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Inferring ventilation and moisture release rates from field psychrometric data only using system identification techniques

M.J. Cunningham*

Building Research Association of New Zealand (BRANZ), Private Bag 50908, Moonshine Road, Judgeford, Porirua, New Zealand

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Abstract

System identification techniques are developed allowing room or building ventilation and moisture release rates to be inferred from field psychrometric data only. The techniques have been developed primarily to allow the surveying of a large number of houses so that statistical properties can be compiled, in which high accuracy of individual results is not required. This system provides an alternative to PFT tubes, with some economic advantages.

These techniques give rise to two parameters (describing the hygroscopic properties of the room) from which ventilation and moisture release rates can be calculated given indoor and outdoor psychrometric data only. Results within 30% of measured values have been obtained, except for the case of moisture release rates under air-tight conditions where results seem unreliable. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

1.1. Background

There are applications where it is desirable, or necessary, to estimate ventilation levels and moisture release rates over a large sample of houses, e.g. when assessing the level of mould and condensation across a large group of buildings, or surveying the relationships between socio-economic measures and housing measures such as indoor climate.

Accurate measurement of room or building ventilation rates is usually done with tracer gas techniques in various injection modes (pulse, constant, constant concentration, etc. [1]). These measurements require sophisticated, expensive, and bulky apparatus, they require skill and time, and the process is very invasive. Furthermore, only one building at a time can be measured with this type of measurement. Alternatively, Perfluorocarbon Tracer (PFT) tubes can be used [1] if large numbers of buildings are to be measured and where it is necessary only to know ventilation rates averaged over time periods of the order of a day. A single analysis giving an average ventilation rate over the measured time period can be done at a cost of a few hundred dollars per sample, analysed in an out-sourced laboratory; alternatively, PFT samples can be analysed in-house by purchasing the appropriate capital equipment in the order of scores of thousands of dollars.

There does not seem to be any direct way to measure moisture release rates in the field, so these are usually assigned fixed values taken from the literature [2], or inferred indirectly from indoor and outdoor vapour pressures and known (or assumed) ventilation rates. Often the steady state formula

$$p_o = p_e + \frac{S}{\gamma F}$$

i.e.

$$S = \gamma F(p_0 - p_e)$$

where

* Tel.: +64-4235-7600; fax: +64-4235-6070.
E-mail address: branzmjc@branz.org.nz (M.J. Cunningham).

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Nomenclature

a_1, a_2, b_0, b_1, b_2	coefficients associated with various ARX models
A_h	effective area of room hygroscopic contents available for mass transfer (m^2)
c_e	outdoor vapour concentration (kg m^{-3})
c_o	indoor vapour concentration (kg m^{-3})
F	ventilation rate (s^{-1})
m_h	effective moisture concentration in the room hygroscopic contents (kg m^{-3})
p_e	outdoor water vapour pressure (Pa)
$\bar{p}_e$	average outdoor water vapour pressure (Pa)
p_h	water vapour pressure in the room hygroscopic contents (Pa)
p_o	room water vapour pressure (Pa)
$\bar{p}_o$	average room water vapour pressure (Pa)
p_{sat}	saturated vapour pressure (Pa)
r	effective vapour resistance for mass transfer between the room and its hygroscopic contents (N s kg^{-1})
R	universal gas constant (8310 J K^{-1} $kmole^{-1}$)
S	moisture release rate (kg s^{-1})
t	time (s)
t_1, t_2	times which characterise the room hygroscopic properties (s)
t_3	a time associated with the rate of change of temperature (s)
T	temperature (K)
V_h	effective volume of room hygroscopic contents (m^3)
V_o	room volume (m^3)
W	molecular weight of water (18 kg $kmole^{-1}$)
z_{pole}	the value of the pole of an ARX model
Greek symbols	
Δt	sampling time interval (s)
γ	see Eq. (9)
φ	relative humidity

$$\gamma = \frac{V_o W}{RT}$$

is used.

This work offers a third technique intermediate between the tracer gas real time approach and the PFT approach. This technique allows large numbers of buildings to be surveyed, and also gives some detailed knowledge of how shorter term ventilation performance is affected by a range of indoor and outdoor conditions and a range of occupant behaviour. This approach requires installing relative humidity and temperature sensors only, inside and outside of each building to be measured. The capital cost for this procedure is one or two hundred dollars per building.

The indoor temperature and relative humidity are set by moisture release rates, the hygroscopic parameters of the house or room under consideration, the ventilation rate, and the outdoor temperature and relative humidity: so the question arises whether ventilation and moisture release rates in the field can be inferred from these psychrometric parameters only. The author has shown how to infer ventilation rates, but not moisture release rates, from psychrometric data for the particular case of sinusoidal climate parameters [3], but this is very much a special case that only exists approximately and irregularly in any psychrometric data set.

