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PAPER 4

THE USE OF EQUIVALENT ELECTRICAL CIRCUITS TO DESCRIBE THE MOISTURE BEHAVIOUR OF STRUCTURES

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THE USE OF EQUIVALENT ELECTRICAL CIRCUITS TO DESCRIBE THE MOISTURE BEHAVIOUR OF STRUCTURES

M J Cunningham

SYNOPSIS

Earlier work on analytical models of the moisture behaviour of structures is used to show that after suitable linearisation approximations, the models are similar in form to those describing the performance of electrical circuits. This enables the theory of electrical circuits to be used to calculate the moisture performance of the structures under any driving forces. The equivalent circuit for the performance of a structure over longer time periods (much greater than one day) is shown to be a simple series combination of a capacitor and a resistor, which implies that one parameter only, here called the drying time constant, is needed to describe the performance of the structure under these conditions. An expression is given showing how this time constant increases over the drying time of the unenclosed hygroscopic material.

LIST OF SYMBOLS

A area (m^2)
c_i concentration of moisture in region i (kg m^{-3})
c_o concentration of moisture in the cavity air (kg m^{-3})
C capacitance (F)
F air change rate (s^{-1})
g surface mass transfer coefficient from the evaporating surface to the cavity (kg N^{-1} s^{-1})
i current (A)
I Laplace transform of current (A s)
k proportionality constant linearising the sorption curve of a hygroscopic material (m^2 s^{-2})
m moisture concentration (kg m^{-3})
M initial moisture concentration (kg m^{-3})
p vapour pressure (Pa)
$\bar{p}$ weighted mean of vapour pressures (Pa)
p_g water vapour pressure due to evaporating surface (Pa)
P Laplace transform of vapour pressure (Pa)
r_{ij} vapour resistance between region i and j (N s kg^{-1})
R total vapour resistance (N s kg^{-1} m^{-2})
R universal gas constant (8310 J K^{-1} $kmole^{-1}$)
R_{ae} total vapour resistance between framing material and external regions via the cavity (N s kg^{-1} m^{-2})
R_{ao} total vapour resistance between framing material and cavity (N s kg^{-1} m^{-2})
R_{be} total vapour resistance between framing material and external regions via the linings(N s kg^{-1} m^{-2})
R_{oe} total vapour resistance between the cavity and the external

regions

R_{wa} total vapour resistance of a half-width of framing material facing the cavity($N\ s\ kg^{-1}\ m^{-2}$)

R_{wb} total vapour resistance of framing material facing the linings ($N\ s\ kg^{-1}\ m^{-2}$)

t time (s)

t_a unenclosed drying time constant through the edge of the framing material which will face cavity (s)

t_b unenclosed drying time constant through the edge of the framing material which will face the linings (s)

t_d drying time constant for the enclosed framing material (s)

t_w drying time constant for unenclosed framing material (s)

T Kelvin temperature (K)

v voltage (V)

V Laplace transform of voltage (V s)

V volume (m^3)

W molecular weight of water (18 kg $kmole^{-1}$)

ϕ phase lag (radians)

ω angular frequency (radians s^{-1})

Subscripts

a edge of the framing material which will face the cavity

b edge of the framing material which will face the linings

i,j external regions

o cavity

w framing material

1. INTRODUCTION

The traditional tools (Marsh[1],Keiper,Cammerer and Wagner[2], Glaser[3]) for predicting the moisture performance of structures have a number of deficiencies:

1. Air leakage which is usually the most important moisture transfer mechanism is not allowed for or not handled completely.
2. The hygroscopic nature of building materials is not allowed for.
3. There is an underlying assumption of steady state so that the dynamics of the structures' moisture performance is not taken into account.

In order to address these problems, the author in a series of publications (Cunningham[4-7]) has examined the moisture performance of structures by developing mathematical models based on conservation of moisture in various parts of the structure. The models are lumped and linearised which allows analytical solutions to be given.

This paper summarises these developments and places a slightly different emphasis on the topic by highlighting the value of using electrical circuit analogies to understand and predict moisture performance of structures. The differential equations of the physical model, once linearised, consist of a series of coupled first order differential equations, which can be seen to be directly equivalent to an analogous set of equations governing the performance of the corresponding electrical circuit. Although the mathematics for the two cases is the same and their performance is correspondingly similar, there exists a large body of knowledge and a well-established methodology for analysing electrical circuits that can now be tapped into directly.

The paper begins by outlining the development of two similar models developed by the author. One of these models is examined in detail to show how, after linearisation, it can be seen to be equivalent to an electrical network consisting of capacitors and resistors. It is shown that if one is interested chiefly in longer time periods, much greater than one day, then only the very simplest of circuits need be considered, namely a series combination of a capacitor and a resistor. This implies that the performance of the circuit and therefore the moisture performance of the structure, is characterised by only one parameter, namely the time constant of the circuit. An expression is given for the corresponding time constant for the moisture performance of the structure, called here the "drying time constant". The paper concludes with examples taken from earlier work demonstrating the calculation of the drying time constant and demonstrating how the structure's moisture performance under an arbitary driving force can be derived by exploiting the electrical circuit analogy. The driving force used in this example is the seasonal periodic fluctuations in climate.

