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# Investigation of a Model for the Ventilation of Suspended Floors

**Terry Williamson[1] and Angelo Delsante[2]**

[1] School of Architecture, Landscape Architecture & Urban Design, The University of Adelaide, Australia
[2] CSIRO Sustainable Ecosystems, Highett, Australia

ABSTRACT: International Standard ISO 13370 “Thermal performance of buildings — Heat transfer via the ground — Calculation methods” provides a method to calculate the R-value of a suspended floor. The method is a modification of a methodology first published in the CIBSE Environmental Design Guide A -1998. The thermal network that forms the basis of the CIBSE calculation includes radiative transfer between the suspended platform and the ground, conductive components and a sub-floor ventilation component. In the ISO 13370 methodology the surface resistance (the inverse of the combined convective and radiative co-efficient) is used as a proxy for the more explicit calculation (as is done in most building heat transfer calculations). This paper deals with the ventilation component of the ISO 13370 calculations. This component would seem to have its origins in an infiltration model developed during the late 1970s and early 1980s by Max Sherman and others at LBL. It is a single-zone model that incorporates both stack and wind induced effects. This paper investigates whether this model can in fact be applied to sub-floors and shows how an “exact” formulation may be derived from first principles.

Conference theme: Building and energy
Keywords: ventilation, floors, dwellings, standards and regulations

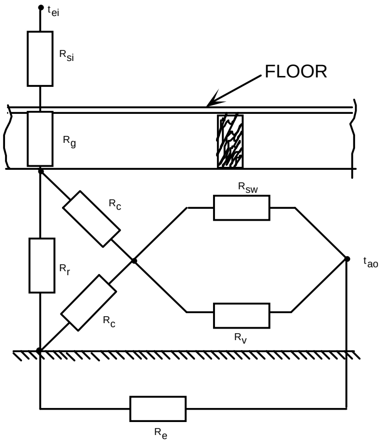
## INTRODUCTION

The energy-efficiency provisions into the Building Code of Australia (BCA 2006) for Class 1 and 10 buildings specify deemed-to-comply R-values for building elements. However no standard method to calculate these R-values exists in Australia. For many years the AIRAH Handbook (AIRAH 2000) has been accepted as a default standard, specifying assumptions for factors such as surface resistance values. However, when considering the R-value of suspended floors the AIRAH Handbook takes a simplified approach and deals only with the suspended platform, neglecting the complex radiation and convective heats flows that contribute to the actual performance of the floor construction. Dealing realistically with the heat flows is especially important when the resultant values are being used for the comparison of floor constructions which may have different driving stimuli, for example, comparing the performance of a suspended timber floor with a concrete slabs-on-ground floor. Accurate calculations at short time intervals (eg 1 hour) can realistically be done only using computer methods. Many such programs treat the sub-floor space as a building zone and model the heat flow from the internal zones of the building to a sub-floor zone. This heat is then considered to flow partly to the ground, and partly, via walls and ventilation openings, to the outside. In the case of manual methods, a more sophisticated approach is necessary than the traditional one of summing values for the internal and external surface resistances and resistances of the floor components. One method that allows for some elements of the complexity of the situation is found in the CIBSE Environmental Design Guide A prior to 1999 (CIBSE 1998). Here the methodology simplifies all the storage and perimeter/sub-floor effects to an equivalent steady-state U-Value that is said to give reasonable predictions of heat losses in practice. The calculation of the U-Value is based on the resistance network (see Figure 1 below) that includes the radiation exchange between underside of floor and ground surface together with ventilation and conduction heat flows. A delta to star network transformation was employed to perform the calculations.