This work addresses this issue by using system identification techniques [4]. Such an approach has been widely used for building thermal properties [5–7], but not, to the author's knowledge, for the moisture properties of buildings. In this work autoregressive (ARX) models are set up, connecting input (outdoor temperature and relative humidity) to output parameters (indoor temperature and relative humidity). The parameters of the system identification models are, in the first instance, black-box parameters in that they are not connected to the physical parameters of the building or room under investigation. These physical parameters are: the ventilation rate; the moisture release rate; and the hygroscopic properties of the room in question. However, in this work, a physical model is developed, which is described by differential equations, which are then discretised enabling an identification of physical parameters with the system identification black-box parameters. In this way values of the physical parameters can be extracted from the ARX system identification model.

2. Brief review of relevant parts of system identification theory

Consider an input signal, say a varying outdoor humidity, and an output signal, say an indoor vapour pressure, connected together by the rate that the output air is ventilating through a room, and influenced by such factors as the hygroscopic elements in the room (see Fig. 1). The input and output signals are sampled and represented as time series, viz input signal is

$$u(t),\ u(t+1),\ \ldots,\ u(t+M-1)$$

and the output signal is

$$y(t),\ y(t+1),\ \ldots,\ y(t+N-1)$$

The system, the room with its hygroscopic contents in this example, is assumed to linearly transform a contiguous portion of the input signal plus a noise term $e(t)$ (white noise with variance λ) into a contiguous portion of the output signal as represented below

$$y(t)+a_1y(t-1)+\cdots+a_ny(t-n)$$

$$=b_1u(t)+b_2u(t-1)+\cdots+b_mu(t-m+1)+e(t)$$

The parameters $a_1, a_2, \ldots, a_n$ and $b_1, b_2, \ldots, b_m$ define the model and the process of finding them is known as system identification [4]. The parameters can be regarded as black-box quantities (see Fig. 2), or can be connected to actual physical factors such as, in this case, the room ventilation rates and the room hygroscopic elements.

The model is often written as

$$A(q)y(t)=B(q)u(t)+e(t)$$

where

$$A(q)=1+a_1q^{-1}+\cdots+a_nq^{-n}$$

$$B(q)=b_1+b_2q^{-1}+\cdots+b_mq^{-m}$$

and where q is the shift operator

$$q^{-p}u(t)=u(t-p)$$

The particular model of this example is known as an ARX model.

Both the input and outputs of the model can be multivariate, giving rise to a series of equations characterising the model, written as

$$A(q)y(t)=B(q)u(t)+e(t)$$

where y is a column vector of n variables, u a column vector of m variables, and $A(q)$ is an $n\times n$ matrix of polynomials in the shift operator q^{-1}

$$A(q)=I_n+A_1q^{-1}+\cdots+A_{na}q^{-na}$$

and $B(q)$ is a $n\times m$ matrix

$$B(q)=B_0+B_1q^{-1}+\cdots+B_{nb}q^{-nb}$$

There is an extensive literature [4] on how to find the model parameters given an input and output stream of signals, and consequent model properties such as pulse and step responses, poles and zeros, model time constants, spectral properties, etc.

3. The physical model

The room or building of volume V_o (m^3) is modelled as a zone exchanging air with the outdoors, and with vapour pressure driven moisture transfer to and from the hygroscopic elements in the room. These hygroscopic elements are lumped as one node with an effec-

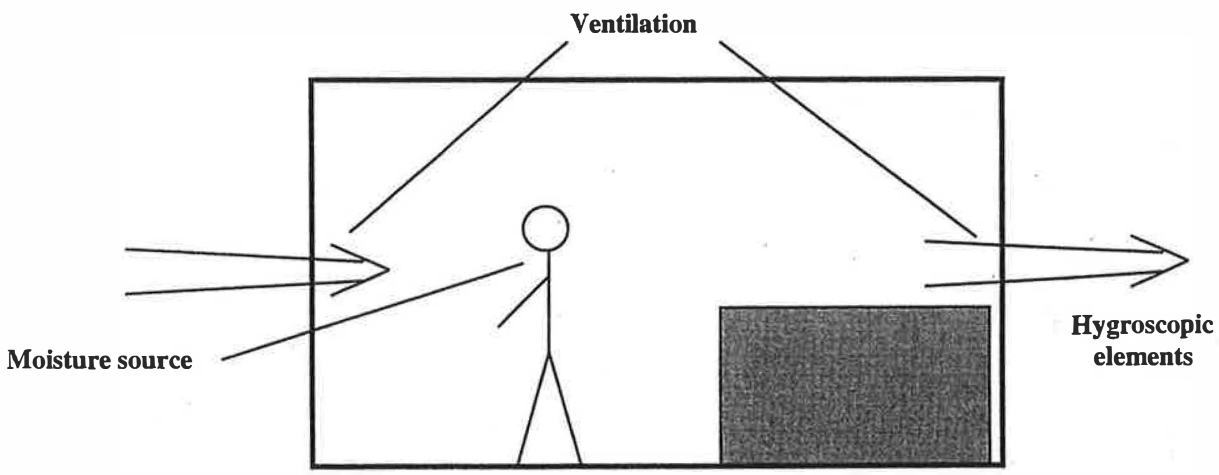

Fig. 1. The physical model. The input parameter is outdoor vapour pressure, the output parameter is room vapour pressure, and the factors influencing these are: the ventilation rate; the room moisture release rate; and the hygroscopic properties of the room contents.

tive volume of V_h (m^3), an effective area for mass transfer with the room of A_h (m^2), and an effective surface mass transfer vapour resistance of r (N s kg^{-1}) (see Fig. 1).