2. PHYSICAL MODELS

In this section physical models are developed for two different structures taken from Cunningham[6,7]. The first most general model considered is a structure containing hygroscopic material, e.g. timber framing, and an air filled cavity as shown in Figure 1(a). In this case the hygroscopic material has a moisture flow path to the cavity but no significant flow to the linings. This model would simulate a structure such as a timber framed pitched roof where much of the framing is not in contact with any lining.

The region i shown in Figure 1(a) represents one of n moisture sources/sinks e.g. indoors, outdoors, other building cavities, extractor fans etc. The possiblity of an evaporating water surface inside the cavity is also allowed for (e.g. an open water tank or soil surface.) Two moisture transfer mechanisms are assumed, namely vapour diffusion driven by water vapour partial pressure difference p_1-p_o, and air convection characterised by a mean air change rate F_{io} (from region i to the cavity) and F_{oi} (from the cavity to region i) measured in s^{-1}. The cavity has volume Vo and the hygroscopic material has volume V_w.

The second model considered here is a flat roof or wall with a framing material which is joined to the inside and outside linings and an associated cavity filled with insulation or air, see Figure 1(b). Both framing and cavity material can store moisture but the hygroscopic properties of the linings are ignored. Any membranes such as vapour barriers, building paper, sarking etc are lumped in with the linings. In this model no evaporating surface inside the cavity has been included and for simplicity only two regions external to the structure are considered: indoors and outdoors. It is, however, straight forward to include these details if required.

A key simplication is now made. The hygroscopic material is lumped and its drying and wetting assumed to be exponential, see Cunningham[7] i.e.

$$V_w \frac{dm}{dt} = \frac{p - p_w}{R_t}$$

where
p is the vapour pressure external to the hygroscopic material (Pa)

p_w is the vapour pressure of the hygroscopically bound moisture in the framing material at moisture content m as determined by the sorption curves for that material (Pa)

R_t is the lumped total vapour flow resistance (including surface area weighting) between the hygroscopic material and the surrounding medium. ($N\ s\ kg^{-1}\ m^{-2}$)

The validity of this exponential drying approximation has been discussed elsewhere (Cunningham[7]). Cunningham[7] derives an expression giving the connection between R_t and other physical parameters such as the diffusion coefficient for moisture transfer in the hygroscopic material and the surface mass transfer coefficient for transfer in and out of the material.

The physical model of the performance of these structures is established by writing down the conservation equations for moisture in the cavity, the hygroscopic material and the air in the cavity. We have,

> Increase in cavity moisture per unit time=flow of moisture from external regions by diffusion+flow of moisture to and from external regions by air leakage-flow of moisture to the framing material

which results in the equation

$$V_o \frac{dc_o}{dt} = \frac{p_w - p_o}{R_{wo}} + g A_g (p_g - p_o) + \sum_i \left(\frac{A_{io}(p_i - p_o)}{r_{io}} + V_o (F_{io} c_i - F_{oi} c_o) \right) \tag{1}$$

for the first model and the equation and

$$V_o \frac{dm_o}{dt} = \frac{p_w - p_o}{R_{wo}} + \sum_{i=1}^{2} \left(\frac{A_{io}(p_i - p_o)}{r_{io}} + V_o (F_{io} c_i - F_{oi} c_o) \right) \tag{2}$$

for the second model.

Also

> Increase in hygroscopic moisture per unit time=flow of moisture from cavity+flow in moisture from exterior regions through the linings
>
> giving

$$V_w \frac{dm_w}{dt} = \frac{p_o - p_w}{R_{wo}} \tag{3}$$

for the first model and

$$V_w \frac{dm_w}{dt} = \frac{p_o - p_w}{R_{wo}} + \sum_{j=1}^{2} \frac{A_{jw}(p_j - p_w)}{r_{jw}} \tag{4}$$

for the second model.

Here

c_i is the moisture concentration in the air in region i (kg m^{-3})

m_i is the moisture concentration(kg m^{-3}) in the material in region i

g is the surface mass transfer coefficient from the evaporating surface to the cavity (kg N^{-1} s^{-1})

r_{pq} is the series sum of all vapour resistances between region p and q (N s kg^{-1})

A_{pq} is the area (m^2) between region p and q

F_{pq} is the air change rate (s^{-1}) between region p and q

R_{wo} is the total vapour resistance (including area weighting) between the hygroscopic material and the cavity material (N s kg^{-1} m^{-2}).

