THE STUDY OF HEAT FLOWS IN MASONRY WALLS IN A THERMAL TEST BUILDING INCORPORATING A WINDOW

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ABSTRACT

Over the past four years, the University of Newcastle, in conjunction with the Clay Brick and Paver Institute, has embarked on a research program to study the thermal performance of masonry construction under Australian climatic conditions. This has led to the construction of a guarded hot box apparatus and the instrumentation of three purpose built modules on the University campus. This paper presents results for the third module, which features a large north-facing window with the walls being constructed using cavity brickwork. The results indicate that the window becomes the dominant factor in the thermal performance with the exterior heavy mass walls being subjected to bi-directional heat flows. This report gives an overview of the instrumentation and data collection and describes typical results obtained during the six months of monitoring under free-floating internal conditions.

KEYWORDS: cavity brickwork, thermal mass, heat flux, thermal performance, laminated glass

INTRODUCTION

Energy efficiency in housing is now an important issue in Australia with a ‘star rating’ scheme being applicable for all new housing. This involves the estimation of the energy required to maintain the interior of the building within a comfortable temperature range, (given the building fabric, design, orientation and locality) using specific software. A star rating is obtained by comparing the energy estimate against set values for the climate zone. Failure to meet minimum criteria requires changes to the building design or fabric. A review of the various rating schemes such as NatHERS (National House Energy Rating Scheme) and the requirements by the different states is presented by McLaren [1].

Over the past four years, the University of Newcastle, in conjunction with the Clay Brick and Paver Institute and the Australian Research Council (ARC), has embarked on a research program to study the thermal performance of masonry construction under Australian climatic conditions [2, 3 and 4]. The project has three distinct phases:

Phase 1. The construction of a guarded hot box apparatus for R-value determination of full-scale wall assemblies.

Phase 2. The construction and instrumentation of three purpose built modules on the University campus to develop a qualitative and quantitative understanding of the thermal performance of typical masonry construction used in Australia.

Phase 3. The development of hybrid energy simulation software derived using zonal and computational fluid dynamics (CFD). The experimental data collected from the modules will be used for validation purposes.

This report deals with Phase 2 of the investigation. The three modules are shown in Figure 1. They represent brick veneer construction-Module 1 (right), cavity brick-Module 2 (centre) and cavity brick with a window-Module 3 (left). The first two modules have been constructed in a manner to reflect the thermal behaviour of the masonry walls, and therefore, do not contain any windows or openings that allow direct solar access or provide ventilation. Therefore, the thermal response of the first two modules represents an upper bound limit for summer and a lower bound limit for winter. Each module has been instrumented with temperature, humidity and heat flux sensors, which are continuously monitored. The thermal response can be assessed in two ways: a 'free-floating' state, where the temperature in the building is determined by the influence of the external weather conditions or, in a 'driven' state, where the internal temperature is preset using a cooling/heating system and the energy usage in maintaining the set comfort level is measured. With the exception of the window, Modules 2 and 3 are of identical construction.

Figure 1 – The Three Building Modules for Thermal Testing.

Modules 1 and 2 showed that brick veneer and cavity brick construction, under free-floating conditions, attenuate the external weather effects with the buildings developing a thermal lag ranging from about 5 hours for the brick veneer to 7 hours for the cavity brick construction. The day-night temperature swing experienced internally was also significantly less than the outside air with ranges of 4-5˚C for the brick veneer and ≈3˚C for the cavity brick. The modules also responded slowly taking several days to adjust to major changes in weather patterns, e.g. heat wave or cool changes. Analyses of the wall temperature profiles and heat flux show that much of the solar radiation energy is lost back to the outside environment due to the diurnal temperature swing. This results in the reversal of heat flux across the wall, reducing the net flux entering the building. Results for these modules are reported in greater detail by Sugo et.al. [4].

In 2004, construction of a third module, incorporating a large north orientated window to allow solar ingress during winter, was undertaken. The ingress of solar radiation becomes the driving force for the thermal performance of the module. Whilst this building does not have any internal brick walls, which would normally absorb/release heat, this investigation forms a starting point in developing an understanding and provides quantitative data on the thermal behaviour of heavy mass walls. Preliminary results for this module under 'free-floating' conditions are described at various times throughout the year.