Conservation of moisture within the room implies

$$V_o \frac{\partial c_o}{\partial t} = V_o F(c_e - c_o) + \frac{A_h(p_h - p_o)}{r} + S \tag{1}$$

where S is the moisture source strength (kg s^{-1}) and F is the air-change rate (s^{-1}).

Mass interchange to the hygroscopic lump gives

$$V_h \frac{\partial m_h}{\partial t} = A_h \left(\frac{p_o - p_h}{r} \right) \tag{2}$$

where m_h is the moisture concentration in the hygroscopic lump.

The ideal gas law

$$p = \frac{cRT}{W}$$

is used to rewrite Eq. (1) as

$$\frac{\partial p_o}{\partial t} + \left(F + \frac{A_h}{r} \frac{RT}{V_o W} \right) p_o - \frac{A_h}{r} \frac{RT}{V_o W} p_h = \frac{RT}{V_o W} S + F p_e \tag{3}$$

The moisture concentration in the hygroscopic lump, m_h, is determined by the average sorption curve of the room's hygroscopic materials. This means that

$$\frac{\partial m_h}{\partial t} = \frac{\partial m_h}{\partial \varphi} \frac{\partial \varphi}{\partial t} \tag{4}$$

where φ is the humidity corresponding to an equilibrium moisture concentration of m_h, and where $\partial m_h / \partial \varphi$ is the instantaneous slope of the sorption curve of the hygroscopic lump.

Since

$$\varphi = p_h / p_{\text{sat}} \quad \text{then} \quad \frac{\partial \varphi}{\partial p_h} = \frac{1}{p_{\text{sat}}}$$

so that

$$\begin{aligned} \frac{\partial m_h}{\partial t} &= \frac{\partial m_h}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \frac{\partial m_h}{\partial \varphi} \frac{\partial (p_h / p_{\text{sat}})}{\partial t} \\ &= \frac{\partial m_h}{\partial \varphi} \left(\frac{1}{p_{\text{sat}}} \frac{\partial p_h}{\partial t} + p_h \frac{\partial (1/p_{\text{sat}})}{\partial t} \right) \\ &= \frac{1}{p_{\text{sat}}} \frac{\partial m_h}{\partial \varphi} \left(\frac{\partial p_h}{\partial t} - \frac{p_h}{p_{\text{sat}}} \frac{\partial p_{\text{sat}}}{\partial t} \right) \\ &= \frac{1}{p_{\text{sat}}} \frac{\partial m_h}{\partial \varphi} \left(\frac{\partial p_h}{\partial t} - \frac{p_h}{p_{\text{sat}}} \frac{\partial p_{\text{sat}}}{\partial T} \frac{\partial T}{\partial t} \right) \end{aligned} \tag{5}$$

Eq. (2) then becomes

$$\begin{aligned} &\frac{\partial p_h}{\partial t} - \frac{p_h}{p_{\text{sat}}} \frac{\partial p_{\text{sat}}}{\partial T} \frac{\partial T}{\partial t} + A_h \frac{\partial \varphi}{\partial m_h} \frac{p_{\text{sat}}}{V_h} \frac{p_h}{r} \\ &\quad = A_h \frac{\partial \varphi}{\partial m_h} \frac{p_{\text{sat}}}{V_h} \frac{p_o}{r} \end{aligned} \tag{6}$$

Two time constants t_1 and t_2 are now defined which characterise the hygroscopic properties of the room

$$t_1 = \frac{V_h r}{A_h p_{\text{sat}}} \frac{\partial m_h}{\partial \varphi}$$

$$t_2 = \frac{V_o W r}{A_h RT}$$

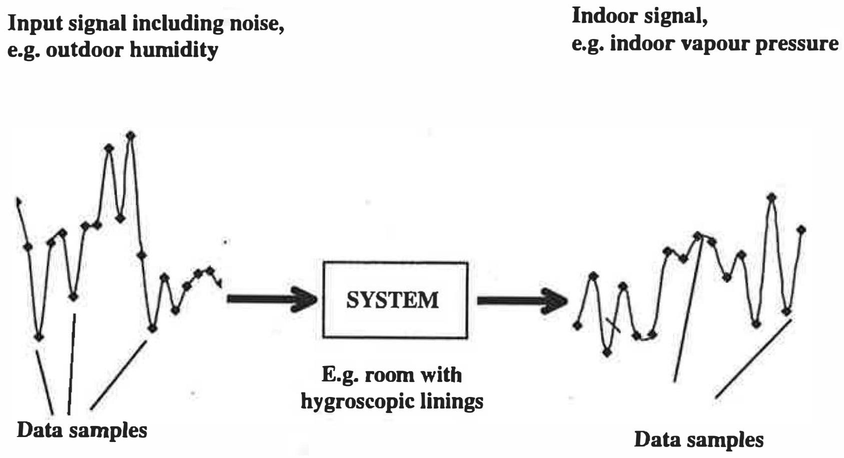

Fig. 2. Schematic illustrating a black-box system.

