A THERMAL PERFORMANCE STUDY OF COMMON AUSTRALIAN RESIDENTIAL CONSTRUCTION SYSTEMS IN HYPOTHETICAL MODULES

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SUMMARY

The software package AccuRate was used to perform a thermal performance study of common Australian construction systems in hypothetical modules.

INTRODUCTION:

Australia's harsh climate places a large demand on electricity for heating and cooling of buildings. Hence, a significant proportion of the electricity used in Australia is for space heating and cooling. Recent data indicates that space heating and cooling accounts for over 40% of total residential operational energy consumption (AGO 2004; CANA 2005). This has led to a growing concern about energy conservation and the sustainability of our living standards (CANA 2005). As a result, achieving better energy efficiency in buildings has become one of the major challenges faced by Australian builders and architects in recent years (Gregory 2007).

Most Australian dwellings are located in metropolitan and regional centres where, despite mild climatic conditions, there are significant diurnal (day to night temperature fluctuations) temperature swings (Wilkenfeld 1998). The importance of thermal mass in such situations cannot be overstated, as considerable benefits in thermal comfort and energy savings in mechanical heating and HVAC (Heating, Ventilating and Air-Conditioning) can be obtained through the smarter use of thermal mass (McKnight 2001). Thermal mass is a measure of the heat storage capacity of the material. It is a function of material density (ρ) and specific heat (C_p). When exposed to external heating, materials with high thermal mass (i.e. heavier and denser materials) can store more heat than their low thermal mass counterparts (Gregory 2007). Also, materials with high thermal mass will take longer to release their heat once the heat source is removed. Hence, it is possible for high mass buildings to suppress maximum indoor temperature (State Projects 1993).

By utilising the properties of thermal mass through the storage of solar energy received by the building during the day and then the gradually release of the energy overnight the diurnal temperature swings can be significantly reduce making the conditions within the building more comfortable. This type of design is known as the Passive Solar Design. In winter, thermal mass will store heat from solar radiation and heaters, gradually releasing over night keeping the building warm. While in summer the same thermal mass can

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absorb heat during the day keeping the building cool, and though the use of sufficient ventilation the heat can be remove overnight.

Whilst there are obvious merits in employing the passive solar design approach in Australia, there is a general lack of understanding about the thermal performance of high thermal mass construction materials in the variety of climate where the major population centres are located (Gregory 2007). In addition, much of the available data originates from studies on conventional Cavity Brick (CB) and Brick Veneer (BV) walling systems (Sugo (a) 2004; Sugo (b) 2004) without much attention being given to more innovative designs.

The present paper provides a comparative study of four different walling systems typically used in Australian residential buildings (Cavity Brick, CB, Brick Veneer, BV, Reverse Brick Veneer, RBV, Light Weight, LW, constructions), in terms of the influence of thermal mass. Comparisons were made using the AccuRate energy star rating tool developed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO).

THE MODEL – AccuRate RATING TOOL

AccuRate is an energy rating tool developed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). It is an indicator of the heat needed to be added or removed to keep the conditioned floor area of the building comfortable. AccuRate assigns a star rating to a residential building based on its calculated annual heating and cooling energy requirements (CSIRO 2004).

The software requires detailed information about the building such as orientation, construction type, insulation levels, window size, window orientation, shading, overshadowing, ventilation, etc (AGO 2005). The mathematical basis of the AccuRate software is the "Frequency Response" method in which the system (i.e. the building) inputs and outputs are viewed as being sinusoidal in time (Walsh 1983). The building is assumed to consist of a number of zones each comprised of elements, such as the floor, roof, ceiling, walls, windows, etc. Each building element is considered to be composed of a series of homogeneous (uniform in structure) layers, referred to as "slabs" (Walsh 1983). By combining the response of the individual slabs, the response of the building to a given input file can be determined. The input file is usually in the form of a weather data file, which is generally a year of data representing the climatic conditions of the specific location. The model calculated heating and cooling energy data on an hourly basis over a period of one year.

The output from the model is a simple report detailing the quantity of heating and cooling energy that would be required to maintain conditions within the building to the assigned comfort zone (Gregory 2007). A one-to-ten star rating is given to the building corresponding to the energy performance with ten stars given to the most efficient building design. In Newcastle, a star rating of ten indicates an energy consumption rate of 6 MJ/m^2 annum whereas a star rating of one denotes an energy consumption rate of 349 MJ/m^2 annum. Star ratings correspond to different energy consumption rate's depending upon the climate zone.