International Standard ISO 13370 “Thermal performance of buildings — Heat transfer via the ground — Calculation methods” provides a method to calculate the R-value of a suspended floor. Equation (6) of ISO 13370 (Eq 1 below) gives the thermal resistance ($\frac{1}{U}$) of a suspended floor as,

$$\frac{1}{U} = \frac{1}{U_f} + \frac{1}{U_g + U_x} \qquad (1)$$

where
$U_f$ is the thermal transmittance of suspended part of floor, in W/(m²·K)
(between the internal environment and the underfloor space). The calculation of $U_f$ includes the effect of any thermal bridging;
$U_g$ is the thermal transmittance for heat flow through the ground, in W/(m²·K);
$U_x$ is an equivalent thermal transmittance between the underfloor space and the outside accounting for heat flow through the walls of the underfloor space and by ventilation of the underfloor space, in W/(m²·K).



| | |
|---|---|
| $t_{ei}$ | inside environmental temperature |
| $R_{si}$ | inside surface resistance |
| $R_g$ | thermal resistance of floor |
| $R_r$ | equivalent thermal resistance due to radiatio |
| $R_c$ | equivalent thermal resistance due to convect |
| $R_v$ | equivalent thermal resistance due to ventilati |
| $R_e$ | thermal resistance of the earth |
| $R_{sw}$ | thermal resistance of the sub-floor wall |
| $t_{ao}$ | outside air temperature |

**Figure 1:** Thermal resistance network for heat flow through suspended floor

Eq (1) is an approximation for the explicit heat flow network given in the CIBSE Guide. In the ISO methodology the surface resistance (the inverse of the combined convective and radiative co-efficient) is used as a proxy for the more specific calculation (as is done in most building heat transfer calculations).

Further $U_x$, given by ISO-DIS-13770 equation (9) is the sum of the heat flow through sub-floor walls and a ventilation component,

$$U_x = 2hU_w / B' + 1450\varepsilon v f_w / B' \qquad (2)$$

where
$h$ is the height of the upper surface of the floor above external ground level, in m;
$U_w$ is the thermal transmittance of walls of the sub-floor space above ground level, in W/(m²·K),
$\varepsilon$ is the area of ventilation openings per perimeter length of under floor space, in m²/m;
$v$ is the average wind speed at 10 m height, in m/s;
$f_w$ is a wind shielding factor.

$B'$ is the "characteristic dimension" of the floor, defined as $B' = \dfrac{A}{\frac{1}{2}P}$

where
$A$ is the ground floor area (m$^2$)
$P$ is the exposed perimeter of the floor (m).

The wind shielding factor relates the wind speed at 10 m height (assumed unobstructed) to that near ground level, allowing for the shielding by adjacent buildings, etc. Representative values from ISO 13370 are given in Table 1.

**Table 1. ISO-DIS-13770 'wind shielding factor' (from Table 2, p11)**

| Location | Example | $f_w$ |
|---|---|---|
| Sheltered | City Centre | 0.02 |
| Average | Suburban | 0.05 |
| Exposed | Rural | 0.10 |

Note: These values can be reproduced using Eq (10) below with a height of 0.2m.

This paper is concerned with examining the ventilation term in Eq. (2).

## VENTILATION IN ISO 13370

Appendix E of ISO-DIS-13770 (eq. E.4, p26) gives the wind-driven ventilation rate $Q_w$ for naturally ventilated sub-floor spaces as,

$$Q_w = 0.59 f_w \varepsilon P v' \quad (\mathrm{m^3/s}), \qquad (3)$$

where
0.59 is said to be a discharge coefficient,
$v'$ is the "design wind speed at 10 m height" (i.e. the weather tower wind speed at 10 m height in terrain category 2),
$f_w$ is the shielding factor as shown in Table 1 above.

The U-value implied by this flow rate, $U_v$, is given by $U_v = \rho Q_w c_p / A$. For calculations in the standard, $Cp$ = 1000 J/(kg·K) (at 10 °C) and $\rho$ = 1.23 kg/m³ (at 10 °C and 100 kPa pressure)

Therefore,

$$U_v = \frac{0.59 \times \varepsilon \times P \times 1000 \times 1.23 \times v' \times f_w}{A} = \frac{1450 \varepsilon v' f_w}{B'} , \qquad (4)$$

Correspondence between the authors and the Convenor of the ISO 13370 committee has confirmed that the factor $f_w$ in Eq (4) was derived from the so called LBL Infiltration model.

