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THE DYNAMIC THERMAL PERFORMANCE OF MASONRY WALLING SYSTEMS

Dariusz Alterman[1]; Adrian W. Page[2]; Congcong Zhang[3] and Behdad Moghtaderi[4]

ABSTRACT

This paper gives an overview of a new approach to the thermal testing and design of Australian walling systems under dynamic temperature conditions. The analysis utilises the dynamic response of the walls to moderate the effect of the temperature variations which occur under typical Australian conditions. The paper shows how to best balance the amount of thermal mass and insulation in housing using dynamic procedures. The thermal mass acts as a temperature regulator producing less interior fluctuations under the external temperature extremes, whilst the addition of insulation also produces more desirable interior temperatures than those for non-insulated walls whilst also moderating the interior temperature changes. The manner in which the appropriate configuration of thermal mass and insulation influences the performance is also discussed. The suggested testing procedure is a significant advance in the assessment of the thermal performance of masonry and other walling systems. This approach also provides a means of determining how much thermal mass is required to obtain comfortable conditions for the occupants of existing housing.

KEYWORDS: *masonry, walling systems, dynamic thermal performance, thermal assessment*

INTRODUCTION

Buildings are exposed to a range of climatic conditions and dynamic temperatures which directly influence their thermal performance. Due to the variability of weather conditions in different locations around the world, there is a need to determine suitable building materials for the relevant environment. Material selection has a major influence on the potential thermal performance and

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[1] Senior Research Fellow, The University of Newcastle, Priority Research Centre for Frontier Energy Technologies & Utilisation, Australia, dariusz.alterman@newcastle.edu.au

[2] Professor Emeritus, The University of Newcastle, Priority Research Centre for Frontier Energy Technologies & Utilisation, Australia, adrian.page@newcastle.edu.au

[3] Research Assistant, The University of Newcastle, Priority Research Centre for Frontier Energy Technologies & Utilisation, Australia, congcong.zhang@uon.edu.au

[4] Professor, The University of Newcastle, Priority Research Centre for Frontier Energy Technologies & Utilisation, Australia, behdad.moghtaderi@newcastle.edu.au

energy requirements over the life cycle of a building. This has been reflected in a number of studies in both laboratory and real house assessments based on diurnal temperature profiles.

To provide realistic (actual) data on the thermal characteristics of Australian walling systems, in collaboration with Think Brick Australia, a major experimental study has been in progress for a number of years at the University of Newcastle on the performance of four full scale housing test modules [1-4]. One of the key conclusions from the study was that for all walling types (cavity brick, brick veneer, reverse brick veneer and lightweight construction), the thermal performance of the modules did not correlate directly with the wall thermal resistance (R-value), with the thermal mass and thermal resistance both playing a significant role in responding to the dynamic temperature conditions.

Dynamic cyclic tests performed on walling systems have the potential to provide a more realistic picture of how various materials perform when exposed to typical temperature fluctuations. By monitoring the temperature and energy flow at various points through the wall, information on heat flow and temperature variations can be obtained. Cyclic tests also demonstrate the ability and mechanism of the material to attenuate the heat flow whilst storing and emitting heat after the exterior temperature begins to change. Since the changing nature of the dynamic cycles does not allow a constant heat flow mechanism to develop in the structure, in contrast to the determination of the thermal resistance (R-value), it is much more difficult define the performance with a single parameter [1-4].

A material property known as “heat capacity” or “thermal capacity” plays a vital role in the performance of the thermal mass. Heat capacity refers to the amount of energy required to raise the internal temperature of a material by one degree. For a material to have high thermal mass it must also have high density and thermal capacity combined with moderate conductivity. If the thermal conductivity is too high the material will expel all the energy quickly and there will be less benefit as the time lag will be shortened. On the other hand if the conductivity of the material is too low, heat energy will be restricted from flowing through it. The density of material is also a major factor affecting the thermal mass of solids. With increased density the kinetic vibrations can travel across the material delivering the heat energy to the opposite surface. Masonry has a high thermal mass in comparison to many other modern day building materials which, if used correctly, can be used to advantage.