AccuRate is a second generation energy rating tool and has made many advances in modelling. The upgrade of the NatHERS software has seen improvements in natural

ventilation modelling, user-defined constructions, improved modelling of roof spaces, sub-floor spaces, skylights and horizontal reflective air gaps, and the availability of many more zones (Walsh 1983).

DETAILS OF BUILDING MODULES AND WALLING SYSTEMS

To keep the study relatively simple idealised building modules were used rather than complete houses. This allowed the direct comparison of various forms of wall construction without the complexities which would be present if a complete house was considered. The floor, roof and internal wall will have significant effect on the overall performance of a module, hence to minimise this effect they were kept constant throughout the study.

Each module was modelled on a 100 mm reinforced concrete slab-on-ground. Floor coverings, such as carpet, act like insulation and prevent the thermal mass of the slab to interact with the internal environment. Therefore, to keep the study simple and examine the effect of exposed thermal mass no floor coverings were modelled. The top surface of the floor slab was assumed to be dark in colour as dark surface have high absorptivity, and absorbs most of impinging solar radiation (Cheng 2005).

The roof construction was assumed to be from light coloured tiles with reflective foil underlay, at a pitch of 22 degrees with a plasterboard ceiling and R 3.5 m^2K/W glass insulation batts. Shading with a blocking factor decreasing to 25% during the winter months was assigned to the north window and all windows were weather stripped. Once again to keep the study simple, no indoor or outdoor shading was present on the east and west windows.

The four different building envelope types were considered (Figure 1):

- <u>Module A</u>: Module A is a rectangular shaped building 6 m x 4 m elongated in the east-west direction to maximise the amount of solar radiation on the module. The module consists of only the exterior walling systems under investigation and with no doors, internal walls or windows.
- <u>Module B</u>: The physical configuration of this module is based on Module A with an additional 5 m x 2 m single glazed 6.38 mm thick window on the north wall to examine the effects of windows.
- <u>Module C</u>: To maximise the effects of thermal lag the amount of heat storing material needs to increase as the area of north-facing glazing increases (BOM 2006), hence Module C has internal walls of bare brickwork panels 2.5 m long to examine the effect of additional thermal mass.
- <u>Module D</u>: Module D is a modified version of Module C in which single glazed (6.38 mm thick) windows with cross sectional areas of 1 m × 1m have been added to the east and west walls.

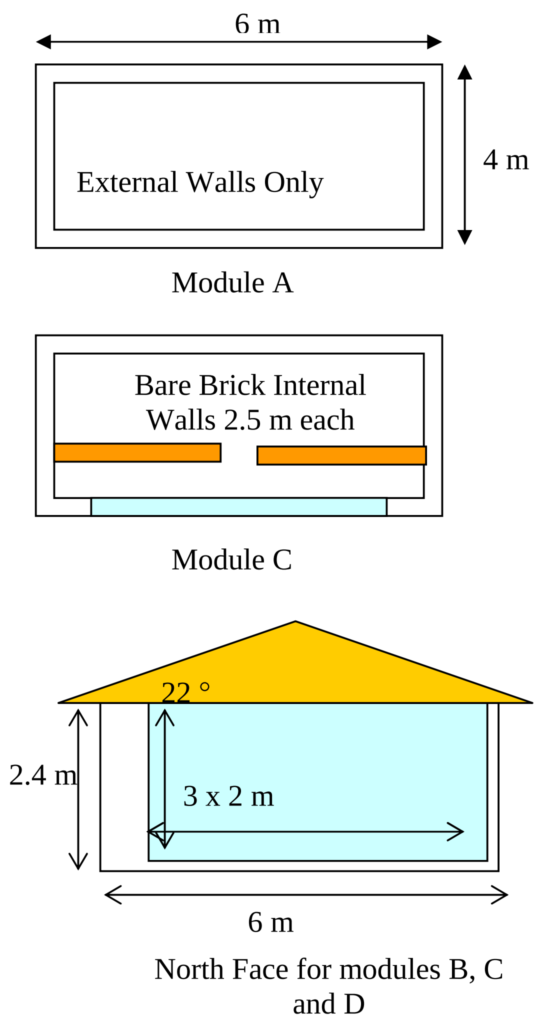

Figure 1: Top and side views of Modules

The thermal performance study was limited to four different constructions systems based on The University of Newcastle's thermal test buildings [11, 12]. These construction systems include those commonly used in the eastern states of Australia (CB, BV, and LW construction) together with an unconventional novel design (Reverse Brick Veneer, RBV). The systems descriptions are given internal to external:

- Brick Veneer: consists of plasterboard timber stud wall containing R 1.5 m^2K/W insulation batts, reflective foil and brickwork for weatherproofing
- Reverse Brick Veneer: internal brickwork, timber stud wall containing R 1.5 m^2K/W batts with a rendered fibro-cement exterior.
- Cavity Brick: two leaves of brickwork with an unventilated 40 mm air-gap separating the two walls. The exposed face of the internal wall is left bare.
- Lightweight Construction: consists of a timber stud wall containing insulation batts of R 1.5 m^2K/W with exterior rendered fibro-cement and plasterboard on the interior walls.

RESULTS AND DISCUSSION

Results from AccuRate were used to conduct a thermal performance study using the different walling systems. The AccuRate software has two modes for rating. Firstly, "Rating mode" calculates the amount of energy entering the system to maintain thermal comfort to a temperature range between 20°C and 24.5°C. As mentioned earlier, the output is a star rating with related annual energy consumption. For the hypothetical modules analysed star ratings of 6 to 7 were considered to be the basic criterion for assessing the suitability of a particular construction. Experience in Australia (Andrews 1990-2010) has shown that the best star ratings for optimum energy efficiency and comfort levels are values between 5 to 6 (i.e. In Newcastle 70-90 MJ/m^2 annum). Star ratings greater generally behave like a heavily insulated box, leading to lower levels of thermal comfort, even if energy efficiency of the building is improved. In increase thermal comfort within a building it is beneficial to utilise the outside environment and use solar radiation and convection for natural heating and cooling in a building.

From "rating mode' it is revealed that RBV walling system offers the most energy efficient design when solar energy is allowed to enter the module (modules B, C and D, refer to Table 1 and 2). Likewise, RBV achieved the maximum star ratings in Module C having a star rating of 6.6 and an energy consumption of 56.0 MJ/m^2 annum. Brick Veneer and CB construction systems gave a maximum energy rating of approximately 5.9 stars ranging between 67 and 69 MJ/m^2 annum while light weight construction gave the lowest energy rating of 5.4 stars at 77.9 MJ/m^2 annum. Hence, all masonry walling systems satisfied the basic 6 to 7 star criterion.

Table 1: Energy Consumption (MJ/m^2 annum)

	Brick Veneer	**Reverse Brick Veneer**	**Cavity Brick**	**Light Weight**
A	70.9	75.3	140.6	79.6
B	105.4	79.5	100.1	90.7
C	69.3	56.0	67.1	77.90
D	93.1	74.4	90.5	102.3

Table 2: AccuRate Star Ratings

	Brick Veneer	**Reverse Brick Veneer**	**Cavity Brick**	**Light weight**
A	5.8	5.5	3.4	5.3
B	4.3	5.3	4.4	4.8
C	5.9	6.6	5.9	5.4
D	4.7	5. 5	4.8	4.4

The second mode of rating is known as "non-rating mode". Non-rating mode simulates a free-floating environment, demonstrating the temperature fluctuations with no artificial heating and cooling allowing the module to interact with the outside environment. A 24 hour period was selected from the summer months being the hottest day in the AccuRate weather cycle. These results have been summarised in Figures 2 to 4. These figures present the plots of indoor temperature versus time for each module as a function of walling system.