Cunningham[7] derives an expression for R_{wo} as a function of physical parameters such as the diffusion coefficient for moisture transfer in the hygroscopic material and the surface mass transfer coefficient for transfer in and out of the material.

Also since the net air flow into the cavity is zero, then for both models

$$\sum_i (F_{io} - F_{oi}) = 0$$

Note that the term $F_{io}c_i - F_{oi}c_o$ in equation (1) and (2) assumes perfect mixing of the air flows in the cavity.

From here onwards only the second (flat roof or wall) model will be developed in detail. Cunningham[6] should be consulted for detailed development of the first model.

Water vapour concentrations c_i are converted to vapour pressure by assuming water vapour to be an ideal gas i.e.

$$p = \frac{c_i R T}{W} \tag{5}$$

where R is the universal gas constant, T is the Kelvin temperature of the air and W is the molecular weight of water.

The sorption curves of the framing and cavity materials are now described by the equations

$$p_w = k_w m_w \tag{6a}$$

$$p_o = k_o m_o \tag{6b}$$

where k_w and k_o are functions of temperature and to a lesser extent of moisture content.

Note that if the cavity material is air then

$$k_o = \frac{RT}{W} \tag{7}$$

from equation (5).

Following Cunningham[7], a number of lumping definitions are now made to simplify these conservation equations, see Figure 2.

Define

$$\frac{1}{R_{oe}} = \sum_{i=1}^{2} \left(\frac{A_{io}}{r_{io}} + \frac{V_o F_{oi} W}{RT} \right)$$

$$\frac{1}{R_{be}} = \sum_{j=1}^{2} \frac{A_{jw}}{r_{jw}}$$

$$R_{ie} = R_{ba} - R_{wb}$$

$$\bar{p}_o = R_{oe} \sum_{i=1}^{2} \left(\frac{A_{io}}{r_{io}} + \frac{V_o F_{io} W}{RT} \right) p_i$$

$$\bar{p}_w = R_{be} \sum_{j=1}^{2} \frac{A_{jw} p_j}{r_{jw}} \tag{8}$$

R_{wa} and R_{wb} are the total vapour resistances (including area weighting) to the surface (but not across it) of the hygroscopic material in the direction parallel and perpendicular to the linings respectively. An expression for these can be found in Cunningham [7].

With these definitions equations (2) and (4) become

$$\frac{V_o}{k_o} \frac{dp_o}{dt} = \frac{p_w - p_o}{R_{wo}} + \frac{\bar{p}_o - p_o}{R_{oe}} \tag{9a}$$

$$\frac{V_w}{k_w}\frac{dp_w}{dt} = \frac{p_o - p_w}{R_{wo}} + \frac{\bar{p}_w - p_w}{R_{bo}} \tag{9b}$$

These equations as written are nonlinear, chiefly because of the strong temperature dependence of k.

Very similar equations follow for the case of the first model.

3. ELECTRICAL CIRCUIT ANALOGIES

Generally it is the long term moisture behaviour of the structure that is of interest; such details as the drying time of wet framing or the amount of moisture accumulated over the winter season. Short term moisture behaviour (say over time periods of a day or less) is usually of less concern and in any case is not well modelled by the equations developed above. Issues such as hygroscopic linings and nonuniform moisture concentrations in the hygroscopic materials are important for short term moisture behaviour and these are not modelled here.

Over the long term then (in the order of months) we can take for the temperature its mean value and therefore take the k_o and k_w constant at their mean values. This linearises equations (9) above and allows them to be solved by conventional techniques given the initial conditions, see for example Cunningham[7]. Further discussion of the implications of this linearisation can be found in Cunningham [7].

At this point the similarity between equations (9) and the corresponding equations for an equivalent electrical circuit can be exploited. Specifically, the following analogies are made in order to establish an equivalent RC electrical circuit to the physical models being used here.

$$\begin{aligned}
&\text{voltage} &&\sim\quad p_i\\
&\text{charge} &&\sim\quad m_i V_i\\
&\text{current} &&\sim\quad V_i\frac{dm_i}{dt} = \frac{V_i}{k_i}\frac{dp_i}{dt}\\
&\text{capacitance} &&\sim\quad \frac{V_i}{k_i}\\
&\text{resistance} &&\sim\quad R_i
\end{aligned} \tag{10}$$

Using these analogies the coupled linear first order differential equations (9) become analogous to a set of equations describing the performance of an electrical circuit consisting of capacitors and resistors. The equivalent circuit to the first and second models are shown in Figure 3. The whole gamut of electrical circuit theory can now be drawn upon to describe the performance of our models under any driving (or excitation) function. The unifying concept usually used is a transfer function for the circuit in the s domain together with the theory of Laplace transforms to derive the circuit performance in the time domain.