This paper presents the major parameters which can be drawn from dynamic tests and the resulting Dynamic Temperature Response theory (DTR) [5, 6] which accounts for the contribution of both the thermal resistance and thermal mass of the building components in a dynamic temperature environment. The principles of the concept were firstly developed from comparisons of external and internal surface temperatures of typical masonry and lightweight walling systems obtained from dynamic hot box tests. They were then verified using thermal performance data under real weather conditions from the four full scale housing test modules [1-2]. Initially, the tests were performed on walls with varying combinations of thermal mass and resistance, and then extended to real enclosures with varying temperature cycles.

A series of tests on walls with varying combinations of thermal mass and resistance subjected to a varying temperature cycle were performed in a modified hot box apparatus. As one extreme of thermal mass, a 110mm thick solid brickwork panel was used in the first tests, with varying amounts of insulation (a polystyrene sheet) being used on the internal or external face. These tests were then extended to include various masonry insulation combinations. A series of temperature cycles were used to cover a range of summer and winter conditions.

DYNAMIC TEMPERATURE MEASUREMENTS

The dynamic thermal tests were carried out using a modified Hot Box apparatus that was originally designed to measure the thermal resistance of wall assemblies under steady-state conditions. This apparatus consisted of two separate chambers with each enclosure surrounded by R3.5 insulation to maintain a constant temperature gradient across the 2.4m x 2.4m test panels. The apparatus included specialised instrumentation for temperature control, temperature and power consumption measurement. Both chambers and test panel were located in a controlled (constant temperature) space to create a steady ambient external environment for the test without any influence of external temperature variations. This also allows heat flux attenuation studies to be performed under cyclic (transient) temperature conditions which mimic day-night temperature variations. A schematic arrangement of the modified Hot Box apparatus is shown in Figure 1.

The dynamic cycles, which represent the outdoor temperature conditions, are created in one chamber, called the “external” chamber. The other uncontrolled free-floating chamber (the “response” chamber) is used to observe the response of the panel under the external temperature profiles. Unlike the steady-state test, no specialised instruments to measure the energy requirements were installed as the temperature profile is the only input parameter. This realistically reflects the real conditions as the performance of a building depends on the outdoor diurnal temperature which is mainly affected by the solar radiation.

All temperature sensors were calibrated in accordance with the ASTM C1363-11 [7], and heat flux sensors were installed in the centre of both sides of the test panel. Prior to the dynamic tests, the test environment was stabilised in a steady-state to minimize any inertia effects. During this step, both chambers together with the test specimen were located in the enclosed room and left opened to the constant temperature of the room. The enclosure room temperature was set to the average of the planned temperature cycle for about 24 hours. Following the initial set up, the dynamic temperature cycles were run in the external chamber, with a few preliminary diurnal cycles being repeated until the consecutive temperature and heat flux profiles become stable. This depended on the temperature range of the cycle and the amount of the thermal mass present in the panel.