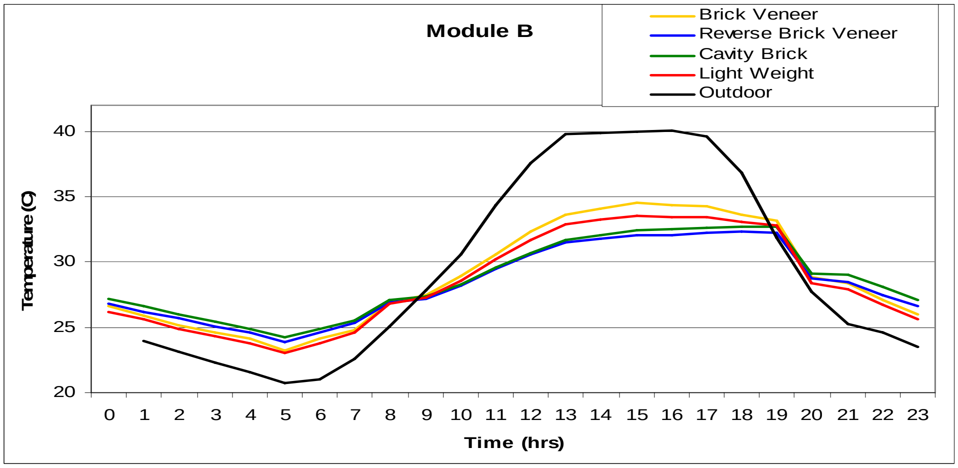

Figure 2: Temperature Profile for Module B in Summer

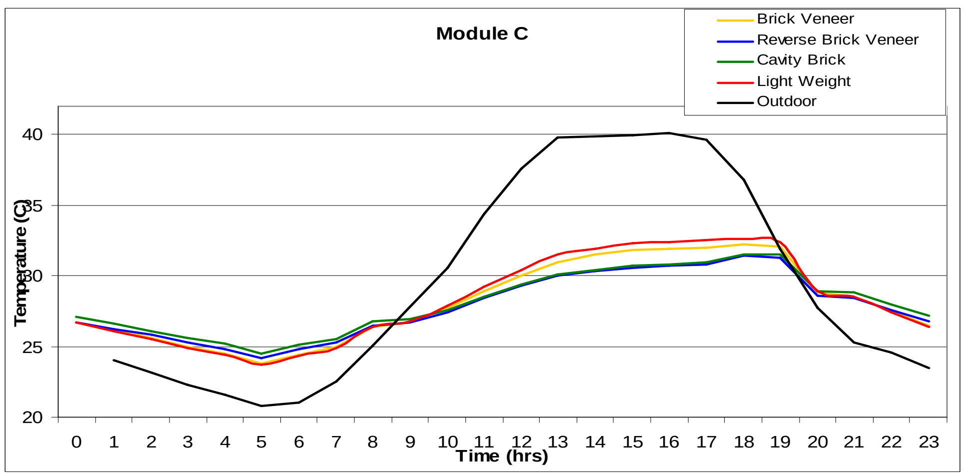

Figure 3: Temperature Profile for Module C in Summer

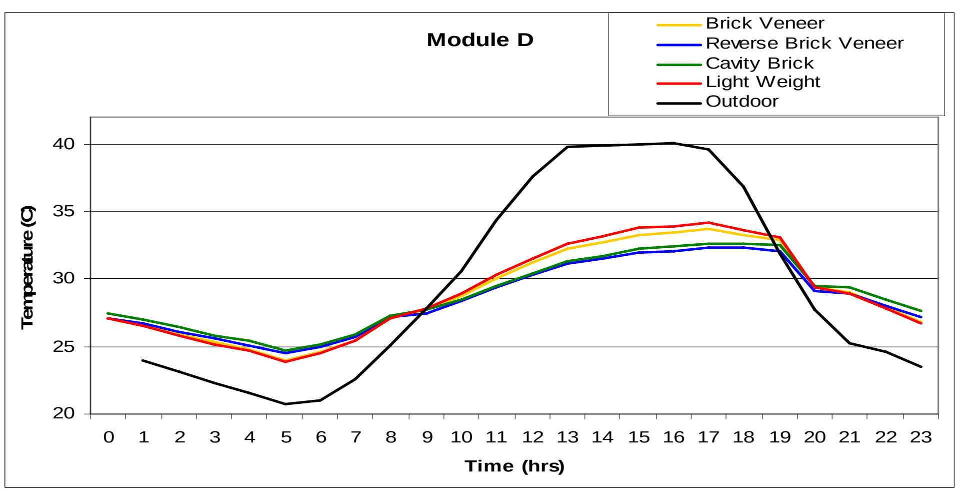

Figure 4: Temperature Profile for Module D in Summer

Thermal comfort requires the temperature profile within in a building to have minor fluctuations. Module A offers the desired profile as the building only slightly reacts to the outside temperature variations. When solar radiation is allowed to enter a building, the interior of the external walls is able to interact with the internal environment. This will change performance of the entire module. As Module A consists of only external walls, this design is not practical for this study. Therefore only Modules B, C and D have been considered in further analysis.

