Multiple-layer bedding materials and the effect of air spaces on 'wet' thermal resistance of dry materials

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Abstract

Variables affecting the 'wet' thermal resistance of infant bedding materials arranged to simulate use are identified. Thermal resistance was determined when the materials were flat, and also when spaced to simulate use, using a guarded-hotplate similar to that specified in ISO11092:1993(E). The relationship between 'wet' thermal resistance and thickness is explored, and the effects of increasing thickness of the air space under and among the various layers of bedding were determined.

Keywords: 'wet' thermal resistance, bedding, multiple layers, air spaces, SIDS

Introduction

Many studies investigating Sudden Infant Death Syndrome (SIDS) focus on issues of infant clothing and bedding. This is not surprising given the diversity of products involved, and the number of infants who died from SIDS who have been reported "hot and sweaty" and/or who have had elevated rectal temperatures (Nelson and Taylor, 1989; Wailoo, et al., 1990). Models used to describe thermal resistance of bedding were developed using adults rather than the much smaller infant. For example, the thickness and tog values of representative bedding items have been used extensively as a means of estimating 'dry' thermal resistance of infant bedding during use (Bolton, et al., 1996; Fleming, et al., 1990; Ponsonby, et al., 1992; Tuohy and Tuohy, 1990; Williams, et al., 1996). Use of representative tog and thickness values has been based principally on the relationship between thickness and 'dry' thermal resistance measured in flat assemblies with relatively small air spaces (Holcombe and Hoschke, 1983; Peirce and Rees, 1946). The effect of layering textiles (with the consequential inclusion of air spaces between the various layers) has also been examined in terms of 'dry' thermal resistance showing increased 'dry' thermal resistance over and above that of the products themselves

(Fonseca, 1970; Fonseca and Breckenridge, 1965; Hassenboehler and Vigo, 1982). (Air spaces investigated were generally small (0.2-6.3 mm).)

The 'dry' thermal resistance of larger air spaces has been reported by Wilson, et al., (1999a) and Fujimoto, et al., (1989) (up to 120 mm and 'atmosphere' respectively), using a method which allowed the maximum 'dry' thermal resistance of textile/air bedding composites to be estimated (Wilson, et al., 1999a). Alternative statistical models for estimating i) minimal 'dry' thermal resistance of bedding, i.e. that immediately over an infant's body, where minimal air spaces are formed and ii) resistance of bedding with air spaces between were developed (Wilson, et al., 1999a; Wilson, et al., 1999b). However, these approaches ignore the contributory effect of 'wet' thermal resistance of bedding on total heat loss from infants, that is, resistance of a dry assembly to heat transfer via water vapour transfer ($m^2 kPa/W$) (International Organization for Standardization, 1993). Thus it is unlikely risk of SIDS due to inappropriate insulation over-insulation has been assessed adequately.

Under hot conditions, i.e. those associated with mean skin temperatures greater than 35°C in adults and 36.5 to 37°C in infants, evaporation of sensible water is one of the most effective

mechanisms of heat transfer with 2.43 kJ (0.58 kcal) of energy (known as the latent heat of evaporation) lost per gram of water evaporated (Astrnd and Rodahl, 1986; Brck, 1961). Even when not under thermal stress, evaporative heat loss accounts for approximately 25% of total heat loss in adults with losses up to a maximum of approximately 670 W/hr. possible. In infants, other variables such as maturation of the sweating mechanism, the ability to control heat transfer (both of which affect thermoregulatory efficiency) depend on gestational age. However, evaporative heat transfer remains an important mode of heat loss in infants. For a 3 kg baby heat loss from non-respiratory water sources of 86 W/hr has been estimated, with losses of up to 330 W/hr occurring in mildly hyperthermic babies (Hey and Katz, 1970). Thus failure to consider the effect of 'wet' thermal resistance of bedding is likely to have resulted in underestimation of actual heat loss, with the magnitude of such underestimates not necessarily being the same for all combinations of bedding.

There have been fewer investigations into the relationship between 'wet' thermal resistance and the thickness of material and air space composites than those reported for 'dry' thermal resistance. 'Wet' thermal resistance of air spaces up to 14 mm, 20 mm, 25 mm, and water vapour transport through air spaces ranging from 4 to 35 mm respectively have been evaluated (Gretton, et al., 1998; Ruckman, 1997; Spencer-Smith, 1977; Woo, et al., 1994). However, very little is known about the relationship between the thickness of air spaces and 'wet' thermal resistance of clothing and materials arranged to simulate that which occurs during use. The effect of the thickness of the various air layers on 'wet' thermal resistance continues to be of interest, particularly in bedding, and requires clarification.