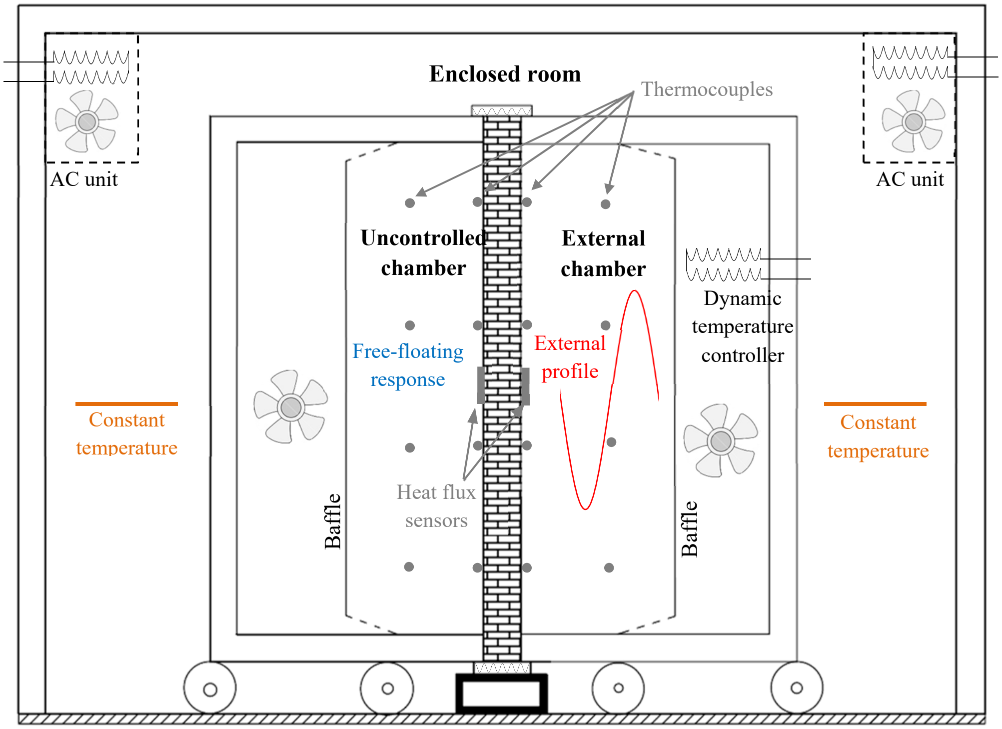

Figure 1: Dynamic testing facilities for the assessment of thermal performance

Temperature cycles corresponding to different Australian weather zones (with different amplitudes and averages) were applied. The system is also capable of simulating any of the eight Australian climate zones, but in particular, summer and winter cycles for Melbourne and Brisbane were tested as shown in Figure 2.

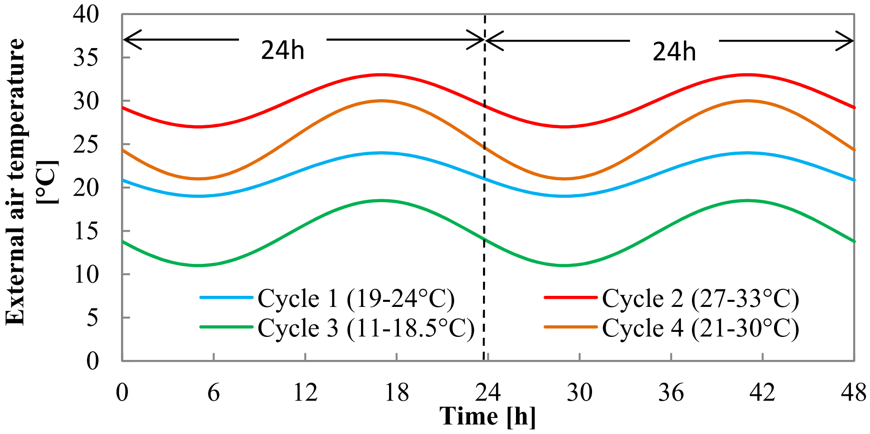

Figure 2: An example of test cycles

The cyclic results provide useful information on the heat flow attenuation and thermal lag of each individual wall element on a comparative basis for any wall type and demonstrate how the systems perform under the influence of a dynamic input. Previous steady-state results illustrate the ability of a wall to attenuate heat flow and provide information on the nature of the temperature gradients established within each wall. The current investigation using a “standard” cyclic dynamic input provides a more ‘realistic’ indication of how a wall system behaves under dynamic conditions and allows the evaluation of the heat transfer characteristics for any walling system.