A further time is defined as

$$\frac{1}{t_3} = \frac{1}{p_{\text{sat}}} \frac{\partial p_{\text{sat}}}{\partial T} \frac{\partial T}{\partial t}$$

From here onwards t_3 will be assumed constant over time periods of interest, i.e. temperature changes that are linear with time, or approximately so, can be accounted for in the model.

Eqs. (3) and (6) become

$$\frac{\partial p_o}{\partial t} + \left(\frac{1}{t_2} + F\right) p_o - \frac{p_h}{t_2} = F p_e + \frac{S}{\gamma} \quad (7)$$

and

$$\frac{p_h}{\partial t} + \left(\frac{1}{t_1} - \frac{1}{t_3}\right) p_h - \frac{p_o}{t_1} = 0 \quad (8)$$

where

$$\gamma = \frac{W V_o}{RT} \quad (9)$$

It is important to note that t_1 and t_2 are parameters that describe the hygroscopic nature of the building or room. They are not the model system response time constants — these are derived below. t_3 is also not a system time constant, but a convenient way of parameterising temperature variation.

4. System identification models

As p_h, the average vapour pressure in the room hygroscopic elements, is not available experimentally, it is natural to eliminate it between Eqs. (7) and (8), resulting in

$$\frac{\partial^2 p_o}{\partial t^2} + \left(\frac{1}{t_1} + \frac{1}{t_2} - \frac{1}{t_3} + F\right) \frac{\partial p_o}{\partial t} + \left(F\left\{\frac{1}{t_1} - \frac{1}{t_3}\right\} - \frac{1}{t_2 t_3}\right) p_o = \left(\frac{1}{t_1} - \frac{1}{t_3}\right)\left(\frac{S}{\gamma} + F p_e\right) + \frac{\partial}{\partial t}(F p_e) \quad (10)$$

This process leads to a second-order ARX model. Unfortunately, we have been unable to derive consistent results with second-order ARX models primarily due to high sensitivity to noise from the second derivative, so a different approach is called for.

First-order models have been much more successful. These are drawn from the above equations, making in some cases appropriate approximations as follows.

4.1. Finding t_2 and ventilation rate — case with no moisture sources

We consider first the loose case (i.e. high ventilation levels) with no moisture sources, governed by Eq. (7) with $S = 0$.

The fundamental time constant t_a for Eq. (7) is

$$t_a = \frac{1}{\frac{1}{t_2} + F}$$

The discrete form of Eq. (7) is

$$p_{oi} - \frac{p_{oi-1}}{\alpha \Delta t} = \frac{p_{hi}}{\alpha t_2} + \frac{F p_{ei}}{\alpha} \quad (11)$$

where

$$\alpha = \frac{1}{\Delta t} + \frac{1}{t_a} = \frac{1}{\Delta t} + \frac{1}{t_2} + F$$

Eq. (11) is an ARX model, first-order in the output variable p_o, and first-order in the input variables p_e and p_h.

Note that no approximations to the underlying model have been made in deriving Eq. (11).

If the ARX model, Eq. (11), is written in the standard form

$$p_{oi} + a_1 p_{oi-1} = b_1 p_{hi} + b_2 p_{ei} \quad (12)$$

then comparison between the coefficients of Eqs. (11) and (12) gives

$$\frac{a_1}{b_1} = -\frac{t_2}{\Delta t} \quad \text{and} \quad \frac{b_2}{b_1} = F t_2$$

i.e.

$$t_2 = -\frac{a_1}{b_1}\Delta t \quad \text{and} \quad F = -\frac{b_2}{a_1 \Delta t} \quad (13)$$

There exist standard algorithms for calculating the coefficients a_1, b_1 and b_2 [4,8], so that t_2 and the ventilation level, F, can be found from Eqs. (13).

4.2. Finding t_1 — tight case with no moisture sources

In the case of low ventilation rates, $F \approx 0$, Eq. (10) with no moisture sources becomes

$$\frac{\partial^2 p_o}{\partial t^2} + \left(\frac{1}{t_1} + \frac{1}{t_2} - \frac{1}{t_3}\right)\frac{\partial p_o}{\partial t} - \frac{p_o}{t_2 t_3} = 0 \quad (14)$$

If the analysis is done in a section of the data where temperature changes are not too rapid ($t_3 \gg t_1$ and t_2) then the $1/t_3$ terms in Eq. (14) can be ignored, giving

$$\frac{\partial^2 p_o}{\partial t^2} + \left(\frac{1}{t_1} + \frac{1}{t_2}\right)\frac{\partial p_o}{\partial t} = 0 \quad (15)$$

Integrating Eq. (15) once yields

$$\frac{\partial p_o}{\partial t}+\left(\frac{1}{t_1}+\frac{1}{t_2}\right)p_o=C \quad (16)$$

where C is a constant determined by initial conditions.