DESCRIPTION OF MODULES

The modules are comparable in size to other buildings used in similar studies [5]. The modules have a square floor plan of 6 m x 6 m and are spaced 7 m apart from each other to avoid shading and minimise wind obstruction. With the exception of the walls/window, the buildings are of identical construction, being built on a concrete slab and aligned in a manner so that the north wall of the buildings is perpendicular to astronomical north. Timber trusses are used to support the roof, consisting of clay tiles placed over a layer of foil sarking. The buildings have a ceiling height of 2450 mm. The ceiling consists of 10mm thick plasterboard with glasswool insulation bats (thermal resistance or R-value=3.5 $m^2.K.W^{-1}$) placed between the rafters. The R=3.5 insulation has been used in the ceiling to minimise the "through-ceiling" heat flow. Entry to the building is via a standard solid timber door located on the southern face of the building. Again, to minimise the flow of heat through the door, a 75 mm thick layer of polystyrene foam has been attached to the back of the door. The door is well-fitting and normally kept shut. It is only opened to allow necessary access, making the building as air-tight as possible. No carpet or other floor covering has been placed over the concrete slab. The building modules have been described previously in greater detail [3, 4].

The masonry walls in Module 3 consist of two 110 mm thick masonry skins separated by a 50 mm air cavity. The inside wall surfaces are rendered by using a cement/sand render with a nominal thickness of 10 mm. The window is a 3-panel sliding door assembly, 2050 mm high x 2840 mm wide, and represents about 20% of the floor area which is typical of a living room area. It is located on the north face and consists of clear, 6.2 mm laminated glass, set in a light coloured aluminium frame. A curtain has been placed behind the window but it is only used at selected times (refer to Figure 2). The window has not been used for ventilation purposes.

INSTRUMENTATION OF MODULES

The instrumentation records the external weather conditions including wind speed and direction, air temperature, relative humidity and the incident solar radiation on each wall (vertical plane) and on the roof (horizontal plane). For each module, temperature and heat flux profiles through the walls, slab and ceiling are recorded in conjunction with the internal air temperature and relative humidity. In total, approximately 104 data channels are scanned and logged every 10 minutes for each of the modules all year round. The data is recorded using a Datataker DT600 data logger located in each building. All temperatures are read using Type T thermocouples connected to three 30 channel expansion modules. To minimise any cold junction compensation errors, all the thermocouple inputs are maintained at uniform temperature through the use of a thick wall aluminium box as shown in Figure 2. The temperature recording system (thermocouple wire characteristics, cold junction compensation etc.) has been cross-referenced using a Prema Precision Thermometer and the corresponding temperature offsets are adjusted automatically in the logging process.