THE DYNAMIC THERMAL RESPONSE CONCEPT (DTR)

The dynamic thermal performance can be analysed using a concept, based on temperature measurements; the internal and external surface temperatures for the analysis of a material/panel response and the external and internal air temperatures for a building response [5]. The concept therefore captures the response of the internal surfaces of walls which are being exposed to the external environment of a diurnal cycle. In general, the internal side of a material or wall panel represents the effect of the energy exchanged between the external and internal environment. This process therefore encapsulates and captures the entire mechanism of heat transfer from the external to the internal surface, including the influence of the physical properties of the surface and the thermal properties of the materials. Thus, the DTR concept inherently takes into account all the parameters involved in the heat transfer such as thermal mass and thermal resistance as well as the dynamics of the temperature cycle, solar radiation and wind effects. The basic assumptions of the concept are presented here and more details of the concept and its verification can be found in a previously published paper [5-6].

The dynamic temperature response profile is created by plotting the external and the internal wall surface temperatures for a single diurnal cycle within the Cartesian coordinate system. The response generates an elliptical shape in which the angle of the principal axis of the ellipse is measured [5]. The response of a panel is characterized by this slope which varies depending on the external conditions and the thermal properties of the wall.

The “ideal” relationship of the concept for a diurnal temperature change for the external and internal surfaces of a wall panel is shown schematically in Figure 6. This response is defined as the angle of inclination of the line [5] and has been termed the “Dynamic Temperature Response” (DTR) in degrees or the “T-value” (as a non-dimensional parameter) [5]. The two extreme cases for a panel shown in Figure 3 can be described as:

- a perfect insulator, which does not allow any change of internal surface temperature regardless of the external environment conditions, see Figure 3a, (a flat response, with a DTR of 0 degrees),
- a very poor insulator (i.e. a highly conductive panel), when any small change of external surface temperature is instantly reflected by an internal sur-face temperature of the same magnitude, see Figure 3b, (DTR equals 45 degrees).

A real panel is neither a perfect insulator nor highly conductive, having both inherent properties of thermal mass and thermal resistance to varying degrees. This means the DTR profile lies between zero and 45 degrees; see Figures 3c and 3d. As part of our broader study, it has been shown that a lower DTR consistently correlates with better wall thermal performance [5].

The Dynamic Temperature Response concept has been verified for real walls using data collected from wall system performances for the test modules. The idealised lines of the angle of inclination become (approximate) elliptical-shaped curves which reproduce the "real" response of the walls under diurnal dynamic cycles [5].