Among modules B to D (Figures 2 to 4) Module C has a relatively smooth temperature profile with a minimal daily fluctuation (i.e. diurnal). Reverse brick veneer offering the lowest maximum temperature, and a relatively vertically straight profile. Light weight has a slightly higher peak than other construction types, with the greatest oscillations. In the winter months all walling systems have slightly higher indoor temperatures than those of their counterparts in Modules B, and D. This minimises heating costs and demonstrates that increasing the thermal mass internally can lead to improved thermal performance.

Extra windows in Module D (Figure 4) were predicted to increase cooling efficiency in the summer months. However, Module D's results were almost identical to those of Module B as shown in Figure 2. The extra east and west windows of Module D appear to counteract the effect of thermal mass on the internal walls causing Module D to perform very much like Module B. Although not shown here, the analysis reveals that if the internal thermal mass was increased by the same ratio as that of added window size, the results of Module D would have been similar to Module C rather than B (Gregory 2007).

Thermal lag plays a large part in thermal efficiency. The quick decent of the temperature profile after the daily peak demonstrates the thermal lag. A quick decrease cause thermal comfort within the module to diminish. The desired profile is a slow decrease, allowing the thermal energy to slowly be released into the module. In all modules BV and LW walling systems have a steeper decent as compared to CB and RBV walling systems. This is due to CB and RBV have a relatively high amount of thermal mass and being containing internally and the particular behaviour of LW and BV corresponds to the inadequate thermal mass.

To create a constant base for comparison a decrement factor (equation 1) is applied here. A low decrement factor will offer the least amount of temperature fluctuations (CLEAR 2004).

$$Decrement\ Factor = \frac{T_i - T_D}{T_o - T_D} \quad (1)$$

Where T_D is the desired room temperature
T_i is the inside average daily temperature
T_o is the outside average daily temperature

In Figure 5, the decrement factors for each of the construction types have been compared for one 24 hour period from summer. Module C has the lowest decrement factor in summer and winter. Reverse brick veneer evidently offers the least fluctuation in indoor temperature as calculated through the decrement factor in each module. Clearly light weight construction has the highest decrement factor in all modules, as it

offers the least amount of thermal mass. Cavity brick and BV both have temperature profiles, between LW and RBV.

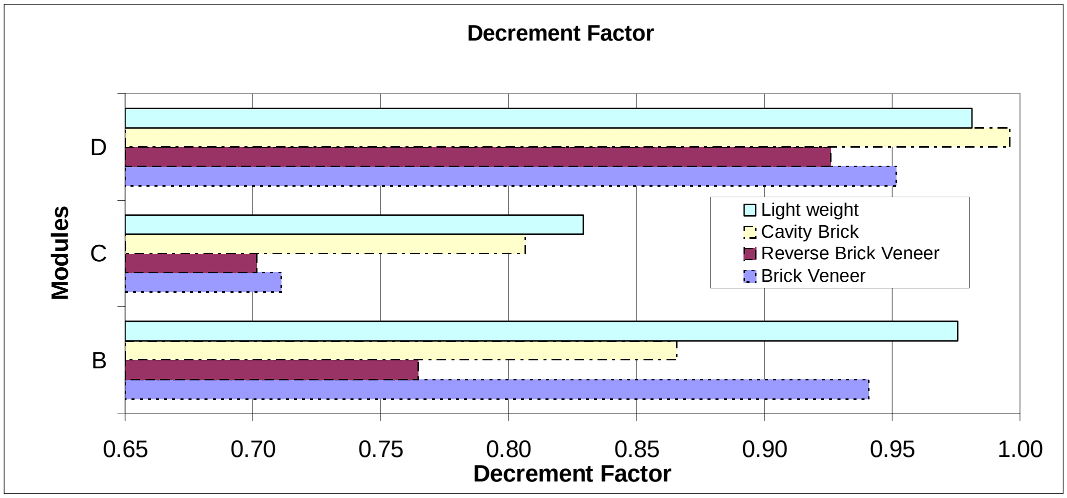

Figure 5: Decrement Factor of Modules in Summer

Overall the temperature profiles of CB and RBV have the most desired temperature profile as the heat stored in the thermal mass is being released into the module suppressing the outside temperature drop. Light weight construction and BV also exhibit similar behaviour although they show higher levels of temperature fluctuations because of their relatively lower thermal mass. From analysis of Module D (Figure 4), the extra windows on the east and west walls will decrease the energy efficiency. Hence, the more windows installed the more thermal mass needed within the building to increase thermal performance. Through analysis it is clear that Module C offers the most energy efficient design and RBV has the best thermal performance in all modules.