## LBL infiltration model, applied to sub-floor spaces

The LBL model for infiltration, developed during the late 1970s and early 1980s by Max Sherman and others is widely recognised. It is a single-zone model that incorporates both stack and wind-induced effects intended to estimate the infiltration characteristics of a building envelope: only the wind-induced effects enter into the ISO formulation Eq (2). However, it is not clear if this model can in fact be applied to sub-floors. Assuming that it can, the flow rate due to wind only is given by Sherman (1980) as,

$$Q_w = f_w A_0 v' \qquad (5)$$

where $A_0$ = ELA (equivalent leakage area), $v'$ is the weather tower wind speed, and

$$f_w = C'(1-R)^{1/3} \left[ \frac{a(H/10)^b}{a'(H'/10)^{b'}} \right], \qquad (6)$$

where primed quantities refer to the weather tower site, unprimed quantities refer to the building site, $C'$ is a 'generalised shielding coefficient', and $R$ is the fraction of leakage in the floor and ceiling. For the purposes of calculating wind-driven flow through the sub-floor vents, we may take $R = 0$.

If we further assume that the weather tower is in terrain category 2 (see Table 2 below), then $a' = 1$, $H' = 10$, and $f_w$ reduces to,

$$f_w = C' a \left( \frac{H}{10} \right)^b . \qquad (7)$$

H is the height of measurement of the wind speed to which the local pressure coefficients are referred.

An explanation of the generalised shielding coefficient is found in Etheridge & Sandberg (1996) who say that as used by Sherman (1980) and Sherman & Grimsrud (1980) it "is a pressure coefficient with the internal pressure as reference. It can be roughly considered as half of the difference between the values of $c_p$ on the windward and leeward surfaces." In a personal communication (May 2005) with Max Sherman he said "David Etheridge's explanation is essentially correct. Class I is "no shielding" but that means we use the pressure coefficients for an isolated structure, which I got from the literature. I then derive the internal pressure coefficient necessary for conservation assuming an equal distribution of leakage and compute the coefficient. This was done for a range of aspect ratios and wind angles and averaged". The literature referred to by Sherman is the data produced by Akins (1976).

Values for *a* and *b* are given in Table 2, while values for *C'* as derived by Sherman are given in Table 3.

**Table 2. Terrain factors.**

| Terrain category | Description | *a* | *b* |
|---|---|---|---|
| 1 | Ocean or other body of water with at least 5km of unrestricted expanse | 1.30 | 0.10 |
| 2 | Flat terrain with some isolated obstacles, e.g. buildings or tress well separated from each other | 1.00 | 0.15 |
| 3 | Rural areas with low buildings, tree,. etc | 0.85 | 0.20 |
| 4 | Urban, industrial or forest areas | 0.67 | 0.25 |
| 5 | Centre of large city | 0.47 | 0.35 |

Source: Sherman 1980

**Table 3. Shielding parameters**

| Shielding class | Description | *C'* |
|---|---|---|
| I | No shielding | 0.324 |
| II | Light | 0.285 |
| III | Moderate | 0.240 |
| IV | Heavy | 0.185 |
| V | Very heavy | 0.102 |

Note: We have found in the literature two versions of values for *C'*. We understand that the original values as shown in this Table are 'correct' and that the other version is a result of a typographical error.

The values of *C*', for classes II-V shown in Table 3 were obtained by Sherman from the Class I value as follows: take one-tenth of the square of the Class I value, and set this to be the square of Class V value. Obtain the squares of the values for the other classes by linear interpolation. But as Sherman has stated, "this was quite arbitrary on my part." (personal communication May 2005)

As explained, below in Sherman's conception, the terrain category (and therefore wind speed profile) for a given building is directly tied to the shielding class.

For sub-floor walls with evenly spaced vents, the ELA may be determined as,

$$A_0 = C_d \varepsilon P , \tag{8}$$

where
$C_d$ is a discharge coefficient
$\varepsilon$ is the area of ventilation opening per perimeter length ($m^2$/m of sub-floor wall),
$P$ is the perimeter.