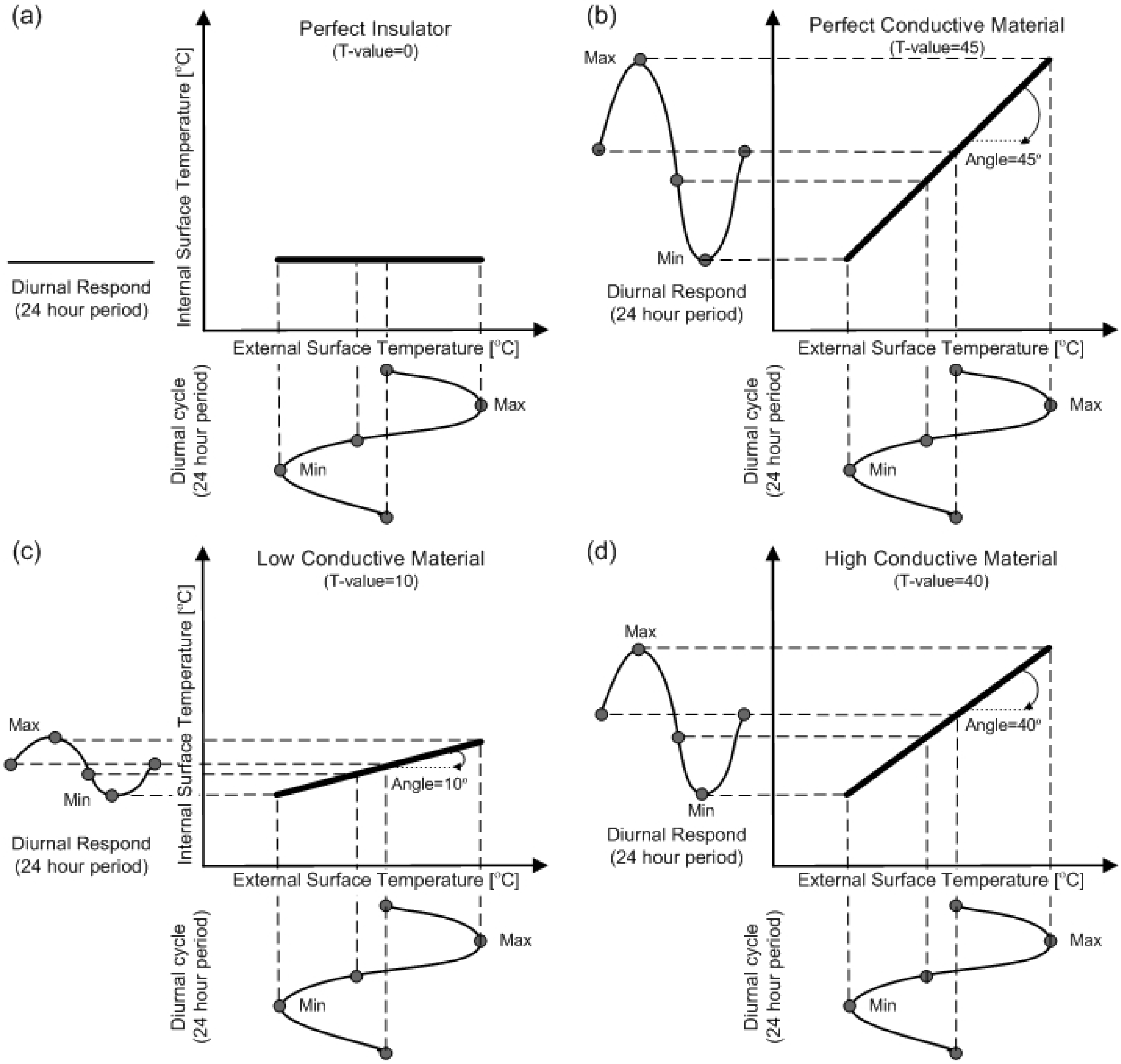

Figure 3: Schematic dynamic temperature response concept of a wall for one diurnal cycle for: (a) perfect insulator; (b) perfect conductive material; (c) low conductive material; (d) high conductive material [5].

The T-value concept was developed for the analysis of building components; however the DTR concept can also be used to reflect the thermal performance of a building enclosure by analyzing the external and internal air temperatures for an enclosure subjected to a diurnal temperature cycle. The response of the interior of the enclosure will be different, depending on the combined effect of the properties and nature of the building (i.e. walling, roof and slab configurations, window size, temperature swings and surrounding environment) for any given external conditions. However, each created elliptical curve can be then classified by a parameter called the Dynamic Thermal Response of the system, (DTRS in degrees).

MASONRY WALL RESPONSE UNDER DYNAMIC CONDTIONS

This preliminary study applying the dynamic external conditions for the masonry wall with/without an insulation layer also provides information on how heavy walling systems such as masonry respond to cyclic weather conditions, absorbing and realising heat. The thermal behaviour of the wall with an internal insulation layer will be similar to that of an insulated brick veneer walling system. The interior insulation slightly increased the thermal lag of the wall system. However, the heat energy penetrated through to the "interior" air and the insulation provided a barrier that made it hard for this energy flow to reverse and flow back to the exterior. However, the results also indicated that the insulation would be more effective in minimising internal air temperature fluctuations in reverse brick veneer construction, where the brickwork forms the inner leaf of the wall, with a layer of insulation in the cavity between the external veneer and the internal masonry. This insulation layer creates a barrier that will reduce the levels of energy exposure of the internal masonry.

