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Estimating ventilation rates in a window-aired room using Kalman filtering and considering uncertain measurements of occupancy and CO_2 concentration

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ABSTRACT

This paper describes a method for estimating ventilation rates in a window-aired room considering "in-use" conditions and uncertainty in occupancy (CO_2 release) and in measurements of indoor air CO_2 concentration. Estimates are drawn from indoor air mass conservation principles and an Extended Kalman Filter, serving as state observer. The modelling procedure is described and tested against synthetic time series generated from pseudorandom values of occupancy and ventilation rate. Additionally, data collected from a case study (a window-aired classroom) is used to illustrate how the procedure is applied and its practical interest. Test results confirm the state observer's tracking capability and confirm its ability to reconstruct ventilation rates in the presence of sudden changes caused by window opening/closing and intermittent occupancy. Results for the case study highlight the benefits derived from knowledge of ventilation rates in window-aired rooms.

1. Introduction

Natural ventilation with window airing is the traditional and still the most common room ventilation solution. It relies on manual opening/closing of windows and ventilation is, therefore, subject to direct control by occupants. When window-aired rooms are heated, self-regulating equipments are generally used, resulting in very simple control solutions. This simplicity has obvious merits, but comes with a consequence: records of indoor conditions (e.g., records of air temperature and CO_2 concentration) are not needed and objective evaluations of the indoor environment are hardly ever made. The lack of objective data is particularly regrettable when studying window-aired rooms because indoor conditions are free-running and without records designers and building managers have no means to assess if and when ventilation design specifications are being met. Feedback from occupants can be used, however, it is difficult to express subjective opinions on ventilation rates and occupants' assessments are typically biased towards their interest in keeping comfortable indoor air temperatures [17]. As a consequence, ventilation rates in window-aired rooms are often inappropriate [1,29,32,37], with harmful consequences to occupants' health [5,15,36] and lower productivity levels [4,26,33,42,43].

Previous studies by Refs. [16] and [41] have shown how knowledge of indoor air CO_2 concentration could be used to influence patterns of window airing and improve indoor air quality in classrooms. Because indoor air quality depends on how the room is used and how it is being ventilated, knowledge of ventilation rates considering "in-use" conditions is a topic of obvious interest. Ventilation studies from the 1980s lay out the generic procedure to determine transient airflows in occupied rooms using occupant-generated CO_2 as tracer gas [30,31,40]; since then, different approaches to this topic were proposed (e.g. [5,24]), however, most approaches assume the CO_2 injected in the room(s) is accurately known, even though this is hardly ever the case for "in-use" conditions; in fact, since the first studies by Ref. [30], it was recognised that the uncertainty in CO_2 release was paramount to obtaining accurate estimates of ventilation rate.

This paper introduces a procedure for estimating ventilation rates in a window-aired room considering "in-use" conditions and contemplating the uncertainty in occupancy (CO_2 release) and in measurements of indoor air CO_2 concentration. The procedure uses indoor mass conservation principles and an Extended Kalman Filter to develop a state observer capable of finding "quasi-instantaneous" estimates of ventilation rate mean and variance. A test to assess the state observer is presented and, to illustrate its practical interest, ventilation rates in an existing window-aired classroom are estimated.

The development of the state observer and details on the implementation of the Extended Kalman Filter are described in the following section.

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Nomenclature

$\boldsymbol{A}$	vector-valued gradient
$c = C - C_{\text{ext}}$	relative concentration of tracer gas, ppm
C	absolute concentration of tracer gas, ppm
$E(\cdot)$	expected value
$f(\cdot)$	scalar-valued function
$\boldsymbol{F}$	state matrix
	output matrix
$\boldsymbol{I}$	identity matrix
$\boldsymbol{K}$	Kalman gain
n	air change rate, s^{-1}
N	number of persons
$\mathcal{N}$	referring to Gaussian probability distribution
$\boldsymbol{P}$	error covariance (predicted or updated)
q	volumetric flow rate per person, m^3/s/person
Q	volumetric flow rate, m^3/s
r	process white noise (discrete scalar)
$\boldsymbol{R}$	process noise covariance
s	production rate of tracer gas per person, cm^3/s/person
S	production rate of tracer gas, cm^3/s
$\boldsymbol{S}$	residual covariance
t	time, s
T	temperature (air), °C
V	volume, m^3
$\boldsymbol{V}$	measurement noise covariance
$\boldsymbol{W}(\cdot)$	Wiener process
$\boldsymbol{x}$	state vector
$\boldsymbol{y}$	noise-free output vector
$\boldsymbol{z}$	noise-corrupted output vector
Δ	time-step duration
ε	residue
ν	measurement white noise
σ	standard deviation
$\sum$	sum
ϕ	state transition scalar
ω	process white noise (continuous scalar)
$\{\cdot\}$	time series or sequence