The discrete form of Eq. (16) is

$$p_{oi}-\frac{p_{oi-1}}{\beta\Delta t}=B \quad (17)$$

where

$$\beta=\frac{1}{\Delta t}+\frac{1}{t_1}+\frac{1}{t_2} \quad \text{and} \quad B=C/\beta$$

Eq. (17) is an ARX model, first-order in the output variable p_o, with a constant input, of the form

$$p_{oi}+a_1 p_{oi-1}=b_0 \quad (18)$$

According to the system identification theory [4], the pole of this model is the root of the equation

$$z\left(1-\frac{z^{-1}}{\beta\Delta t}\right)=0$$

so that

$$z_{\text{pole}}=\frac{1}{\beta\Delta t}=\frac{1}{\Delta t\left(\frac{1}{\Delta t}+\frac{1}{t_1}+\frac{1}{t_2}\right)} \quad (19)$$

where z_{pole} is the value of the pole of the ARX model.

Hence

$$t_1=\frac{\Delta t}{\frac{1}{z_{\text{pole}}}-\frac{\Delta t}{t_2}-1} \quad (20)$$

There exist standard algorithms for calculating the numerical value of the pole of the model given by Eq. (18) (see for example [4,8]), allowing the calculation of t_1 from Eq. (20).

It is restated that, in this case, there are approximations made, namely that ventilation levels are low, $F \approx 0$, and that temperature changes are not too rapid ($t_3 \gg t_1$ and t_2).

5. Averaging

p_h is eliminated between Eqs. (7) and (8), yielding

$$\frac{\partial^2 p_o}{\partial t^2}+\left(\frac{1}{t_1}+\frac{1}{t_2}-\frac{1}{t_3}+F\right)\frac{\partial p_o}{\partial t}+\left(F\left\{\frac{1}{t_1}-\frac{1}{t_3}\right\}-\frac{1}{t_2 t_3}\right)p_o=\left(\frac{1}{t_1}-\frac{1}{t_3}\right)\left(\frac{S}{\gamma}+Fp_e\right)+\frac{\partial}{\partial t}(Fp_e) \quad (21)$$

In principle, quantities such as the moisture release rate S, or the ventilation level F, can be derived at any instance from Eq. (21) by rearranging — for example, S would become

$$S=\left\{\frac{\gamma}{\frac{1}{t_1}-\frac{1}{t_3}}\right\}\left\{\frac{\partial^2 p_o}{\partial t^2}+\left(\frac{1}{t_1}+\frac{1}{t_2}-\frac{1}{t_3}+F\right)\frac{\partial p_o}{\partial t}+F(p_o-p_e)\left(\frac{1}{t_1}-\frac{1}{t_3}\right)-\frac{p_o}{t_2 t_3}-\frac{\partial}{\partial t}(Fp_e)\right\}$$

This can be discretised and a formula derived allowing for the calculation of S. However, in practice, equations so derived do not work because of the extreme sensitivity to noise arising from the first and second derivatives.

Instead, an integral form of Eq. (10) is used — integrating Eq. (10) between $t=a$ and $t=b$ gives

$$\int_a^b\left\{\frac{\partial^2 p_o}{\partial t^2}+\left(\frac{1}{t_1}+\frac{1}{t_2}-\frac{1}{t_3}+F\right)\frac{\partial p_o}{\partial t}+\left(F\left(\frac{1}{t_1}-\frac{1}{t_3}\right)-\frac{1}{t_2 t_3}\right)p_o\right\}\mathrm{d}t=\int_a^b\left\{\left(\frac{1}{t_1}-\frac{1}{t_3}\right)\left(\frac{S}{\gamma}+Fp_e\right)+\frac{\partial}{\partial t}(Fp_e)\right\}\mathrm{d}t$$

If S and F are taken as constant over the time period from $t=a$ to $t=b$, then rearranging gives

$$S=\left\{\frac{\gamma}{\frac{1}{t_1}-\frac{1}{t_3}}\right\}\left\{\left[\frac{1}{T}\left(\frac{\partial p_o}{\partial t}+\left(\frac{1}{t_1}+\frac{1}{t_2}-\frac{1}{t_3}\right)p_o-Fp_e\right)\right]_a^b+F(\bar{p}_o-\bar{p}_e)\left(\frac{1}{t_1}-\frac{1}{t_3}\right)-\frac{\bar{p}_o}{t_2 t_3}\right\} \quad (22)$$

$$\bar{f}=\frac{\int_a^b f\,\mathrm{d}x}{b-a}$$

and

$$[G(p_o)]_a^b=G(p_o=b)-G(p_o=a)$$

in the normal way.