This study, applying the dynamic external conditions for the brick wall with a varying insulation layer position, provides information on how heavy walling systems respond to cyclic dynamic weather conditions through absorbing, storing and releasing heat. The cyclic testing provides useful information on the heat flow attenuation and thermal lag of each individual wall element on a comparative basis for any wall type and demonstrates how the systems perform under the influence of a dynamic input. The current investigation using a "standard" cyclic dynamic input provides a more realistic indication of how a wall system behaves under dynamic conditions and allows the evaluation of the heat transfer characteristics for any walling system. Through analysis of the results the information on the thermal lag, the influence of thermal mass and the position of the insulation can be obtained.

With the layer of insulation on the side corresponding to the interior face of the wall in Figure 4, the external surface temperature peaked at 27ºC, 2.4 hours after the peak of the one summer cycle (see Figure 2, cycle 4). The peak temperature of the interior surface of the brick wall was 26ºC occurring 6.5 hours after the peak of the exterior temperature cycle. The interior insulation decreases the internal air fluctuation range to 2.5ºC from minimum to maximum for the summer cycle. This wall configuration was effective for the summer cycle as it allowed the thermal mass to expel heat during the night whilst receiving enough energy during the day to prevent the temperature dropping excessively. Artificial cooling would be necessary from lunch to midnight for this cycle to maintain a comfortable level.

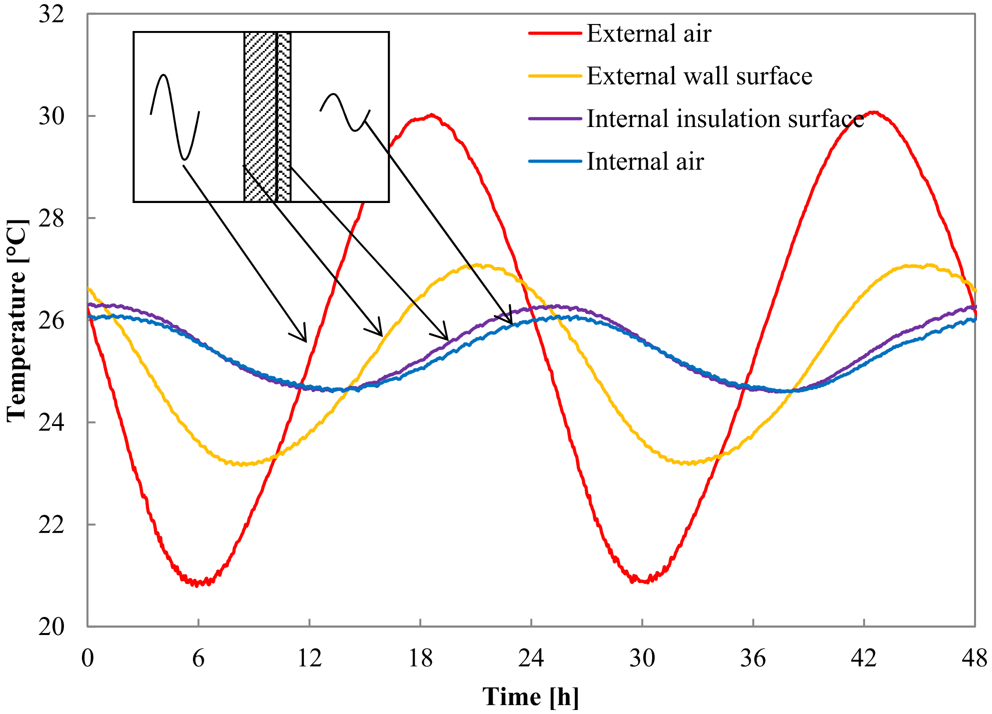

Figure 4: Temperature profiles of internally insulated solid brick wall under dynamic cycle

With the insulation layer on the "external" face of the wall (Figure 5), the exterior surface temperature of the insulation reached a maximum temperature of 29.2ºC. Considering the exterior air temperature reached a maximum of 30ºC the surface of the insulation is extremely warm. The exterior surface of the insulation peaked 0.25 hours after the peak of the external temperature cycle. The peak temperature on the external brick surface was 26ºC which occurred 3.5 hours after the peak of the external cycle. The insulation panel reduced the temperature and energy passing towards the interior, since the solid brick wall was receiving a reduced energy exposure from the external cycle, only a minimal temperature oscillation of 0.7ºC was observed.