Thus

$$Q_w = C_d C' \varepsilon P a \left( \frac{H}{10} \right)^b v' = 0.59 f_w \varepsilon P v' , \tag{9}$$

where $f_w$ is defined as in Eq (7).

## THE AKINS DATA

In the mid 1970s Robert Akins at Colorado State University conducted a large series of wind tunnel tests to determine wind loading on structures. The wind tunnel studies consisted of a series of model flat-roofed rectangular 'buildings' of varying geometries immersed in four turbulent boundary layers simulating typical flow conditions. The 'buildings' comprised three side ratios(width/length - 1.0, 0.5, 0.25) and aspect ratios (height/width) in the range 1.0 to 8.0. Descriptions of the boundary layers used by Akins are shown in Table 4.

**Table 4:** Akins Boundary Layer Details

| Boundary Layer | Power-Law Exponent (see Eq 12 below) | Terrain Description |
|---|---|---|
| 1 | 0.12 | Level surfaces with very small surface obstructions, grassland |
| 2 | 0.26 | Rolling or level surface broken by numerous obstructions such as trees or small buildings |
| 3 | 0.34 | Heterogenous surfaces with structures larger than one storey |
| 4 | 0.36 | Heavily built up suburban area, typical of metropolitan area |

Source: (Akins 1976, p116)

Akins presented his data generally in terms of local pressure coefficients that is, based upon the velocity at the height of the measurement location. This local pressure coefficient had the advantage of being independent of boundary layer and height of building. Local pressure coefficients $C_{Pmean}$ are reported averaged for different aspect ratios and boundary layers over a surface grid. Data are presented for wind approach angles 0,20,40,70 and 90 degrees (Akins 1976 p254-260).

The local pressure coefficients reported by Akins may be transformed to a pressure coefficient related to the approach wind speed at the height of the building (flat roof level) by the power-law expression Eq (10) (Grosso 1992). Note the exponent term is the same as the *b* term in Eq (9) above.

$$\frac{v(z)}{v(z_{ref})} = \left\{\frac{z}{z\,ref}\right\}^{b} \tag{10}$$

From this expression the surface pressure coefficient *Cp* at a location with reference wind velocity at $z_{ref}$ (local wind speed at height *h*) and velocity profile exponent *b*, may be transformed to a new value *Cp'* referenced to $z'_{ref}$ (height of structure H). Where the transformation applies to different heights this reduces to,

$$Cp' = Cp\left\{\left(\frac{h}{H}\right)^{b}\right\}^{2} \tag{11}$$

Eq (11) is used to convert Akins local pressure coefficients to pressure coefficients at roof level as adopted by Sherman in the LBL infiltration model.

## ‘FIRST PRINCIPLES’ MODEL

For a single zone with several openings, each with area $A_i$, the flow rate at opening *i* is given by

$$Q_i = C_d A_i v \frac{\left(c_{pi} - c_{pI}\right)}{\left|c_{pi} - c_{pI}\right|^{1/2}}\,, \tag{12}$$

where *v* is the wind speed at the reference height, $c_{pi}$ is the appropriate external pressure coefficient at opening *i*, and $c_{pI}$ is the unknown internal pressure coefficient, given by

$$c_{pI} = \frac{2p_I}{\rho v^2} \tag{13}$$

where $p_I$ is the internal pressure. A positive value of $Q_i$ indicates inflow. The total flow $Q_w$ is obtained by summing all positive values of $Q_{i.}$. Thus

$$Q_w = C_d v \sum_{positive} A_i \left|c_{pi} - c_{pI}\right|^{1/2}. \tag{14}$$

The wind speed at a reference height *H* is related to the wind tower speed *v*' by

$$v = a\left(\frac{H}{10}\right)^{b} v'. \tag{15}$$

assuming the tower is 10 m high. Therefore

$$Q_w = C_d\, a\left(\frac{H}{10}\right)^{b} v' \sum_{positive} A_i \left|c_{pi} - c_{pI}\right|^{1/2}, \tag{16}$$

Equation (16) can now be directly compared with Eq (9). Thus the shielding coefficient implied by Eq (16) is given by

$$C' = \sum_{positive} \frac{A_i \left|c_{pi} - c_{pI}\right|^{1/2}}{\varepsilon P}. \tag{17}$$

A value of *C'* according to Eq (17) averaged over a range of side ratios and wind directions may be calculated and compare with Sherman’s results.