Conversely, Eq. (22) can be rearranged to give F as

$$F=\frac{S\left\{\frac{\frac{1}{t_1}-\frac{1}{t_3}}{\gamma}\right\}-\left[\frac{1}{T}\left(\frac{\partial p_o}{\partial t}+\left(\frac{1}{t_1}+\frac{1}{t_2}-\frac{1}{t_3}\right)p_o\right)\right]_a^b+\frac{\bar{p}_o}{t_2 t_3}}{(\bar{p}_o-\bar{p}_e)\left(\frac{1}{t_1}-\frac{1}{t_3}\right)-\left[\frac{p_e}{T}\right]_a^b} \quad (23)$$

Table 1
A description of the experimental runs carried out to find room hygroscopic parameters, ventilation levels and moisture release rates

Run number	Run details	Purpose
1	Higher ventilation. No moisture source	To find t_2 and to find F under loose conditions
2	Lower ventilation. No moisture source	To find t_1
3	Continuation of run 1 with a moisture source	To find S under loose conditions
4	Lower ventilation. No moisture source	To find F under tight conditions
5	Continuation of run 4 with a moisture source and changing room temperature	To find S under tight conditions and changing temperature

Note that under steady state conditions or when conditions are periodic such that the psychrometric quantities take the same values at $t=a$ and $t=b$, Eq. (22) is just the well-known steady state case, viz

$$S = \gamma F(\bar{p}_o - \bar{p}_e)$$

It is important to note that the ventilation rate F must be known if the source strength S is to be calculated using Eq. (22), or conversely S must be known if F is to be calculated using Eq. (23) — see further comments below of how this is handled in practice.

6. Experimental

6.1. Description

This section describes the experiments undertaken to test the effectiveness of the system identification models developed above.

A bedroom in a 40-year-old weather-board house was used as the indoor space. The bedroom was 4 × 4 × 2.4 m. It contained a doublebed, bedroom furniture, drapes and a fully carpeted floor.

Various combinations of ventilation levels, moisture release rates and heating were realised in the room and the indoor and outdoor temperatures and humidities measured with thermistors and capacitive humidity sensors. Data from these sensors was collected every 5 min by a datalogger.

Ventilation levels were changed by closing or partly opening windows into the room. The bedroom door to the rest of the house was left closed — in this way the bedroom zone exchanged air with the outdoors only, with minimal air-change between the bedroom and the rest of the house.

Ventilation levels achieved were measured by manually releasing pulses of carbon dioxide into the bedroom air and logging the decay of room air carbon dioxide levels using a non-dispersive IR carbon dioxide detector (TSI Q-Trak IAQ Monitor Model 8550).

Moisture was released into the room in a controlled and measurable manner with a small open topped container on a hot plate turned to a very low heat. Heating was provided from a radiant on/off thermostatted electric heater.

Several experiments of a few hours duration were carried out (see Table 1), each aimed at finding different variables. It is necessary to find the room hygroscopic parameters t_1 and t_2 before other variables can be found. t_2 is found by analysing the psychrometric data under conditions of higher ventilation using the first-order ARX model described by Eq. (11); then t_1 is found under conditions of low ventilation using the first-order ARX model described by Eq. (17). In both cases there is no moisture source.

Table 2 outlines which methods were used to find the required parameters. Averaging using Eq. (23) was taken over a period of 2 h for run 3 and 1 h for run 5. The derivatives in Eq. (23) were taken over 30 min.

Theoretical results were calculated using MATLAB© to calculate the system model parameters followed by using formulae (13), (20), (22) to find t_1, t_2, F, and S.

7. Results

Figs. 3–5 show the measured psychrometric quantities, and Table 3 gives the results for the various parameters calculated by the methods described in Table 2, and compared to experimentally measured quantities.

Table 2
Methods and equations used to calculate room hygroscopic parameters, ventilation levels and moisture release rates

Run number	Method used to calculate result
1	ARX model, Eqs. (11) and (12) with Eq. (13)
2	ARX model, Eqs. (17), (18) and (12) with Eq. (20)
3	Averaging, Eq. (22)
4	ARX model, Eqs. (17), (18) and (12) with Eq. (20)
5	Averaging, Eq. (22)