The purposes of this study were i) to assess the appropriateness of using thickness of single-layer materials measured flat and the thickness of air spaces formed during use to predict 'wet' thermal resistance of flat multiple-layer materials and to identify those variables (and interactions among variables) which affect 'wet' thermal resistance of bedding spaced to simulate use, ii) to determine the effect of the size and distribution of air layers on 'wet' thermal resistance of selected bedding combinations, and iii) to develop a method for estimating 'wet' thermal resistance of multiple layer bedding combinations during use.

Methods

Materials investigated were those commonly used to clothe and wrap New Zealand infants (Wilson, 1992; Wilson, et al., 1994). Bedding combinations were identical to those previously used to determine thickness and 'dry' thermal resistance of commonly used bedding combinations results of which are reported elsewhere (Wilson, et al., 1999a; Wilson, et al., 1999b). Items were:

- i cotton *sheet*, plain weave, napped, 18.8 x 16.6 yarns/cm, 2.5 mm thick, 0.09 m²K/W;
- ii wool *blanket*, cellular or 'air-cell' (leno weave), 5.2 x 4.0 yarns/cm, 6.0 mm thick, 0.14 m²K/W;
- iii wool *blanket*, herringbone (twill) weave, napped, 8.0 x 9.3 yarns/cm, 6.7 mm thick, 0.18 m²K/W;
- iv panel quilt or *duvet* (bulked polyester filling) polyester/cotton, plain weave cover, 32.8 x 19.5 yarns/cm, 34.8 mm thick, 0.79 m²K/W.

'Wet' thermal resistance of single-layer, and four multiple-layer bedding combinations was determined when specimens were arranged flat. Multiple-layer combinations were spaced to simulate the arrangement in use either with no spaces between or with spaces between as occurs during use (Wilson, et al., 1999b). Combinations represented the lightest, typical (two), and heaviest bedding combinations used by New Zealand care givers to cover infants (Table 1 a) (Wilson, 1992; Wilson, et al., 1994).

A randomised two replicate factorial design was used and factors and levels investigated (including those previously shown to affect thickness and distribution of bedding and air spaces through the bedding during use are described in Table 1 b-d. (Distribution refers to the patterns of proportion of textile and air vertically through the bedding.) Tucking arrangements have been depicted in Wilson, et al., (1999a). Air space thickness represented that occurring at two sites (100 mm and 450 mm) chosen to represent the arrangement of bedding immediately adjacent to the body during use and found to be most sensitive to effects of tucking and manikin position on the bedding (Figure 1). The total thickness of air layers at site 100 mm ranged from 35-55 mm, and at site 450 mm from 55-120 mm. Thickness of the individual air layers ranged from 10-105, 5-15, 5-15 and 5-40 mm for the first to fourth spaces respectively

(Table 2), with the air layers distribution through the bedding also given. Where the combination involved more than four textile layers (e.g. sheet plus nine 'air-cell' blankets), subsequent layers were stacked with minimal air spacing.

A modified version of the sweating-guarded-hotplate specified in ISO 11092:1993 was used to measure 'wet' thermal resistance of dry materials under steady-state environmental conditions i.e. all specimens ($n=2$) were conditioned for twenty-four hours at $35 \pm 2^\circ\text{C}$ and $50 \pm 2\%$ R.H. and were measured under these conditions (International Organization for Standardization, 1993). The diameter of the measuring unit of the hotplate and specimens were 250 mm, and the dry guard was 97 mm wide. The total hotplate diameter was 485 mm. The reservoir under the measuring unit's porous plate was filled with de-oxygenated milli Q™ (re-distilled deionised water) to avoid formation of bubbles in the water dosing device. The sintered plate was covered with a support grid and a layer of NFPA thermal resistance reference material to prevent water coming into contact with the test specimen(s) (National Fire Protection Association, 1990). Thus the 'wet' thermal resistance (R_{et}) of dry specimens was determined.