Superscripts

$\hat{\cdot}$	estimate (predicted or updated)
$\tilde{\cdot}$	error (predicted or estimated)
$\bar{\cdot}$	average
c	referring to indoor tracer gas concentration
n	referring to ventilation rate
S	referring to tracer gas release
T	transpose
$\dagger$	noise-corrupted, measured or synthetic variable

Subscripts

0	initial condition
ext	referring to outdoor (or atmospheric)
int	referring to indoor
k	timestep
meas	referring to measurement
proc	referring to process

2. Development of the state observer

For a window-aired room, ventilation rates can be estimated from the conservation equation of a tracer gas released in the room. In the traditional volumetric form this equation reads[1] (see Refs. [20,39],

$$\frac{dC}{dt} = -n(C - C_{\text{ext}}) + \frac{1}{V}S\,, \tag{1}$$

with initial condition $C(t = 0) = C_0$.

Different methods that start off from Equation (1) to determine ventilation rates in single zones are presented in standards [13] and [3] when n and S are constant. Unfortunately, for window-aired rooms and "in-use" conditions, both n and S vary with time, therefore, standards are of little use.

To solve Equation (1) with varying values of n and S a "quasi-instantaneous" approach is generally used. Time series of indoor tracer gas concentration and tracer gas release are divided into smaller parts of duration Δ, and the regression, integral or averaging techniques described in Ref. [39] are used. A literature review suggests the regression technique is probably the most common [5,27,30,31,40]; it consists in finding[2] the air change rate n that best fits the sequence of tracer gas concentration $\{C\}$, using a mean value for S obtained from the sequence of tracer gas release $\{S\}$.

At first sight, use of the regression technique should pose no difficulty; yet, various researchers have reported problems with the selection of duration Δ, given the presence of noise in time series of tracer gas concentration.

2.1. Considering the uncertainty in tracer gas concentration

As described by different authors [28,39,40], records of tracer gas concentration typically include high frequency noise. If the "quasi-instantaneous" approach described previously is used and intervals Δ are too small, estimates n are influenced by this noise. On the other hand, if intervals Δ are too large, the "averaging" implied in the above-mentioned techniques becomes excessive, hindering the ability to track sudden changes in ventilation rates. The selection of Δ requires, therefore, a compromise between noise reduction and tracking capability (see Ref. [40]).

To reduce the effect of noise some researchers [28,40] choose to prefilter time series $\{C\}$ prior to applying the regression technique. However, for window-aired rooms and especially when room occupancy is intermittent, careful consideration should be given to the choice of the filter cutoff frequency. Indeed, the stochastic nature of the drivers of natural ventilation (i.e., wind speed and direction, outdoor air temperature) combined with erratic patterns of window/door opening, lead to sudden and often large changes in tracer gas concentration, not related to sensor's noise. Under these circumstances, choosing an inadequate cutoff frequency may end up filtering relevant information, compromising ventilation rate estimates.

To reduce the subjectivity implied in the choice of Δ or in the choice of low-pass filter characteristics, Ref. [6] (that studies the concentration of radon in an unoccupied room) shows how a Kalman Filter and mass conservation principles can be used to find air change rates from time series of tracer gas concentration and release. Indeed, the Kalman Filter has been successfully applied in many different fields, including navigation, image processing or finance, and provides a general method to estimate a signal in the presence of noise. According to [22], the Kalman Filter provides optimal trade-off between tracking ability and noise sensitivity.

The use of a Kalman Filter combined with the conservation equation (1) requires that a distinction is made between noise-corrupted and noise-free values of tracer gas concentration and, traditionally, implies the assumption of an additional term in Equation (1) to account for

[1] A list with the meaning of the symbols used is presented above.

[2] In the least squares sense and for each part of duration Δ of the original time series.