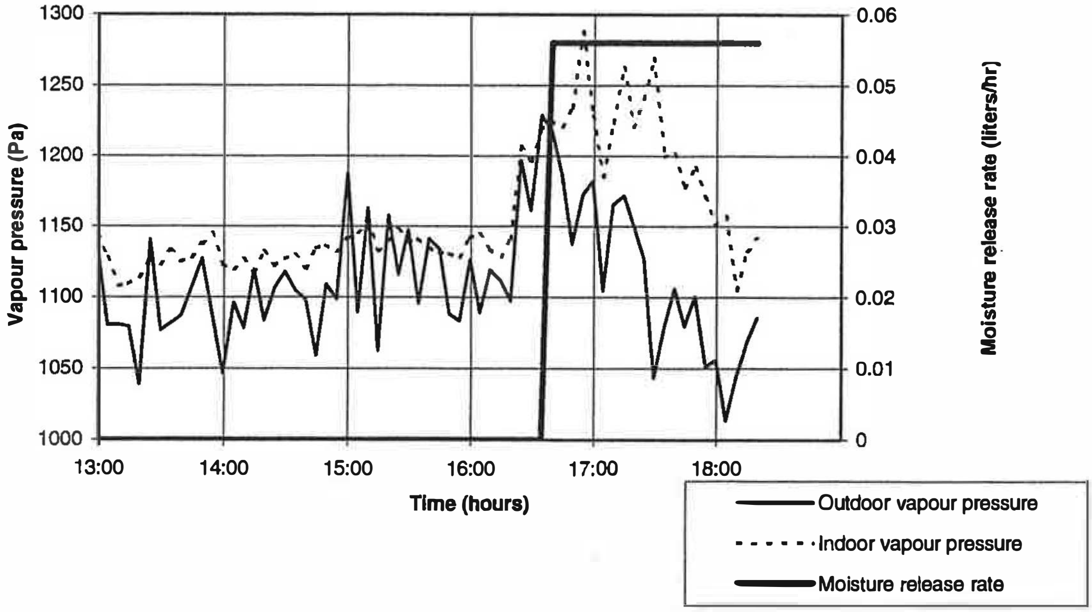

Fig. 3. Runs 1 and 3. Vapour pressures and moisture release rates at higher ventilation levels. Run 1 data (1300–1639 h) was used to find t_2 and the ventilation rate for a loose room. Run 3 data (1639–1819 h) was used to find the moisture release rate under higher ventilation levels.

8. Discussion

8.1. Accuracy

Ventilation levels calculated at the higher air-change rates agreed with measured values to within 10%, and at lower levels to within 30%. Moisture release rates agreed to within 27% at higher air-change rates, but differed by more than a factor of three at lower air-change rates. In general it appears that the methods described in this work give useable results at higher ventilation levels for both air-exchange values and moisture release rates, and perhaps for air-exchange values at lower ventilation levels, but cannot well predict moisture release rates under air-tight conditions.

This lesser performance level for more air-tight

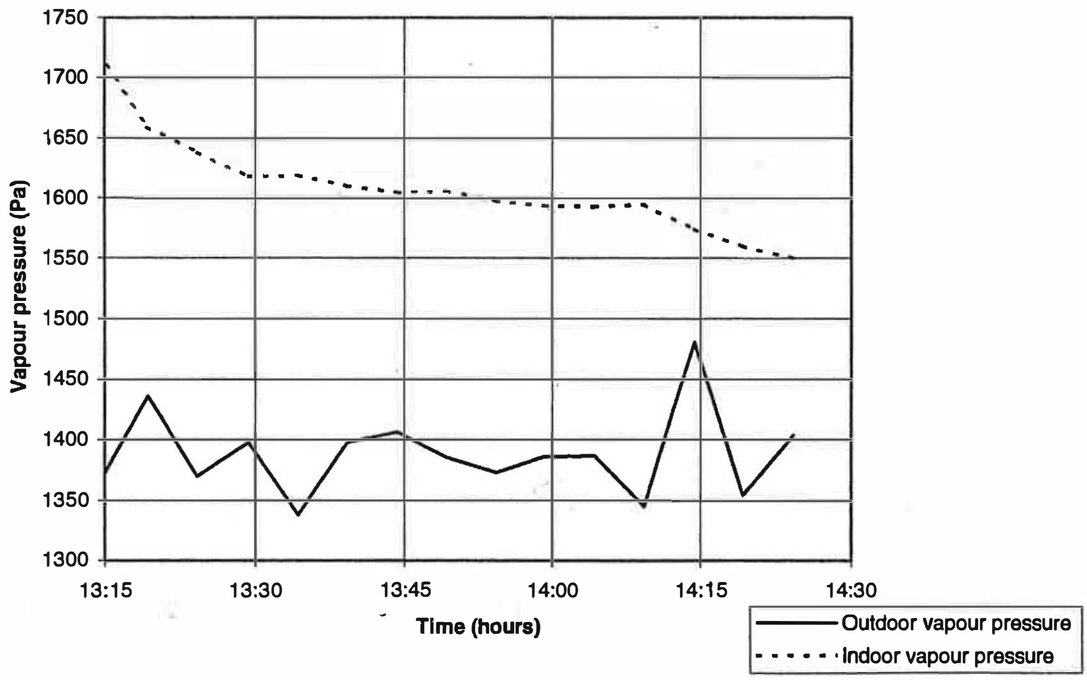

Fig. 4. Vapour pressures under lower ventilation levels with no moisture release. This data was used to find t_1 for the room.