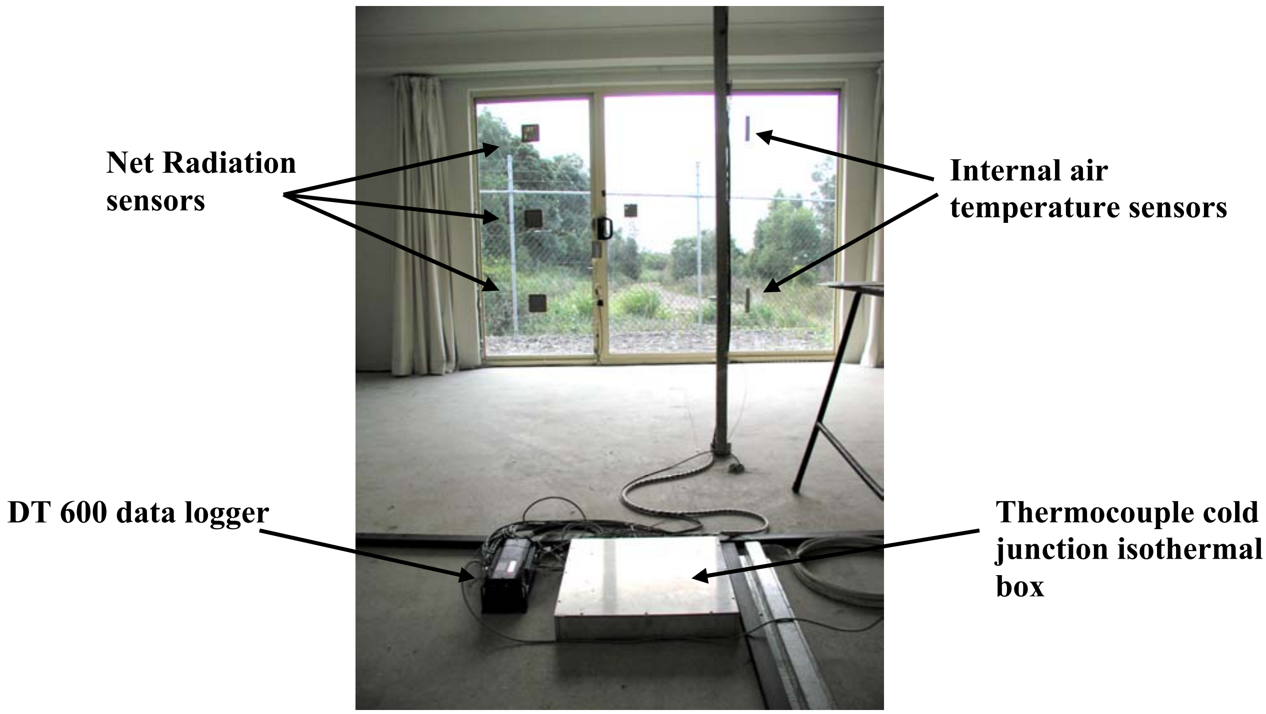

Figure 2 – Internal View of Module 3.

Heat flux profiles across the wall were measured with using 100 x 100 mm ultra-thin sensors with typical sensitivities in the order of 25 $\mu V/W/m^2$. The heat flux sensors were placed on the wall in such a manner that the proportion of masonry unit/mortar ratio being measured was representative of that in the masonry wall. An attempt was made to match the absorbance and emissivity of the heat flux sensors to that of the masonry units by painting the exterior sensors a similar colour to that of the bricks. The interior sensors were painted white, to match the walls, whilst the sensors located in the cavity were painted black to allow radiation heat transfer. Heat flux sensors were also located on the concrete slab, adjacent to the window (in direct sunlight) and at the rear south-east corner. Thermocouples were placed on the surface of the slab at various locations between the window and the centre of the room.

Three net radiation sensors were placed at different heights along the glass panel to assess the incoming/outgoing radiation (refer to Figure 2). These sensors are suspended 100 mm away from the glass surface and have a spectral range between the wavelengths of 0.3 and 20 µm. The surface temperature of the glass was recorded and additional heat flux sensors have been placed on the aluminium frame.

RESULTS AND DISCUSSION

Results will only be presented for selected time periods in July (winter), October (spring) and January (summer). Due to the large volume of data, the discussion in this paper will be limited to the internal and external air temperatures, the heat entering via the window, as this represents the driving force in the building, and the response of the slab and the internal wall surfaces. For ease of interpretation, the data presented in this report has been selected for clear, sunny days.

Winter Observations

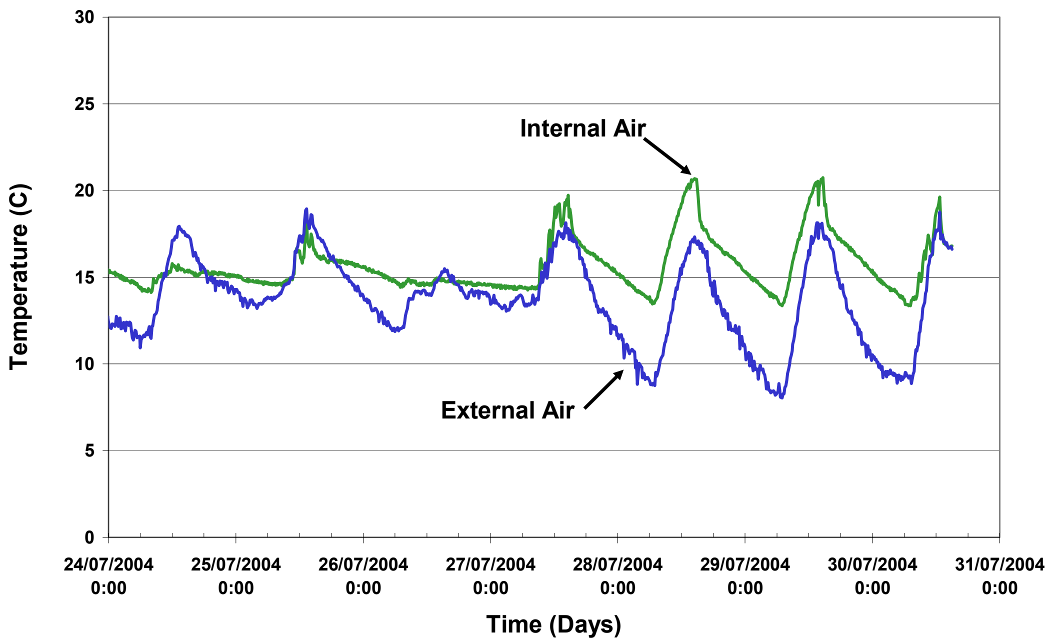

Figure 3 – Internal and External Air Temperature, week ending 31 July 2004.