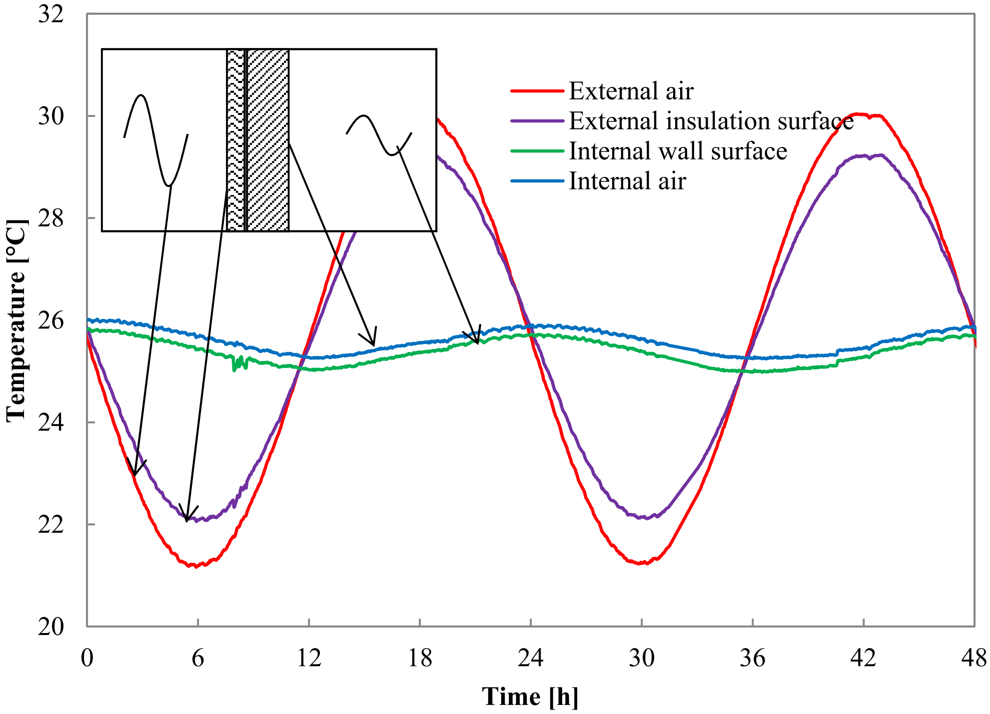

Figure 5: Temperature profiles of externally insulated solid brick wall under dynamic cycle

The exterior insulation arrangement was the most efficient in reducing the interior temperature fluctuations and energy transfer. This is a result of the high resistivity of the insulation on the exterior face. The insulating panel prevents the majority of energy from reaching the thermal mass and penetrating through to the interior. To increase the temperature of the thermal mass a large amount of energy is required, and the insulation is essentially blocking this from occurring. The exterior surface of the insulation panel had a large temperature fluctuation in all cases mirroring the temperature cycle, with less than a 1ºC difference between the external temperature cycles. A light weight material has less thermal mass and therefore requires less energy to raise its core temperature. As a result, the interior surface temperature for a light weight construction material will be greater than that of a high thermal mass material when exposed to the same external temperature cycle. The response of the low thermal mass construction is more immediate and it therefore adjusts faster to the exterior heat cycle than its heavy weight counterpart.