The specimen was placed inside a ring arrangement similar to that described by Wilson, et al., (1999a). In the absence of a sweating guard, a second inner water-impermeable ring (250 mm diameter) the same height as the outer ring was used to enclose the measuring unit, thus ensuring all water vapour was forced up through the specimen(s). Spacers, the diameter (approximately 248 mm) such that they could be slipped inside the inner impermeable ring, were also used to provide for air spaces of various specified thicknesses between bedding layers. This arrangement ensured that the conditioned air, which flowed through the housing at 1.18 m/s, flowed across and parallel to the upper surface throughout the test period. Air flow 15 mm above the uncovered measuring unit was measured at the beginning and end of each test sequence using a hot wire anemometer (Wilson, et al., 1999a).

Specimens were positioned flat on the measuring unit with bubbles and/or wrinkles, which were not an inherent characteristics of the material, eliminated. Where the materials exhibited a 'face' which would normally lie uppermost (e.g. the duvet), they were placed face

up. The upper-most surface of the test specimen(s) was exposed to the ambient air (conditioned as previously described) for the duration of the investigation. Specimens were arranged so the warp yarns were parallel to the direction of airflow, and combinations were stacked in the order in which they were most likely to be used (i.e. the sheet was placed against the plate (skin)).

Energy was supplied to the plate in discrete regulated pulses initiated by the temperature controller. The energy pulses at equilibrium were used to determine the rate of average energy input (W) over the duration of the test. Equilibrium was identified as the time when the rate of energy required to maintain the measuring unit at $35 \pm 0.1^\circ\text{C}$ changed by less than 3% per hour (calculated over 30-minute time periods) (National Fire Protection Association, 1990). (Materials typically reached equilibrium within 2 hours.) The plate was calibrated using standard materials of known 'wet' thermal resistance as specified in Appendix B of the National Fire Fighters Protection Association (NFPA) (1990) standard. The plate was pre-heated and run at equilibrium for 18 hours prior to testing.

The guard width and experimental set-up were such that textile and air combinations of up to 166 mm could be measured free from edge losses (International Organization for Standardization, 1993), and this was confirmed using up to seven layers of 29 mm thick bulked polyester (total thickness approximately 194 mm). Any departure from linearity in the relationship between measured resistance and thickness of the bulked polyester indicates edge losses are occurring. A calibration check was carried out every tenth test run.

The 'wet' thermal resistance of each bedding specimen, and bedding and air combination, was

where

$$R_{et} = \frac{(P_m - P_a)A}{H - \left(\frac{T_m - T_a}{R_{ct}} \right)} - R_{et0}$$

$$T_m = T_a \quad \text{then} \quad R_{et} = \frac{(P_m - P_a)A}{H} - R_{et0}$$

and

$$R_{et0} = \frac{(P_m - P_a)A}{H}$$

where:

- A = area of the measuring unit (m^2)
 H = the heating power supplied to the measuring unit (W)
 P_a = water-vapour partial pressure (kPa) of the air in the test enclosure at temperature T_a
 P_m = saturation water-vapour partial pressure (kPa) at the surface of the measuring unit at T_m
 R_{ct} = 'dry', thermal resistance excluding resistance of the adhering air layer ($\text{m}^2\text{K/W}$)
 R_{et} = 'wet', water vapour resistance excluding resistance of the adhering air layer ($\text{m}^2\text{kPa/W}$)
 R_{et0} = bare plate 'wet' thermal resistance ($\text{m}^2\text{kPa/W}$)
 T_a = air temperature in the test enclosure ($^{\circ}\text{C}$)
 T_m = temperature at the surface of the measuring unit ($^{\circ}\text{C}$)

(National Fire Protection Association, 1990).

Statistical analysis

Descriptive statistics were determined for all data. Differences in 'wet' thermal resistance among the various specimens were identified using univariate ANOVA and Tukey's multiple comparison tests to identify where differences among means occurred (Hair, et al., 1987). The thermal resistance of single- and multiple-layer assemblies were described statistically using regression analysis and curve estimation.

Results

'Wet' thermal resistance of specimens ranged from 0.01 to 0.06 $\text{m}^2\text{kPa/W}$ respectively for single-layer specimens and from 0.01 to 0.06 $\text{m}^2\text{kPa/W}$ for multiple-layer assemblies with minimal air spaces between. The main difference among single-layer specimens was between the duvet and the other fabric structures ($F_{3,4}=291.67$, $p<0.001$) (Figure 2 a). As the number of layers increased, 'wet' thermal resistance increased, and was greater in combinations including twill than those including air-cell blankets.