It was stated at the beginning of this section that the long term moisture performance is of most interest to us. By considering the size of the various parameters involved, see Cunningham[7], it can be shown that once the initial transients have died down (after a few hours) the capacitor representing the cavity material in the models developed here becomes fully charged and no longer contributes to the circuit performance. In this case we are left with the capacitor representing the hygroscopic material and the resistors connected to it. These resistors can be lumped giving a value of

$$R_{ae} \tag{11a}$$

for the first model and

$$\frac{R_{ae} R_{be}}{R_{ae} + R_{be}} \tag{11b}$$

for the second model.

Hence for long term cavity performance we are left with a simple series combination of a resistor and a capacitor, see Figure 4. The differential equation describing the performance of this RC circuit is

$$v_c + iR = v$$

where
v_c is the voltage across the capacitor
v is the driving voltage across the capacitor and resistor
i is the current in the circuit
Since

$$i = \frac{dq}{dt} = C\frac{dv_c}{dt}$$

this can be written as

$$v_c + RC\frac{dv_c}{dt} = v$$

Performing a Laplace transform upon this equation gives

$$V_c = \frac{V + RC\,v_c(0)}{1 + sRC}$$

where
V_c is the Laplace transform of the capacitor voltage
V is the Laplace transform of the driving voltage
$v_c(0)$ is the initial value of the capacitor voltage.
In other words

$$V_c = \frac{V + t_c v_c(0)}{1 + s t_c}$$

where t_c is the time constant of the RC circuit defined as

$$t_c = RC \qquad (12)$$

This takes the form

V_c=transfer function x excitation function

where

transfer function= $\dfrac{1}{1 + s t_c}$

and

excitation function= $V + t_c v_c(0)$

The corresponding time constant for the physical model will be labelled t_d so that the physical model analogy is seen to be

$$P_w = \frac{P + t_d p_w(0)}{1 + s t_d}$$

We have now reached the point where the complete (long term) moisture behaviour of our structure is characterised by only one parameter, namely the time constant t_d (although it must be remembered that a second parameter k_w is also needed if we wish to translate from vapour pressure to moisture content within the hygroscopic material). Physically the time constant can be interpreted as the time constant for the hygroscopic material to dry from its initial moisture content (at the time of construction or, say, at the end of winter) to its long term equilibrium value over the time period of interest. However it is important to reiterate that given this single drying time constant,the moisture performance under all other driving functions can be deduced,insofar as the linearisation approximation is valid. In particular the performance can be derived under periodic seasonal variations in the climate driving forces, see Cunningham[6]. Examples are given later to illustrate this point.

4. PROPERTIES OF THE DRYING TIME CONSTANT

In the case of the second model, from equations (10), (11b) and (12) we have

$$t_d = \frac{V_w}{k_w} \frac{R_{ae} R_{be}}{(R_{ae} + R_{be})}$$

i.e.

$$\frac{1}{t_d} = \frac{k_w}{V_w} \left(\frac{1}{R_{ae}} + \frac{1}{R_{be}} \right)$$

$$= \frac{k_w}{V_w} \left(\frac{1}{R_{ae} + R_{ao} + R_{oe}} + \frac{1}{R_{wb} + R_{ie}} \right)$$

$$= \frac{k_w}{V_w} \left(\frac{1}{R_{wa}(1+\gamma)} + \frac{1}{R_{wb}(1+\delta)} \right)$$

where

$$\gamma = \frac{R_{ao} + R_{oe}}{R_{ae}}$$

and

$$\delta = \frac{R_{ie}}{R_{wb}}$$

Intuitively, one would expect that once the framing material has been enclosed its drying time constant t_d would be longer than for the unenclosed material. This can be put on a quantitative basis by comparing the value of the enclosed drying time constant t_d with the time it would take for the hygroscopic material to dry unenclosed to air under conditions where this open air drying is diffusion limited, i.e., diffusion to the surface of the material is very much slower than surface mass transfer. If t_a is the time taken for the unenclosed material to dry through the side which will face the cavity and t_b is the time taken to dry through the side which will face the linings, it can be shown, see Cunningham [7], that

$$t_a = \frac{V_w}{k_w} R_{wa} \tag{13a}$$

and

$$t_b = \frac{V_w}{k_w} R_{wb} \tag{13b}$$

The time t_w for the unenclosed hygroscopic material to dry was shown in Cunningham [7] to be

$$\frac{1}{t_w} = \frac{1}{t_a} + \frac{1}{t_b} \tag{14}$$

Therefore

$$\frac{1}{t_d} = \frac{1}{t_a(1+\gamma)} + \frac{1}{t_b(1+\delta)} \tag{15}$$

A similar expression can be derived for the first model.

Equation (15) shows how the long term time constant-physically the drying time of the framing material once enclosed in the structure-is increased over the unenclosed value,according to the air and vapour tightness construction details of the structure and the driving forces upon it.