## CONFIRMATION OF SHERMAN RESULTS

Sherman (1980 p185) explains his method for calculating the ‘Generalised Shielding Coefficient’. While explanations of this coefficient are given above, essentially they represent the internal pressure coefficient to produce a balanced mass flow, averaged over all wind directions (0-180deg) and side ratios in the range 1.0, 0.5 and 0.25. Each coefficient corresponds to a particular velocity profile (or boundary layer). While at the time Sherman may have struggled to perform the necessary calculations, an Excel spreadsheet can easily be set up to carry out the many computations, using the original Akins data. For R in the range 0 to 0.5 and boundary layer 1 (*b*=0.12) the relationship C’’= 0.331 $(1\text{-R})^{0.3324}$ may be derived. When this is linearised using the exponent 1/3 we get C’’= 0.327$(1\text{-R})^{1/3}$ which closely matches Sherman’s value. The maximum introduced error is 6% with a correlation $R^2$=0.9.

While Sherman calculated the Shielding Coefficients for Classes II to V as described above, it appears these may also be calculated directly for each shielding class by “scaling” the pressure coefficient to account for the terrain constant *a* relative to Class I. Equation (18) gives the “scaled” pressure coefficient.

$$Cp' = Cp\left\{\frac{a'}{a}\left(\frac{h}{H}\right)^{b}\right\}^{2} \qquad (18)$$

where
*a* is the terrain constant in Class I, equal to 1.3
*a’* is the terrain constant in the appropriate class, see Table 2.

Table 5 shows the calculated Shielding coefficients, which may be compared with the Sherman results in Table 3.

**Table 5:** Shielding Coefficients Directly Calculated

| Shielding Class (Boundary Layer) | $C''$ |
|---|---|
| I | 0.327 |
| II | 0.240 |
| III | 0.196 |
| IV | 0.142 |
| V | 0.095 |

As a digression, calculating shielding class I employing the Swami and Chandra low-rise version of their formulation to determine the pressure on building faces with $C_p$ at zero incidence derived from the Akins data of 0.76 and using Eq (17) summed over the range of wind directions and aspect ratios, yields *C’*=0.322. (Swami and Chandra 1988)

## LBL MODEL APPLIED TO SUB-FLOOR VENTILATION

The previous section shows that with a reasonable degree of accuracy the Sherman Shielding Coefficient for Boundary Layer I can be replicated. However, it is clear from Sherman (1980) that the method used by ISO to derive the sub-floor ventilation rates via the Sherman expressions is not correct. There appear to be three errors or misconceptions in ISO’s application of Sherman’s model to air flow through sub-floor vents.