The response of the module under winter conditions can be observed in Figure 3. At the beginning of the week, the presence of cloud cover attenuated the external and internal air temperatures. Clearer conditions occurred towards the end of the week with the night-time minimum dropping to 8.3˚C and the day-time maximum reaching 18.1˚C at 3 pm. The response of the module is strongly influenced by this weather pattern with the incoming solar radiation via the window becoming the dominant driver for the internal temperature. The minimum internal air temperature occurs at 7 am being about 13.6˚C and rises nearly linearly to a maximum of 20.6˚C at 3 pm. The internal air temperature drops 3˚C between 3 pm and 4 pm and then continues to decrease at a slower rate (linearly) during the night. Note that during this week the curtain was closed from 5 pm to 7 am to reduce heat losses via the window.

Figure 4 shows the heat exchange via the window, the slab and, the internal wall surfaces (east, south and west walls) for the 28th and 29th of July shown in Figure 3 above. The peak incident solar radiation falling on the north-facing window is in the order of 800 W/m^2 with 500-600 W/m^2 entering the building (measured in the vertical plane). At 3 pm, the heat entering via the window decreases sharply and coincides with the observed drop in internal air temperature. Note that the polarity of the heat fluxes shown in Figure 4 are defined as positive if heat enters the internal surface of the module, and negative when it flows out.

