conditions that do not negatively affect the health, comfort, and performance of occupants [1]. Indoor air has multiple sources of pollutant emission as well as many types of pollutants [2]. This makes indoor air as a very complex media to manage. While thermal comfort can be achieved by heating/cooling, good IAQ may be achieved by multiple measures, among which are ventilation, air cleaning, source control, and prevention (using low emitting building materials, avoiding combustion sources indoors, cautiously using personal care products etc.) [3,4].

* Corresponding author. Fax +370 300 152.
E-mail address: dainius.martuzevicius@ktu.lt (D. Martuzevicius).

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Nomenclature

N_p	pollutant concentration in a room (ppm for VOCs, mg/m^3 for PM_{10}, #/cm^3 for $PM_{2.5}$)
t	time (s)
N_O	pollutant concentration in the outdoor (ventilation supply) air (ppm for VOC, mg/m^3 for PM_{10}, #/cm^3 for $PM_{2.5}$)
P_i	supply air flowrate (m^3/s)
S	pollution source intensity (ppm/s for VOC, mg/m^{3}s for PM_{10}, #/cm^{3}s for $PM_{2.5}$)
a_0, b	parameters of sigmoidal function, representing an increase in concentration
a_i, b_i	parameters of exponential function representing the decrease in concentration
$N[i]$	air pollutant concentration in time (ppm for VOC, mg/m^3 for PM_{10}, #/cm^3 for $PM_{2.5}$)
k_p, k_i, k_d	proportional, integral and derivative component
ΔN	maximum change of the VOC, fine and coarse particle concentration (ppm for VOC, mg/m^3 for coarse PM, #/cm^3 for fine PM)
N_m	threshold value of a specific compound: N_{m_FP} fine particles (#/cm^3), N_{m_CP} coarse particles (mg/m^3), N_{m_VOC} volatile organic compounds (ppm)
N_{FP}, N_{CP}, N_{VOC}	concentration levels of fine particles, coarse particles and volatile organic compounds (ppm for VOC, mg/m^3 for PM_{10}, #/cm^3 for $PM_{2.5}$)

Greek symbols

λ	air change rate (outside air flow divided by indoor air volume) (s^{-1})
λ_{max}	maximum possible value of λ (s^{-1})
$\lambda[i]$	air change rate in time i (s^{-1})
λ_d	particle deposition rate (s^{-1})
$\Delta\lambda$	step of the ventilation change rate (s^{-1})
β	condition that none of pollutant concentration exceeds threshold values

Subscripts

FP	fine particles
CP	coarse particles
VOC	volatile organic compounds
1	first group
2	second group

Ventilation based systems are usually most efficient, and coupled with the recent progress in control systems it may be some of the most effective solutions currently [5]. Current algorithms of heating, ventilation, and air conditioning rely on control algorithms based on real-time sensing of control parameters. Various modeling approaches have been utilized to predict and manage such systems, including white box, black box, and grey box [6,7]. White box models are entirely based purely on the deterministic equations representing physical processes. If these are not entirely known (which is usually a case with complex systems such as indoor air), the relationships between input and output signals is approximated using experimental data (measured input and output signal values). In grey box models, analytical solutions to equations of the processes are known while experimental data is used only for determination of some parameters for analytical solutions. The above modeling approaches have been transferred to applications such as sub-zonal and multizone models, Computational Fluid Dynamics, and Windows-based IAQ simulation [8–12].

The modeling of HVAC (heating, ventilating, and air conditioning) systems usually prioritizes energy saving since HVAC systems use in average 40% of household energy [13]. Currently, HVAC systems are mostly managed using three parameters: temperature, relative humidity, and carbon dioxide (CO_2) concentration. The first two assure thermal comfort of residents while the CO_2 concentration represents indoor air quality as polluted by humans [14–15]. CO_2-based measurement systems are mostly employed in public premises having large amounts of humans in closed environments.

In residential environments, the range of indoor pollutants is much broader and does not depend only on the presence of human body. For example, carcinogenic radon gas which originates from rock and soil has been utilized as one of parameters for controlling HVAC [16]. Volatile organic compounds (VOCs) is another very broad group of pollutants, uniting hundreds of species originating from multiple indoor sources, such as cooking, cleaning, furniture, building materials etc. Indoor VOCs have been shown as threat to human health, causing irritation of nose and eyes [17], asthma attacks in premises with recently painted surfaces [18,19], even having cancerous effects [20]. Particulate matter (PM) has also been documented as a health-threatening pollutant. The relationship between coarse (larger than 2.5 µm in diameter) PM concentration and cardiovascular diseases has been established [21]. Fine particles (smaller than 2.5 µm in diameter) have been indicated as even higher health hazard causing mortality [22–24]. Both sizes of particles target different areas of a human respiratory system and are emitted by different sources, thus must be accounted separately [25].