5. EXAMPLES

The following examples are taken from Cunningham[7] and are used to illustrate the calculation of the drying time constant t_d, and the use of the equivalent electrical circuit to calculate the response of structures to seasonal driving forces.

Two structures are considered and two subcases are considered for each structure. Structure 1 has 50x50mm timber joists spaced at 500mm centres with the cavity in between filled with fibreglass. Structure 2 is similar except that the joist is 50x100mm and is orientated so that the cavity between the joists is 100mm deep and also filled with insulation.

For each structure two subcases are considered. Subcase (a) has the internal linings plus membranes with a vapour resistance of 2 GNs kg^{-1} and the external linings with a vapour resistance of 1 GNs kg^{-1}. Subcase (b) has the internal linings with a vapour resistance of 20 GNs kg^{-1} and the external linings with a vapour resistance of 10 GNs kg^{-1}.

In all cases the driving air pressures and air permeabilities are such that the air change in the cavity is 0.5 air changes per hour. (To calculate the long term time constant the direction of air movement is not needed). The mean temperature of the structure is taken as 11°C. The diffusion coefficient (vapour pressure driven) for the wood is taken as 7.32×10^{-12} s and for the insulation as 1.67×10^{-10} s. k_w is taken as 20 m^2 s^{-2}.

Formulae (13a) and (13b) are used to calculate the time constants for open air drying of the joists, t_a and t_b. These time constants come to 20 days for drying through faces 50mm apart and 80 days through faces 100mm apart. Hence from formula (14) the overall drying time in air will be 10 days for a 50x50mm joist and 16 days for a 100x50mm joist.

Formula (15) is used to find how these drying times increase when the structure is enclosed.Details on how to do this can be found in Cunningham[7]. Table 1 shows the results of these calculations.

To highlight the fact that knowledge of the drying constant t_d implies complete knowledge of the longer term moisture performance of the structure (assuming linearity), the case of periodic driving forces will now be considered. Take for example the important case of seasonal variation in the moisture content of the structure.In this case the driving forces can be approximated as Cunningham[6]

$$p = \tilde{p} + \Delta p \sin \omega t$$

where

$\tilde{p}$ is the mean value of p and Δp is the maximum deviation of the driving force from this mean

and ω is the angular frequency of the driving forces.

The moisture content of the framing material can be simply determined by examining the RC circuit analogy in Figure 4. From circuit analysis the voltage v_c across the capacitor for this circuit is

$$v_c = \frac{v}{\sqrt{1 + (\omega \bar{t}_d)^2}}$$

where v is the driving voltage and $\bar{t}_d$ is the time constant appropriate to the mean of the driving conditions over the time period being considered, see Cunningham[6].

The phase φ of the voltage across the capacitor lags the phase of the driving voltage by

$$\varphi = \tan^{-1}(\omega \bar{t}_d)$$

Taking the driving period as 1 year, Table 2 contains the amplitude response and phase lag of the framing material vapour pressure and hence moisture content compared to the driving forces for each of the four cases analysed in the examples above. For example in the case of the structure with a 100x50mm joist and high vapour resistance linings, the maximum seasonal moisture content in the joist occurs 1.35 months later than the peak driving forces, and the value of the deviation of the moisture content from the yearly mean value is only 77% of that which would be predicted from assuming the timber was in moisture equilibrium with the driving forces. In fact as pointed out elsewhere (Cunningham[6]), the amplitude response and phase lag is only significant for tight structures, that is, structures in which the enclosed drying time constant is significantly longer than the unenclosed time constant.

6. CONCLUSIONS

Earlier work (Cunningham[4-7]) on mathematical models of the moisture performance of structures has been summarised. Once these models have been linearised their equivalent electrical circuit has been found. This enables the large body of knowledge on electrical circuit theory to be utilised to give quick and easy calculation of the moisture performance of the structure under any driving force.

For the approach to be useful it is necessary to understand the range of validity of the linearising approximations used. It has been argued that, provided the longer term performance of the structure is of chief concern, the mean value of the parameters k_w and k_o used to describe the sorption curves of the cavity materials can be used.

Furthermore if only the longer term performance of the structure is of concern it has been shown that the equivalent circuit is a series combination of a capacitor and a resistor, characterised by its time constant. In turn this means that the long term moisture performance of the structure can be completely understood with just one parameter, the drying time constant of the hygroscopic material. An expression showing how this time constant increases over the drying time of the unenclosed hygroscopic material has been given.

It has not been the intention of this paper to examine the experimental validity of this approach. However some preliminary experimental work is being done which tends to point to the usefulness of this approach. Cunningham[8] has shown that framed roofing structures exhibit exponential drying and can thus be associated with a time constant, while in Cunningham[6] field results from a group of houses in Invercargill, New Zealand, were shown to have attic moisture contents in phase with the annual climate driving forces, implying that for these houses the roof timber drying time constant was much less than one year.