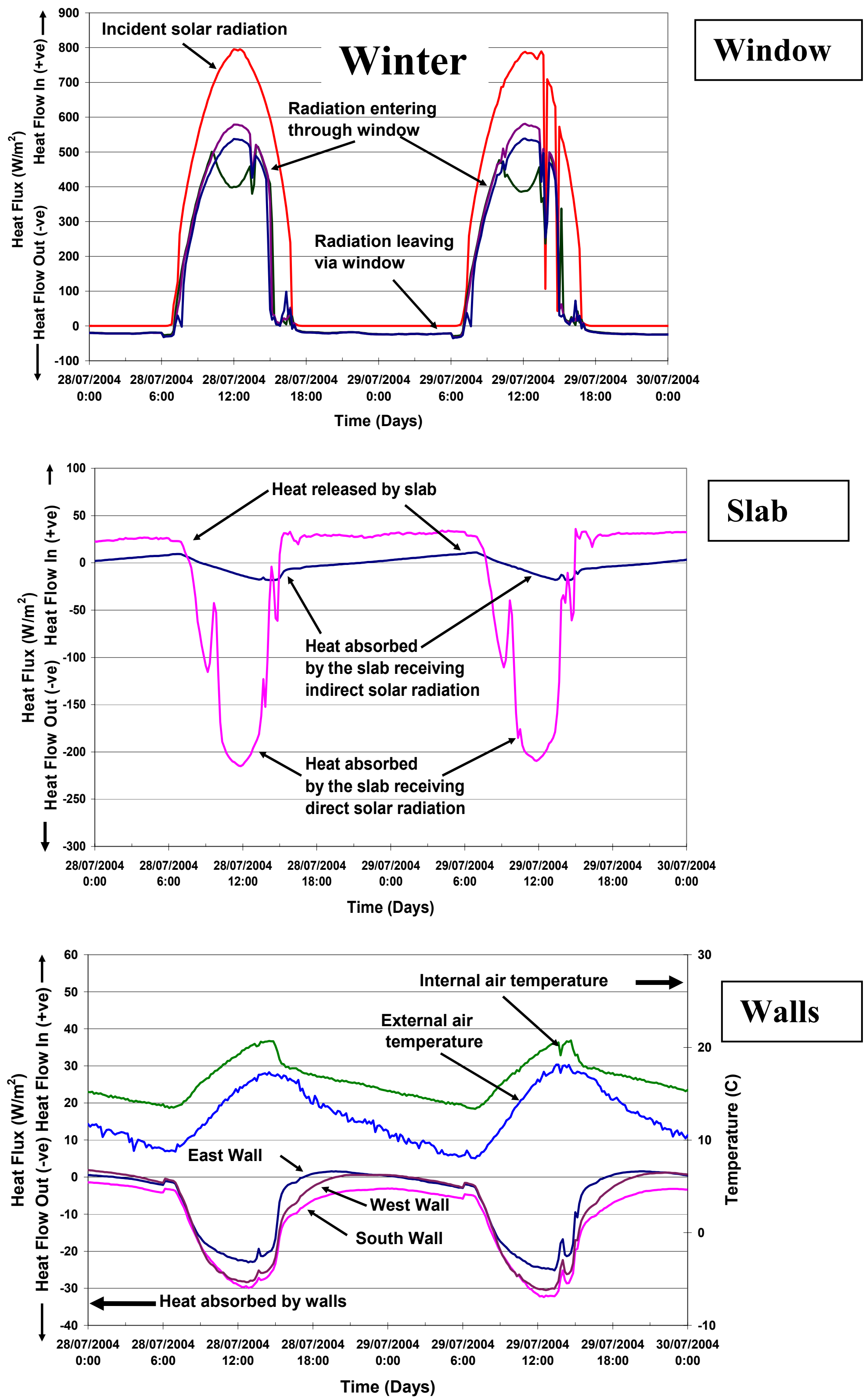

Figure 4 – Heat Exchange via Window, Slab and Interior Walls, 28th and 29th July 2004.

The area of slab, which received direct solar radiation is heated during the day (≈30˚C), and absorbs ≈210 W/m^2 of the incoming flux. (Note that this is measured on the horizontal surface of the slab). The balance of the incoming energy is redistributed in the module via convection and/or radiation. The energy stored in the area of the slab near the window is released back into the internal air space at a steady 30 W/m^2 from 3 pm to 7 am as the room air temperature drops. In contrast, the remaining portion of the slab continues to absorb small amounts of heat until about 10 pm when it then starts to release heat into internal air space peaking at 10 W/m^2 at 7am.

The behaviour of the walls is different. All the walls start to absorb heat as the room temperature increases and peak between 20-30 W/m^2 as shown in Figure 4. There are some differences between the walls, and this can be explained by the combined influenced of the direct solar radiation on the external surfaces and the internal temperature rise resulting in bi-directional heat flow across the wall. This can be seen in Figure 5, which shows the surface temperatures of the internal walls start to increase at 8am in response to the rising internal air temperature. At approximately 12 pm, the temperature of the east wall increases above that of the west and south walls from the external heat moving across the wall as a result of the morning sun. The west wall undergoes a similar process; however, the rise in internal surface temperature is not as pronounced since the peak is observed at about 7:30 pm when the building is already cooling down. Note the slight reduction in all the surface temperatures for the walls at 3 pm due to decrease in internal air temperature (and incoming solar radiation). The south wall remains cooler than the east and west walls.

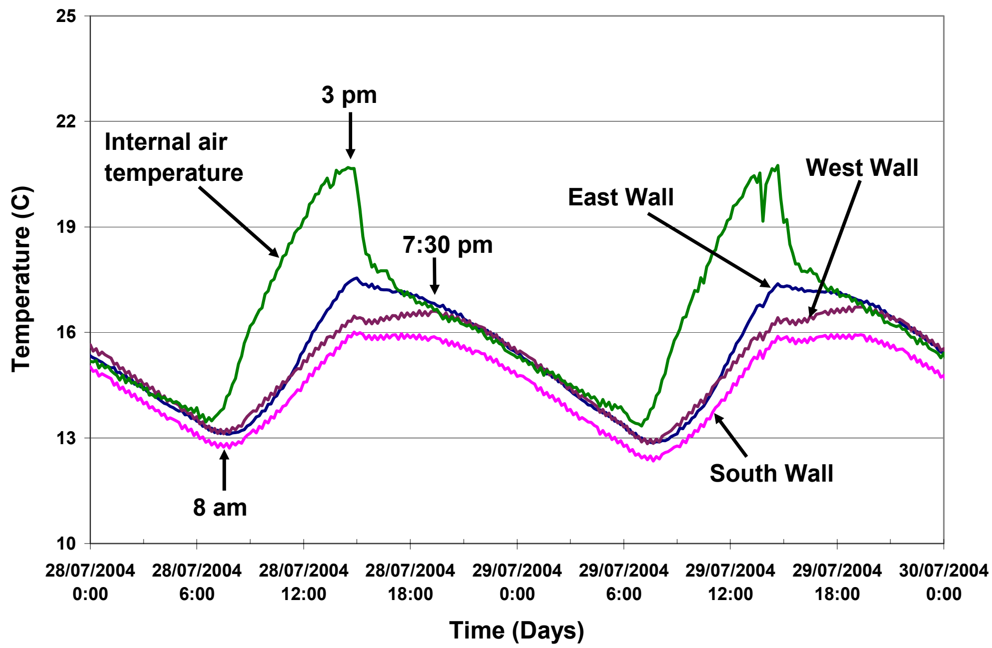

Figure 5 – Surface Temperature for the Interior Walls, 28th and 29th July 2004.