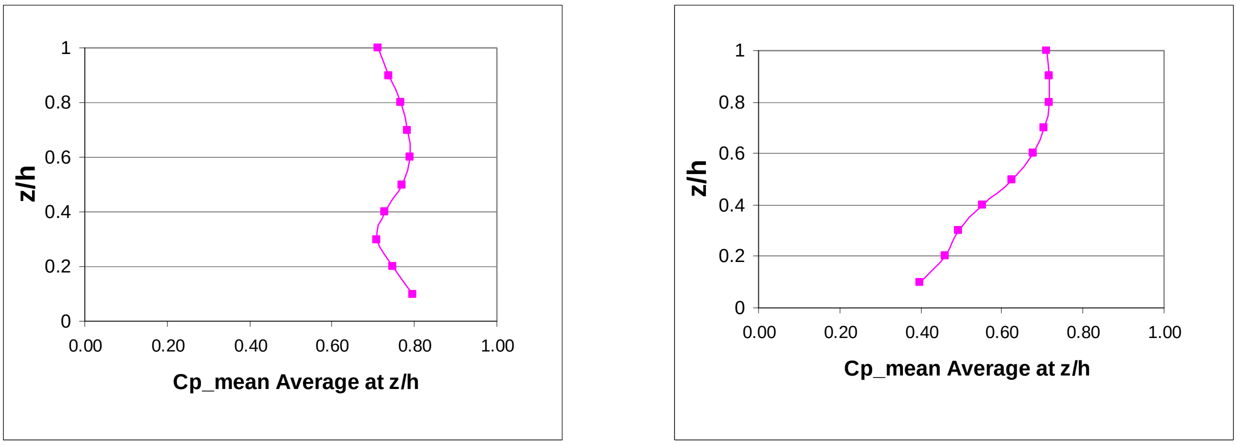
1) Because Sherman was developing a model for infiltration in rooms, the pressure coefficients used by him (taken from Akins) to derive his shielding factors *C’* are average pressure coefficients over the wall surface, and it is uncertain how such surface-averaged pressure coefficients relate to pressure coefficients towards the bottom of a wall where vents are located. Examining Figures 2 and 3 below we might suspect the latter are lower but the combined effect over the range of wind directions and side ratios is less clear.
2) The pressure coefficients used in the Sherman formulation are referenced to wind at the ceiling height of the building. That is, in the expression $f_w = C' a(H/10)^b$ , *H* should therefore be the ceiling height of the building (or more correctly the building height assuming a flat roof) and not the vent height. This has been confirmed by Sherman who said “The pressures on each face are induced by the house/crawlspace together--so the right height to use is the height of the house not the height of crawlspace.” (personal correspondence May 2005). Therefore accepting Sherman’s Generalised Shielding Coefficients but correcting for the roof level as the correct reference height the Wind Shielding Factors should be as shown in Table 6.

**Table 6. ‘Wind Shielding Factors’ for sub-floor vent calculations**

| **Location** | **Example** | $f_w$ |
|---|---|---|
| Sheltered | City Centre | 0.03 |
| Average | Suburban | 0.10 |
| Exposed | Rural | 0.16 |

3) The discharge coefficient employed in the ISO formulation, that is 0.59, approximates to that of a square edged orifice and is unlikely to represent realistic flow through a sub-floor ventilator. Possible blockages by

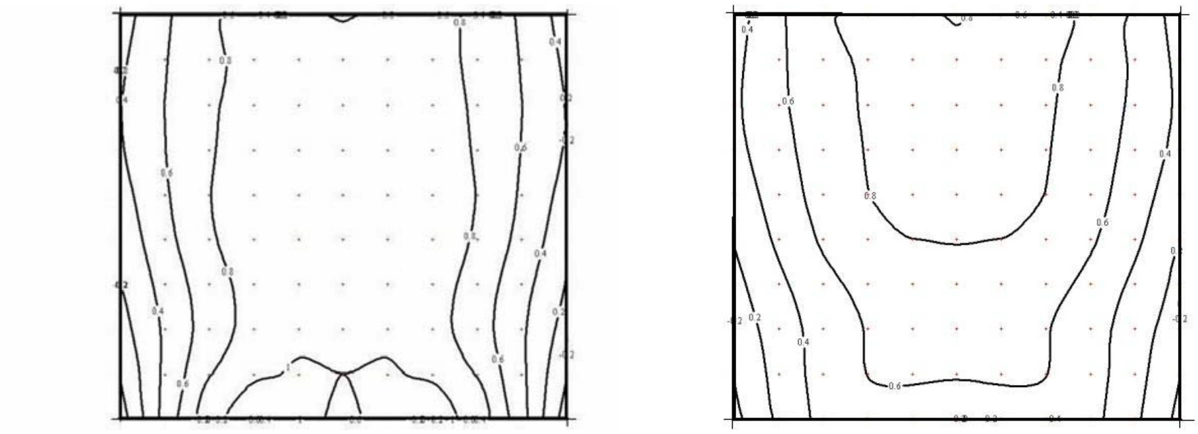
debris, spider webs, etc should be taken into account. In an attempt to account for sub-floor vents that may become partially blocked over time the standard discharge coefficient of 0.6 is multiplied by 0.7.