For multiple-layer combinations 'wet' thermal resistance, as expected, generally increased as mean total thickness of the bedding and air layer increased up to a point (approximately 100 mm), beyond which increasing the thickness of air space did not result in further increases (Figure 2 b).

Resistance was generally greater for specimens arranged with thicker air spaces (i.e. site 450 mm; $F_{1,67}=6.89$, $p<0.05$) irrespective of the distribution of the air space within the combinations. Type of bedding present in the combination, method of tucking and sleep position also affected 'wet' thermal resistance ($F_{3,67}=286.62$, $p<0.001$; $F_{1,67}=12.26$, $p<0.001$; $F_{2,67}=5.75$, $p<0.01$), as well as interactions between measurement site and sleep position ($F_{3,67}=12.26$, $p<0.001$) (Table 2).

Estimating resistance based on thickness

The 'wet' thermal resistance of bedding, with minimal air spaces between and that spaced to simulate their arrangement during use, can be predicted using the actual or estimated thickness of the textiles (with an adjustment made for the presence of a duvet) and that of each of the air layers. 'Wet' thermal resistance (R_{et}) of flat multiple-layer combinations with minimal air spaces between was described statistically as:

$$R_{et(\text{if no duvet present})} = 0.001 + 0.002d$$

$$R_{et(\text{if duvet present})} = -0.007 + 0.001d$$

$$(F_{2,11}=332.67, p<0.001), \text{ and}$$

$$R_{et} = 9.05 \times 10^{-4} + 0.002d_{est} - (0.068_{\text{if duvet present}})$$

$$(F_{2,7}=3587.61, p<0.001).$$

where d = cumulative thickness of the textile layers (mm) and d_{est} = thickness of textile layers estimated by adding single layer thickness (mm). Each description was equally effective for predicting 'wet' thermal resistance and accounted for 98% of the variance in all cases. Results confirmed the gross physical structure (i.e. duvet or other) of the bedding significantly affected 'wet' thermal resistance.

The best description of 'wet' thermal resistance of bedding arranged on the hotplate to simulate the textile and air spacing formed immediately adjacent to the manikin, was:

$$R_{et} = 0.024 + 0.0010d - 0.0002d_{a1} + 0.0018d_{a2} - (0.0346_{\text{if a duvet is present}})$$

$$(F_{6,89} = 65.03, p<0.001),$$

Table 1 Experimental design — factors, levels, and their description

Factors	Level	Description
a	Bedding combinations	
	1	Lightest (sheet)
	2	Typical (sheet and 2 blankets)
	3	Typical (sheet, 2 blankets and a duvet)
	4	Heaviest (sheet and 9 blankets)
b	Site	
	1	Stacked and spaced adjacent to body at site 100 mm
	2	Stacked and spaced adjacent to body at site 450 mm
c	Manikin position	
	1	Lateral
	2	Prone
	3	Supine
d	Tucking	
	1	Loose
	2	Firm (including swaddled)

Table 2 'Wet' thermal resistance and thickness of bedding and air spaces under various conditions

		Ret (m ² kPa/W)		Thickness (mm)					
		$\bar{X}$	s.d	Total (d+da)	da	Air spaces			
						d1	d2	d3	d4
a	Sleep positions								
	Lateral	0.06	0.02	90.6	67.9	56.4	5.0	2.5	14.1
	Prone	0.06	0.02	76.1	48.1	43.8	2.5	2.5	1.3
	Supine	0.06	0.02	71.8	43.8	32.5	10.0	5.0	0.0
b	Bedding combinations								
	S	0.03	0	47.4	45.4	45.4			
	SAA	0.06	0.01	64.6	54.6	45.4	5.8	3.3	
	SAAD	0.08	0.01	114.0	49.0	37.5	6.0	3.5	2
	S + 9A	0.08	0.02	95.8	60.8	45.4	5.8	3.3	6.3
c	Tucking								
	Loose	0.06	0.02	74.4	48.0	32.8	10.0	5.8	12.0
	Firm/swaddled	0.06	0.02	86.6	57.2	54.4	1.7	0.8	4.4
d	Measurement sites								
	100 mm	0.06	0.02	66.8	38.8	30.0	5.8	4.2	2.5
	450 mm	0.06	0.02	92.4	67.7	58.6	5.9	2.5	6.5
e	Measurement sites and sleep positions								
	100 mm Lateral	0.06	0.02	72.4	44.4	35.0	5.0	2.5	7.5
	Prone	0.06	0.02	64.3	36.3	32.5	2.5	2.5	0.0
	Supine	0.06	0.02	63.6	35.6	22.5	10.0	7.5	0.0
	450 mm Lateral	0.07	0.03	114.8	99.2	85.0	5.0	2.5	27.5
	Prone	0.06	0.02	88.0	60.0	55.0	2.5	2.5	2.5
	Supine	0.06	0.02	79.9	51.9	42.5	10.0	2.5	0.0