As in all modelling there are errors and discrepancies that may affect the result. Firstly AccuRate uses a response factor to take into account daily cycles of solar radiation, changing wind speeds and directions, and radiation to the atmosphere at night all calculated from the outside air temperature, which allows room for error and differences from actual weather patterns. Secondly, the analysis for the “non-rating” mode has only been examined for one day. If performed on a different day or over several days the results may differ. Thirdly, as analysis was performed on a hypothetical module it is not known how well these trends transpose to a real house. The floor, roof and internal wall may have a significant effect on the overall performance of a module, and minimise the effects of the different walling systems. These hypothetical modules can be applied to obtain an estimate of the thermal mass properties of different construction types, but not necessarily to base qualitative analysis on. And lastly, the performance of each walling system may differ with the use of different elements such as reflective foil and/or insulation within the design; this will be examined in future studies.

CONCLUSIONS

A thermal performance study of hypothetical modules using the software package, AccuRate reveals that increasing window area requires thermal mass to be increased proportionally; hence the most efficient module was Module C.

In the AccuRate "rating mode" it was tabulated that CB and BV walling systems performed similarly. Although in the "non-rating" mode it was evident that CB and RBV walling systems were similar while BV performed similarly to LW. When analysing the data by using a decrement factor it is clear that RBV exceeds other construction types. Hence, AccuRate highlights that RBV walling system offer the least energy consumption and indoor temperature fluctuations in all of the hypothetical modules. These results are as expected, as it is known that thermal mass performs well within a protective insulating envelope.

The thermal performance study presented in this paper has shown that thermal mass has the ability to significantly reduce the energy usage in residential buildings and therefore has the possibility of maintaining a comfortable internal temperature with no heating or cooling. To create a sustainable future thermal mass in buildings needs to be utilised.

ACKNOWLEDGEMENTS

The authors would like to thank the Australian Research Council (ARC) and Think Brick Australia (formally the Clay Brick and Paver Institute), for their contributions, assistance and support.

REFERENCES:

AGO (2004). Australian Greenhouse Office, Australian Residential Building Sector Greenhouse Gas Emissions 1990 - 2010. D. o. E. a. Heritage. Canberra.

AGO (2005). Australian Greenhouse Office, Your Home Technical Manual, Rating Tools. C. o. Australia.

Andrews, G. (1990-2010). "Australian Residential Building Sector Greenhouse Gas Emissions." Australian Greenhouse Office.

BOM (2006). Heat Storage Capacity, Australian Government, Bureau of Meteorology.

CANA (2005). Climate Action Network Australia (CANA), Inquiry into Energy Efficiency, Submission to Productivity Commission, Review of Energy Efficiency.

Cheng, V., E. NG, B. Givoni (2005). "Effect of Envelope Colour and Thermal Mass on Indoor Temperature in Hot Humid Climate." Solar Energy **78**: 528-534.

CLEAR, C. L. E. A. (2004). Time Lag and Decrement Factor. Athens.

CSIRO (2004). AccuRate Manual. A. C. S. a. I. R. Organisation.

Gregory, K. E. (2007). "B. Moghtaderi, H. Sugo, A. Page, Effect of Thermal Mass on the Thermal Performance of Various Australian Residential Constructions Systems." Energy and Buildings Journal.

McKnight, D. (2001). Dynamic Thermal Performance and Energy Benefits of Using Massive Walls in Residential Buildings, Oak Ridge National Labs and Polish Academy of Science. Roofs and Walls.

State Projects (1993). NSW Public Works Department, Building Energy Manual, Prepared for the Office of Energy, NSW Government, Sydney, Australia.

Sugo (a), H. O. (2004). "A.W. Page and B. Moghtaderi, Proc 7AMC." 192-203.

Sugo (b), H. O. (2004). "A.W. Page and B. Moghtaderi, Proc 13th IBMAC." Amsterdam: 767-776.

Walsh, P. J. (1983). "A.E. Delsante, Calculation of the Thermal Behaviour of Multi-Zone Buildings." Energy and Buildings **5**: 231-242.

Wilkenfeld, G. (1998). "Household Energy Use in Australia, Appliance Energy Labelling Review Committee." national Appliance and Equipment Energy Efficiency Committee(March).