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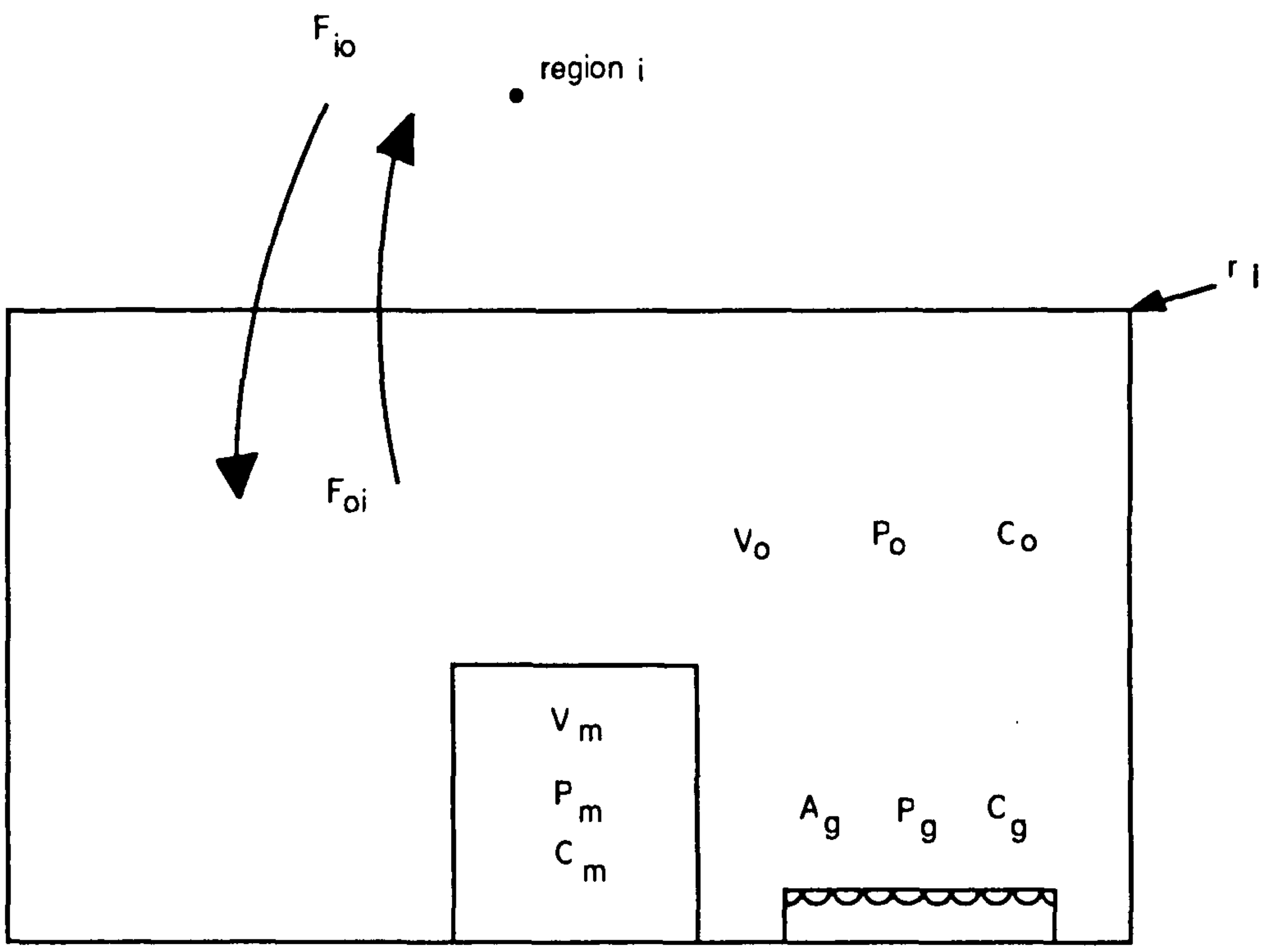
	1. 50x50mm Joist		2. 100x50mm Joist	
Quantity	**1(a) Low resistance linings**	**1(b) High resistance linings**	**2(a) Low resistance linings**	**2(b) High resistance linings**
Drying time constant for unenclosed framing, t_w	10.0 days	10.0 days	16.0 days	16.0 days
Drying time constant for enclosed framing, t_2	17.2 days	36.4 days	25.5 days	47.8 days
Drying time constant for enclosed framing from earlier work.	22.1 days	35.9 days	24.0 days	45.0 days