F/Sw = Firm/swaddled d = thickness of the textile material(s), da = thickness of the air space(s), 0.00 represents s.d. with true value < 0.005

Figure 1 Profiles of loosely tucked bedding in three manikin positions (Wilson, et al., 1999)

b Mean thermal resistance of bedding assemblies at i) both sites and ii) at sites 100 and 450 mm

Both Sites		Site 100		Site 450	
■	S	□	S	▣	S
▲	SAA	△	SAA	▽	SAA
●	SAAD	○	SAAD	⊕	SAAD
⊕	S9A	⊕	S9A	⊕	S9A

c Relationship between 'wet' thermal resistance and thickness of the sheet and air layer

Figure 2 'Wet' thermal resistance of bedding combinations

accounting for 75% of the variance. Where d_{an} = thickness of air layers, $n=1-2$ (mm). Describing 'wet' thermal resistance of bedding (arranged on the hotplate to simulate the textile and air spacing formed immediately adjacent to the manikin) using total thickness of the combination (i.e. cumulative thickness of the bedding plus air) accounted for only 42% of the variance present in the data ($F_{1,90} = 65.15$, $p \leq 0.001$) (which was only marginally better described using bedding and air space thickness (47%)).

Effect of the first air layer on resistance

The 'wet' thermal resistance of the sheet over a layer of air of varying thickness (10 to 105 mm) was measured to determine the effect of increasing the thickness of the air space (Figure 2 c). 'Wet' thermal resistance of the sheet and air combination of bedding (simulating the arrangement formed immediately adjacent to the manikin) was described statistically as follows

$$R_{et} = 0.021 - 0.000141d_{a1}$$

$$(F_{1,22} = 45.50, p \leq 0.001).$$

accounting for 67% of the variance. Results suggested that as the thickness of the first air layer increased, the contribution of the air space to 'wet' thermal resistance decreased. However, visual examination of the distribution of the means of 'wet' thermal resistance (Figure 2 c) suggested that the relationship between 'wet' thermal resistance and total thickness of the combination may be non-linear. Adding a quadratic term to the analysis did not improve the description ($t_{21} = -1.57$, NS) when all data were included in the analysis. Yet examination of the actual and predicted curves, suggested that this linear description of 'wet' thermal resistance was not necessarily an ideal one. 'Power' and log-based descriptions were found to best describe the relationship between 'wet' thermal resistance and thickness of the air space under the sheet, describing 78% and 77% of the variance respectively. For the range of data reported in this paper the 'power' solution best described the non-linear relationship between thickness and thermal resistance. 'Wet' thermal resistance of the first air space was thus described as

$$R_{et} = 0.0111d_{a1}^{0.2411}$$

$$(F_{1,22} = 79.67, p \leq 0.001).$$

Discussion

Increasing 'wet' thermal resistance with increasing total thickness (i.e. that of the textile and air layer) is consistent with the generally accepted relationship between thickness of textile materials and their 'dry' thermal resistance (Figure 2 a) (Holcombe, 1984; Holcombe and Hoschke, 1983; Peirce and Rees, 1946). Results from the present study suggest total thickness was a better predictor of 'wet' thermal resistance of the bedding system than of 'dry' thermal resistance (Wilson, et al., 1999a). The size and way in which air spaces were distributed in each type of bedding combination was also shown to affect 'wet' thermal resistance. However, the effect was less for 'wet' than for 'dry' thermal resistance (Wilson, et al., 1999a).