Wind Angle 0deg, Side Ratio 1:1, Terrain Class I (*b*=0.10). Wall Averaged Cp=0.76, At vent height h=0.1H, Cp=0.80

Wind Angle 0deg, Side Ratio 1:1, Terrain Class IV (*b*=0.25). Wall Averaged Cp=0.60, At vent height h=0.1H, Cp=0.40

**Figure 2**: Average Pressure Coefficients at Height z/h (Referenced to Wind Speed at Height of Building) Source of data: Akins (1976)



Wind Angle 0deg, Side Ratio 1:1, Terrain Class I

Wind Angle 0deg, Side Ratio 1:1, Terrain Class IV

**Figure 3**: Pressure Coefficient Contours (Referenced to Wind Speed at Height of Building) Source of data: Akins (1976)

Applying the same method for calculating the Shielding Coefficients for average wind pressure over the whole surface we may calculate the Shielding Coefficients that apply in the region of the sub-floor ventilators. For example, if the height of the building is nominally 3m and the sub-floor vents are at 300mm, then the appropriate height would be 0.1H. Table 7 shows vent height Generalised Shielding Coefficients, where the $\overline{C}'$ values for shielding classes II-V are scaled using Sherman's explanation above (see text after Table 3), and the $\overline{C}''$ values are directly calculated.

**Table 7:** Generalised Shielding Coefficients at Vent Height h=0.1H, R=0

| Shielding Class (Boundary Layer) | $\overline{C}'$ | $\overline{C}''$ |
|---|---|---|
| I | 0.359 | 0.359 |
| II | 0.316 | 0.246 |
| III | 0.266 | 0.192 |
| IV | 0.205 | 0.128 |
| V | 0.113 | 0.073 |

Combining these coefficients with wind speed calculated at a height of 3m corresponding to the eaves height of the building then the new Windspeed Shielding Factors, calculated as ISO 13370 with the following coupled terrain and shielding combinations, Sheltered: T5/V, Average: T4/IV, Exposed: T3/III are shown in Table 8.

**Table 8: New ‘Wind Shielding Factors’ for sub-floor vent calculations**

| Location | Example | $\bar{f}'_w$ | $\bar{f}''_w$ |
|---|---|---|---|
| Sheltered | City Centre | 0.03 | 0.02 |
| Average | Suburban | 0.10 | 0.06 |
| Exposed | Rural | 0.18 | 0.13 |

These values would be used in conjunction with either Eq (4) where “maximum” ventilation rates are important or Eq (19) if blockage of vents were to be taken into account.

$$U_v = \frac{1033\varepsilon v' \bar{f}'_w}{B'} \tag{19}$$

(Note : Eq (19) is determined as Eq (4) but taking $C_d$ = 0.6 and a blockage factor = 0.7)

## CONCLUSIONS

This paper has examined the ventilation component inherent in the ISO 13370 methodology for calculating the overall R-value of a suspended floor. The ventilation component based on Sherman’s LBL infiltration method is shown to have at least three shortcomings when applied to estimating ventilation in sub-floor spaces.

The suspended floor R-value for a standard construction calculated with “correct” formulation can be up to 15% lower compared with the value calculated when adopting the ISO 13370 numbers. This has significant implications when regulatory authorities set minimum construction specifications.

The nature of science is concerned with objective knowledge and describing this knowledge in terms of laws and theories, but often the way in which the results are applied receives little attention. The principle of evidence-based regulation applied in the building/construction realm demands that scientific models such as the ISO 13370 ventilation model are validated by full scale case-studies against stated objectives. While this principle continues to be ignored design decision-making informed by building science will be the poorer.

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