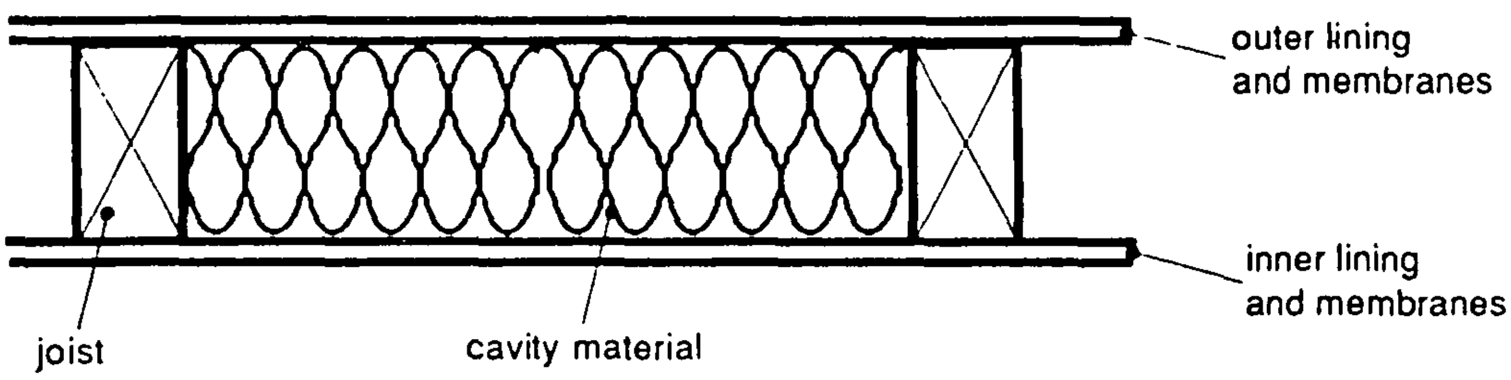
Table 1: Drying time constants for various structures.

	1. 50x50mm Joist		2. 100x50mm Joist	
Quantity	**1(a) Low resistance linings**	**1(b) High resistance linings**	**2(a) Low resistance linings**	**2(b) High resistance linings**
Drying time constant for enclosed framing, t_2	17.3 days	36.8 days	25.8 days	48.5 days
Phase Lag	0.56 months	1.10 months	0.81 months	1.35 months
Amplitude response	0.96	0.84	0.91	0.77

Table 2: Seasonal moisture behaviour for various structures.



1(a) first model



1(b) Second model

Figure 1: Physical models

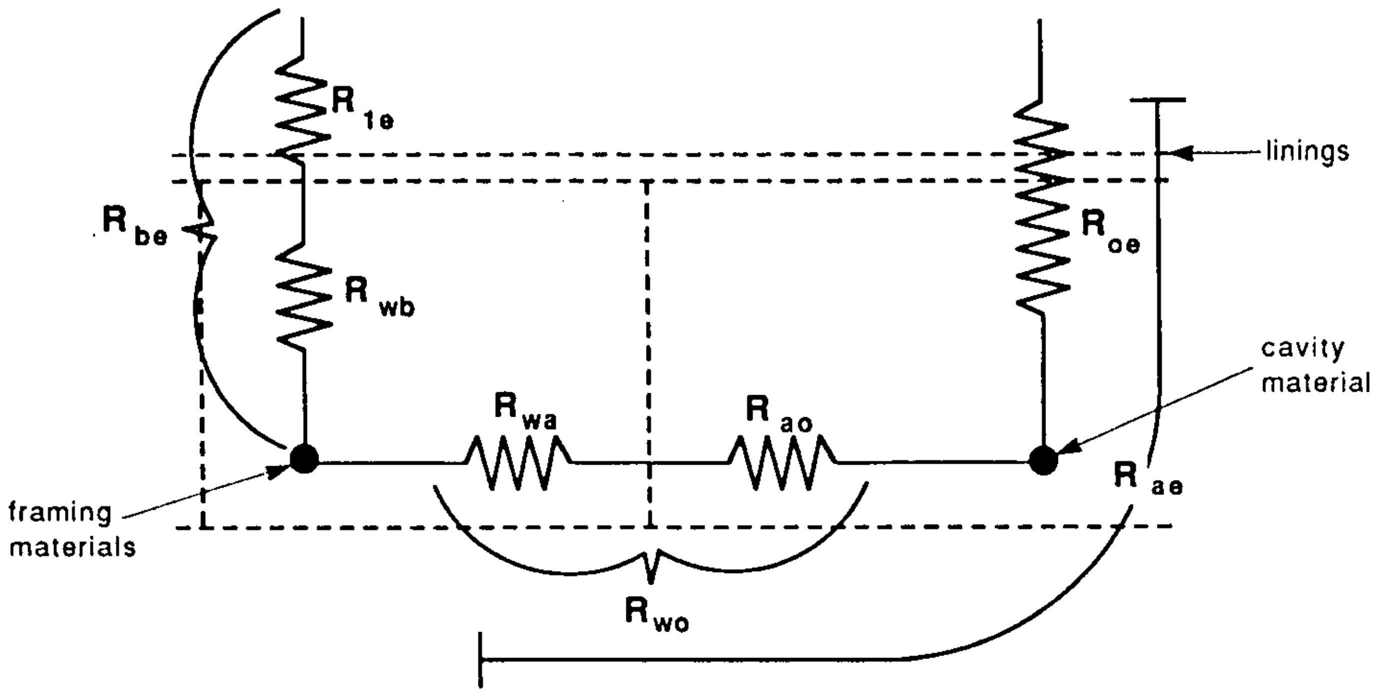
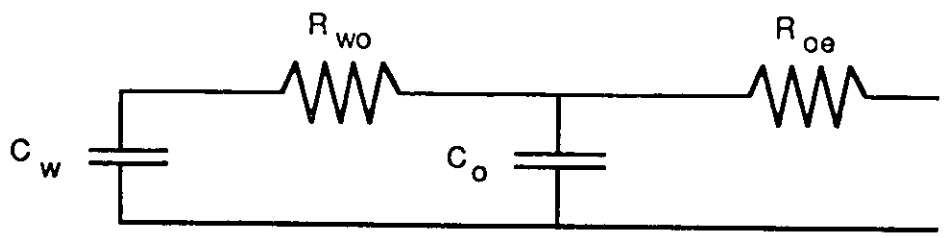
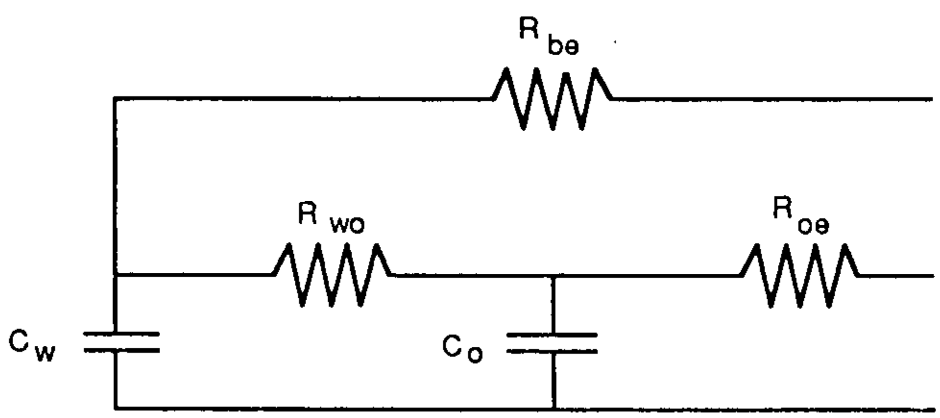