In the absence of incoming solar radiation, the internal air temperature comes to equilibrium with the surface temperatures of the east and west walls between 7:30 pm and 7 am. During this period of time, the low heat flux values shown in Figure 4 are close to the limit of reading, but would indicate that these walls contribute a small amount of heat to the ambient air (<2 W/m^2) until about 3 am and then show a small negative heat flux. The south wall shows a loss of heat in the order of 3-6 W/m^2. It is likely that the release of heat back into the room is reduced since all these walls are exterior walls. This would not be the case in a dwelling with internal walls. The radiation loss via the window, with the curtain closed, is about 20-25 W/m^2 and occurs between 5 pm and 7 am. In addition, heat is lost through the glass and aluminium frame via conduction. The loss of heat via the building envelope is driven by the internal air temperature always being greater than the outside air.

Spring Observations

The data for spring exhibits similar patterns to those shown in winter. Figure 6 shows the energy entering/leaving the module on the 3rd and 4th of October. The higher solar altitude reduces the incident flux on the north-facing window with peak values in the order of 350-400 W/m^2 (measured on the vertical plane) for the lower and mid-height sensors. The upper radiation sensor is in the shade provided by the eave and only detects the diffuse and reflected solar radiation components (≈80 W/m^2). The higher solar altitude reduces the solar footprint on the slab, compared to winter, but induces a higher flux on the horizontal slab surface with peak values approaching 300 W/m^2 at 11:30 am. The night-time release rate is in the order of 15-20 W/m^2. The remainder of the slab generally absorbs heat and the peak value of 15 W/m^2 coincides with the maximum internal air temperature at 2 pm.

The lower plot in Figure 6 shows the internal and external air temperatures together with the heat flux exchange for the internal walls. The milder external air conditions are reflected inside the module, with the internal air temperature having a smaller diurnal swing, ranging from 16-22˚C. The heat flux exchange on the internal walls follows a similar pattern to winter although the influence of the bi-directional heat flow is more noticeable. The flux absorbed by the walls is smaller, generally less than 20 W/m^2. The east wall absorbs less heat, due to the influence of direct solar radiation on the exterior of the wall. The west wall introduces heat into the room between 5:30 pm and 7:30 am, with peak values around 12 W/m^2 although the net contribution over the 48 hour period is close to zero. The east and south walls show little heat exchange during the night. The night-time radiation loses through the glass are also reduced, with values ranging from 12-25 W/m^2 from 6:30 pm to 6 am. Note that the curtain was not closed at night during this period.

Summer Observations

Figure 7 shows the relationship for the fluxes entering and leaving the module in mid-January 2005. Note the scale for the window and slab heat flux plots has been expanded. Due to the high solar altitude at this time of the year no direct radiation is recorded on the north face of the building. The observed values are due to the reflected and diffuse radiation components. This energy enters the building from 6:30 am until 7 pm, peaking in the order of 120 W/m^2 at 12:30 pm. After 7 pm, heat is lost via the window with the peak value being 23 W/m^2 at 5 am. The curtain was not closed at night during this period. The absence of direct solar radiation falling on the slab reduced the peak flux absorbed to less than 30 W/m^2.

The external air temperature ranges from 15-35˚C and 19-35˚C for the two days shown. Again, the internal air temperature has a small diurnal swing, ranging from 22.2-26.6˚C and 24.3-28.8˚C respectively. Note that between 7:30 pm and 7:00 am the building is warmer than the outside air and could be cooled by introducing ventilation.