The dynamic temperature profiles highlight the differences in the response of the enclosures and reflect the contribution of all of the building components, not just the presence of either thermal mass or insulation. As an illustration of this, as part of the larger investigation, the DTR concept was employed to assess the thermal performance of insulated brick veneer (InsBV) and insulated reverse brick veneer (InsRBV) walling systems. These two walls had the same wall insulation properties and R-value and the same thermal mass, but with different locations of the thermal mass (the brickwork leaf) in relation to the cavity insulation (outside the insulation layer for the InsBV and inside for the InsRVB). As can be seen from Figure 6, the InsRBV walling system had a lower DTR-value of about 0.5 compared to the InsBV walling system with a DTR-value of about 15. This again illustrates the significance of not only the presence of insulation and thermal mass in a wall, but also the location of that thermal mass in relation to the insulation layer.

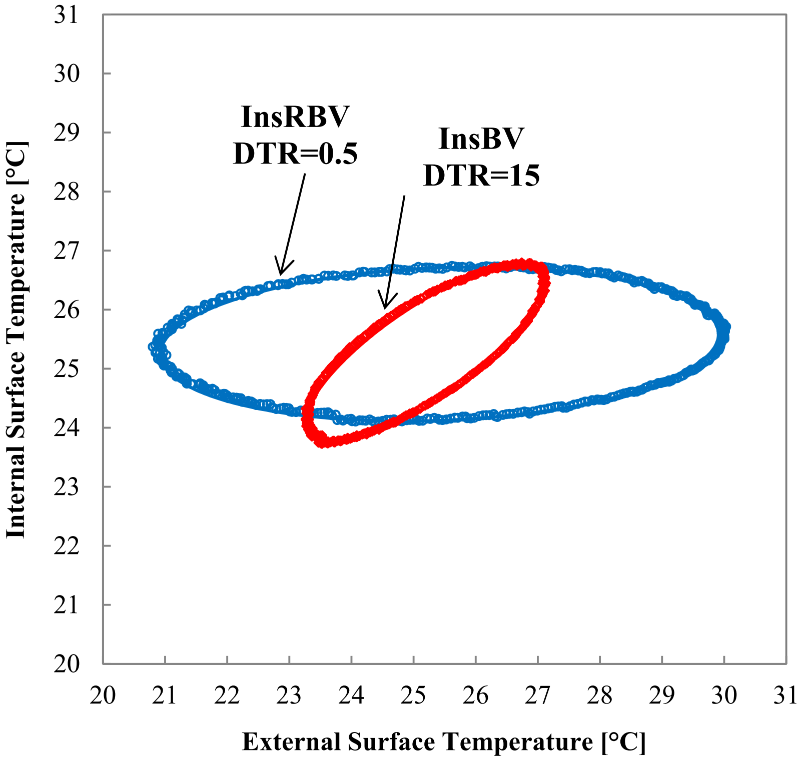

Figure 6: DTR parameter for externally and internally insulated solid brick walls

CONCLUSIONS

In an on-going study on wall thermal performance, various wall configurations and types are being subjected to dynamic temperature conditions using a modified hot box apparatus. The tests have shown that through effective design and correct incorporation of thermal mass it is possible to minimise internal air temperature variations, thus reducing the need for heating and cooling during a diurnal temperature cycle. The thermal mass of masonry acts as a temperature regulator reducing interior temperature fluctuations. The addition of insulation produced more desirable interior temperatures than for a non-insulated wall whilst effectively moderating interior temperature changes. However, the location of the insulation layer in relation to the thermal mass is critical, as illustrated by the relative performance of insulated brick veneer and reverse brick veneer systems with the same R value and thermal mass.

The modified hot box apparatus described here is capable of determining the thermal properties of materials under both static and dynamic conditions, so that the results under both conditions become more reliable and comparable. This assists in finding the potential links between static and dynamic thermal properties.

Work is proceeding on the detailed development of the DTR measure and an accompanying standard test for its evaluation for various walling systems. Once fully developed, such a comprehensive metric has the potential to improve the accuracy and effectiveness of current energy efficiency measures and ultimately lead to more thermally efficient house designs as well as more effective retrofitting of existing housing stock.

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