'Wet' thermal resistance increased with increasing thickness of the air layer to a point beyond which any further increase in the thickness of the air space did not increase resistance. This finding is consistent with that of Ruckman (1997) who suggested a critical air space dimension of 15 mm above which any further increase resulted in only minimal decrease in water vapour transfer rate. Additionally increasing the thickness of air spaces beyond a critical thickness has been shown to apparently reduce the thermal resistance of assemblies (Wilson, et al., 1999a) possibly by increasing losses by convection (in air spaces greater than 13 mm) (Cain and Farnworth, 1986; Fowle, 1933) or in the case of assemblies with openings, by increasing the potential for convective losses (Kerslake, 1991).

Results of the present work show that (as with 'dry' thermal resistance) the separate contributions of the air and textile components need to be considered when predicting 'wet' thermal resistance. Separating thickness of the textile and that of each air space (and adjusting for the effect of a duvet when present) allows each component to be weighted in the description according to its contribution to resistance. However, the distribution of the air spaces through the combination while still important, was less critical for 'wet' thermal resistance than the presence of air spaces and the total thickness of each combination. The importance of total thickness and the presence of air spaces is consistent with the suggestion that water vapour is transferred through the voids between the various parts of the assembly and in the case of

non-wovens, through open air spaces and along curved channels in the fabric structure (Wang and Yasuda, 1991; Whelan, et al., 1955; Woo, et al., 1994).

Addition of a product classification (i.e. data categorised according to whether combinations included or excluded a duvet) meant that the relationship between thermal resistance and thickness did hold true for all multiple-layer combinations. The gross effect of product type probably reflected air trapping between the various parts of and/or under the duvet. Including a duvet in the bedding combination changed the relationship between textile thickness and thermal resistance. Because of its thickness, the duvet increased thermal resistance overall. However, the 'wet' thermal resistance of the duvet was *less* per unit thickness than that of other bedding materials, a finding consistent with the observations on 'dry' thermal resistance (Wilson, et al., 1999a). The difference in relationship between thermal resistance of the duvet and thickness was possibly due to the absence of many small air layers which are trapped between bedding layers of comparable thickness but which excluded a duvet.

The type of bedding, site of measurement, tucking method and sleep position all affected the thickness and distribution of air spaces throughout the bedding. However, these effects were relatively more important influences of 'dry' than 'wet' thermal resistance (Wilson, et al., 1999a). Differences in 'wet' thermal resistance among sleep positions and bedding combinations were small and did not appear to be related to the distribution of air spaces between the various layers of the combination.

By examining the 'wet' thermal resistance of the 'sheet' only, the effect of air layer thickness was evaluated. 'Wet' thermal resistance increased with thickness of the air space up to a critical thickness of approximately 40 mm and was thus not linearly associated with the thickness of air spaces, thereafter, increasing air space thickness was associated with only small increases in 'wet' thermal resistance. This trend was greater than but consistent with that proposed by Ruckman (1997) whose critical value was 15 mm, and Spencer-Smith (1977) who identified a non-linear relationship between thermal resistance and air spaces up to 20 mm thick but did not define a critical value.

Conclusions

There are four conclusions from this investigation.

Firstly, variables affecting 'wet' thermal resistance are similar to those affecting thickness and 'dry' thermal resistance. There is a need to distinguish between i) those bedding assemblies which include a duvet from those which do not and, ii) the effects of the textile and the air layers.

Secondly, body position and tucking method (that is whether loosely or firmly tucked or swaddled) significantly affected thickness and 'wet' thermal resistance of the assembly due to the formation of air layers between material layers.

Thirdly, 'wet' thermal resistance of bedding increased as thickness of the bedding increased (as expected), but a critical thickness (i.e. total material and air thickness of approximately 40 mm) existed above which 'wet' thermal resistance tended to increase only marginally as thickness increased.

Fourthly, 'wet' thermal resistance immediately over the body (i.e. minimal air spaces) was estimated as follows:

$$R_{et \text{ over the body}} = 9.05 \times 10^{-4} + 0.002d_{est} - (0.068_{if \text{ duvet present}})$$

and the arrangement that occurs immediately adjacent to the body, can also be estimated from measurements of the thickness of flat single-layer specimens as:

$$R_{et \text{ immediately adjacent to the body}} = 0.024 + 0.0010d - 0.0002d_{a1} + 0.0018d_{a2} - (0.0346_{if \text{ a duvet is present}})$$

No attempt has been made to accommodate other variables such as the effect of the surface area available for heat loss which are known to affect thermal resistance and the model is based on a cross-sectional profile only.

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