Figure 2: Definitions of the lumped total vapour flow resistances.



3(a) First model



3(b) Second model

Figure 3: Equivalent circuits for each model

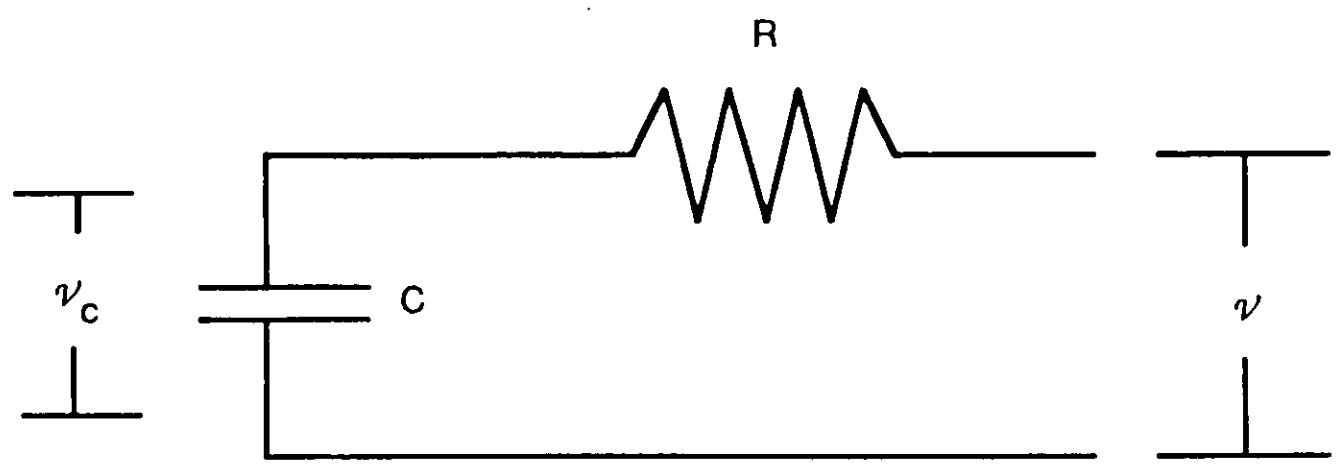


Figure 4: RC equivalent circuit

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The use of equivalent elec
trical circuits to describ

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