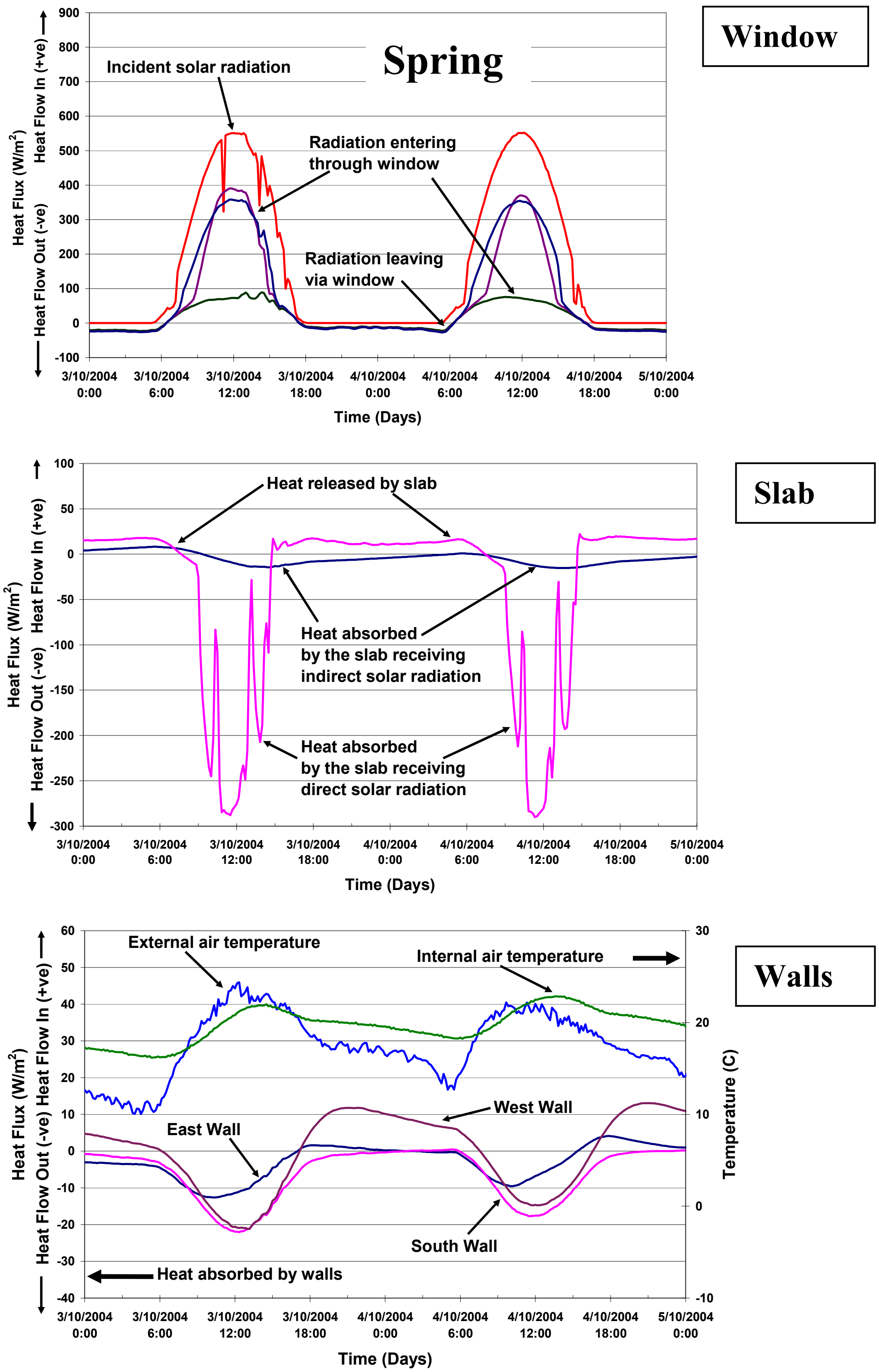

Figure 6 – Heat Exchange via Window, Slab and Interior Walls, 3rd and 4th October 2004.