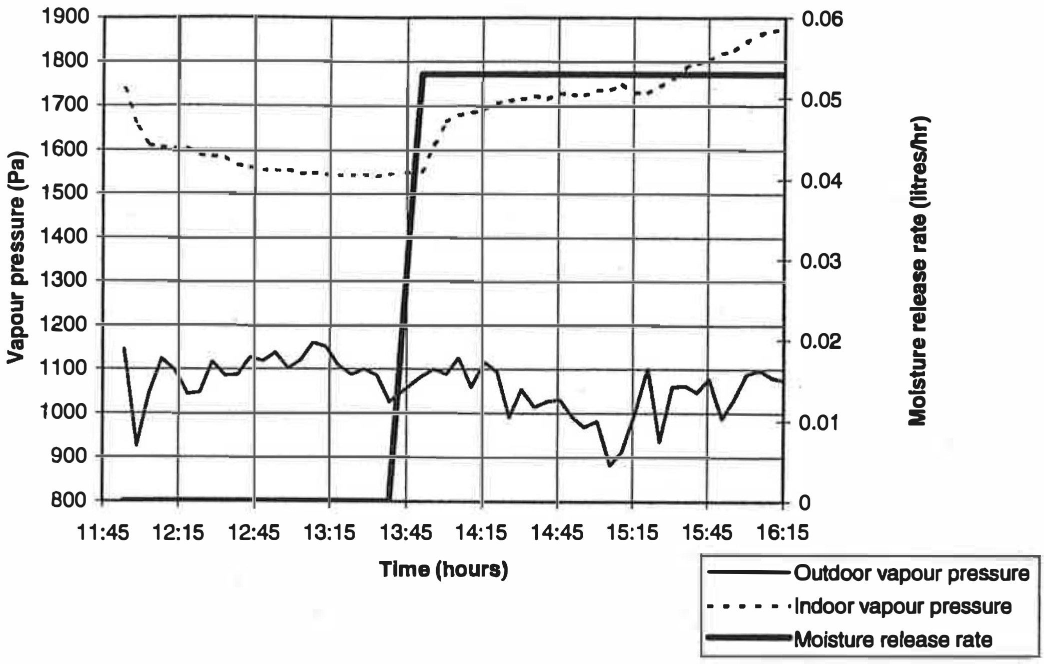

Fig. 5. Vapour pressures and moisture release rates at lower ventilation levels. Run 4 data (1153–1338 h) was used to find the ventilation level of the room. Run 5 data (1350–1615 h) was used to find the moisture release rate under lower ventilation levels.

rooms probably arises because, under these tight conditions, the room hygroscopic materials influence substantially the time dependency of the room relative humidity and vapour pressure. In order to fully model this hygroscopic influence a more accurate physical model than the one used here is clearly needed. Furthermore, it is unclear where in the room temperatures and humidities should be measured to fairly represent the room as one zone when, because of less external ventilation, room air circulation is lower.

The main purpose for which this method is designed is to allow a large number of buildings to be surveyed for ventilation levels and moisture release rates, so that statistical properties can be compiled which place buildings into category systems such as very tight/tight/intermediate/loose/very loose. For this purpose, 30% accuracy is quite acceptable. This standard has been met except for the case of moisture release rates under air-tight conditions. Further work is required under these conditions to ascertain whether there is always a problem assessing the moisture release rates under air-tight conditions with this technique and whether any relatively simple modification of the techniques under study will improve this result.

Even for small numbers of buildings, in many cases the higher accuracy obtainable using tracer gas techniques may not be strictly necessary, and it may be acceptable to use this much easier and cheaper technique in such cases.

8.2. Use in practice

In practice, in order to find the hygroscopic par-

Table 3
Experimental and calculational results[a]

Run number	t_1 (h)	t_2 (h)	Ventilation		Moisture release rate	
			Calc. (h^{-1})	Exp. (h^{-1})	Calc. (L/hr)	Exp. (L/hr)
1		0.28	5.5	5.0		
2	0.46					
3					0.072	0.056
4			1.3	1.0		
5					0.18	0.05

[a] Read these in conjunction with Table 1 describing the run and Table 2 describing methods used.

ameters t_1 and t_2, it is necessary to: firstly scan the psychrometric data to find times when there are no moisture sources under conditions of higher ventilation to allow the use of Eq. (13) for t_2; and secondly to find times when there are no moisture sources under conditions of lower ventilation to allow the use of Eq. (20) to find t_1.

One finds in practice that this is not difficult. Almost no room has continuous moisture sources, and most rooms will have times of higher or lower ventilation levels according to ambient conditions and occupant behaviour. Times of higher ventilation levels are identifiable because indoor and outdoor vapour pressures do not differ by much (see Fig. 3). Lower ventilation levels are identifiable because substantial indoor–outdoor vapour pressure difference can exist (see, for example, Fig. 4). It is usually possible to distinguish this case of low ventilation from the case of non-zero moisture source, because moisture sources are usually present at predictable times and in predictable patterns, e.g. sharp spikes of increased vapour pressure occur in bathrooms morning and night when showering; in bedrooms a low background moisture source is present during night-time from sleeping occupants' respiration; step functions of moisture occur during cooking times in the kitchen.

It is not possible with these techniques to determine the rate of moisture release and the ventilation rate simultaneously. In practice, when a moisture source of unknown strength is present, it is assumed that the ventilation rate is the average of the calculated ventilation rates [using Eq. (23)] before and after the moisture source episode. Using this average, the moisture release rate can be calculated using Eq. (22). Since moisture sources, once established, tend to be constant, another iteration using Eq. (23) can be used to calculate a better value for the ventilation rate; or Eq. (23) can be used at different time intervals during the moisture release episode to follow ventilation rate changes.

9. Conclusions

System identification techniques have been described that allow, from psychrometric data only, the approximate calculation of building air-change rates and moisture release rates. The techniques have been developed primarily to allow the surveying of a large number of houses so that statistical properties can be compiled. The technique potentially offers a cheap and moderately accurate alternative to tracer gas injection techniques or PFT tubes.

Results within 10 to 30% of actual values have been obtained, except for the case of moisture release rates under air-tight conditions. Here, room hygroscopic properties start to dominate in determining the internal climate and it may be that the simple physical model used here is inadequate. This particular case will need to be examined more closely.

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