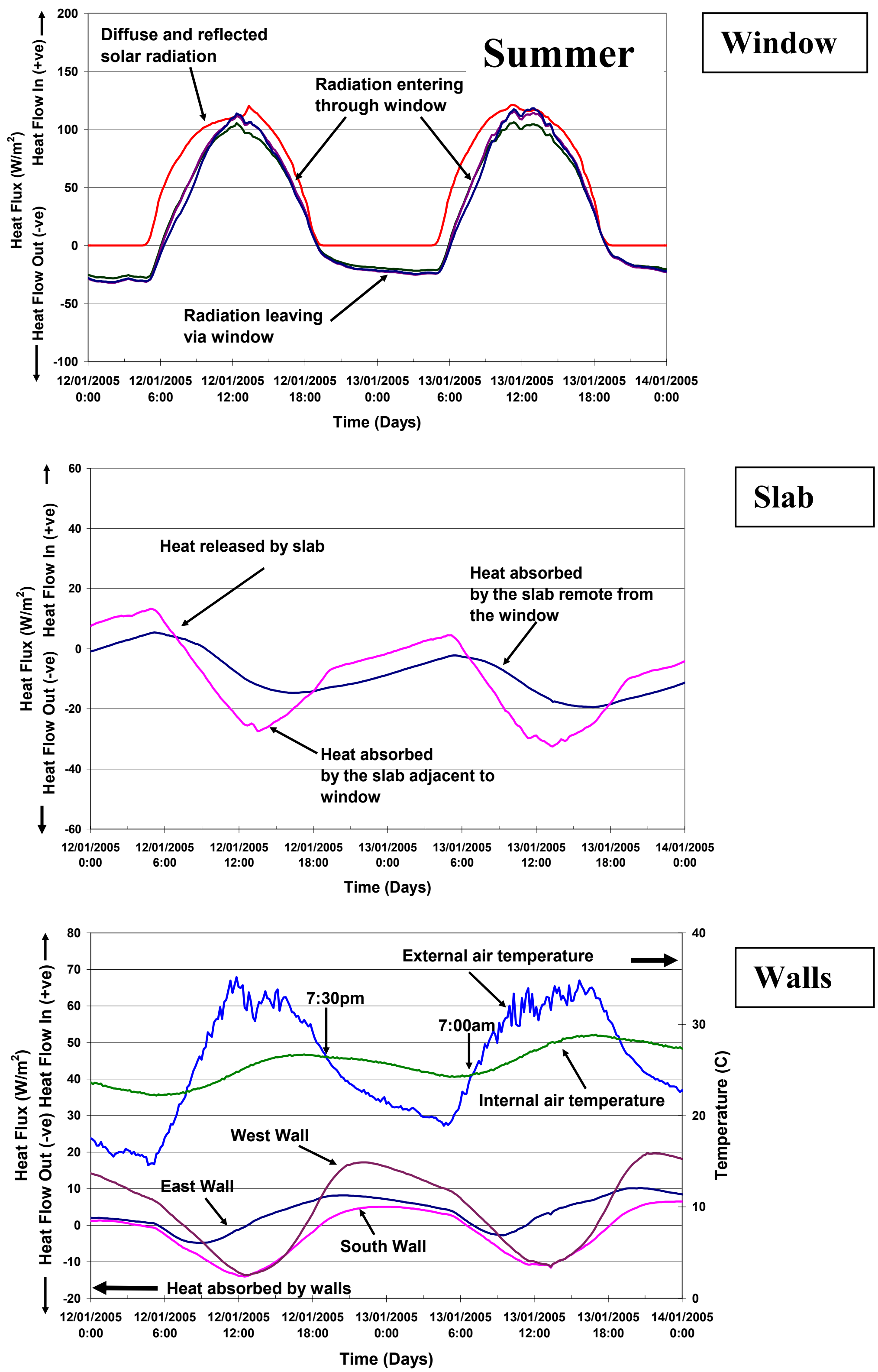

Figure 7 – Heat Exchange via Window, Slab and Interior Walls 12th and 13th January 2005.

The heat flux exchange on the internal walls follows a pattern similar to spring with the absorbed fluxes being less than 15 W/m^2 for the west and south walls. It can also be observed in Figure 7 that all walls introduce some of the stored heat into the room during the night. The peak values range from about 10 W/m^2 for the east wall and up to 20 W/m^2 for the west wall. This west wall value is higher than the peak flux of 13 W/m^2 observed in Module 2, of identical construction but windowless, during heat wave conditions (42.5ºC) in February 2004 [3, 4].

CONCLUSION

Preliminary findings are presented in this report on the heat entering and leaving a cavity brick thermal test building incorporating a large, north-facing window. The data presented has been selected for clear, sunny days when the solar radiation entering via the window becomes the dominant driving force. Under these conditions, the area of the slab receiving the direct solar radiation is heated during the day with the heat being released during the night. Some heat is absorbed by the internal surfaces of the exterior walls, and this is also influenced by the solar radiation on the exterior surface resulting in bi-directional heat flow across the wall. Further analysis of the heat transfer process is required to understand more thoroughly the factors involved and provide quantitative data. Examination of the data is also required for sequential days where abrupt changes in the weather occur. It would also be beneficial to add an internal wall and introduce ventilation into the building to evaluate the response of heavy mass walls, as this would more closely resemble the conditions in a domestic building.

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