





FACULTY OF ENGINEERING AND BUILT ENVIRONMENT

www.newcastle.edu.au

# A STUDY OF THE EFFECT OF GROUND HEAT TRANSFER ON THE THERMAL PERFORMANCE OF BUILDINGS

This study has been undertaken on behalf of The Department of Climate Change and Energy Efficiency and funded by all Australian jurisdictions represented through the National Framework for Energy Efficiency (NFEE)

Prepared by: Dr D. Alterman<sup>\*1</sup>, Dr C. Luo<sup>1</sup>, Prof. B. Moghtaderi<sup>1</sup> and Dr Dong Chen<sup>2</sup>

> <sup>1)</sup> Priority Research Centre for Energy Chemical Engineering, School of Engineering Faculty of Engineering & Built Environment The University of Newcastle Callaghan, NSW 2308

> > <sup>2)</sup> Urban Systems Program CSIRO Ecosystem Sciences

\* Corresponding author's email: Dariusz.Alterman@newcastle.edu.au

Date: 25/07/2012

# **EXECUTIVE SUMMARY**

This document summarises the results of a project aimed at validating the ground model in the Chenath calculation engine against experimental measurements obtained from a slab-on-ground test house module at the University of Newcastle.

The purpose of the Chenath ground model is to quantify the amount of heat gained or lost between a dwelling's internal environment and the ground below it (via the slab) for each hour of an annual simulation.

The analysis indicated reasonable correspondence between actual heat flux measurements and the predictions generated by the Chenath ground model algorithm. However, it is noted that the measured heat flux has been generalized for a whole slab area based on a 100mmx100mm sensor located 1 metre from the centre of the slab, limiting the precision of the current investigation.

The research also demonstrated that the heat exchange dynamics predicted by the Chenath ground model is consistent with 3-dimensional modelling software, HEAT3.

Overall, the results indicate reasonable validity of the Chenath ground model. However, further investigation is required to validate the ground model more precisely.

# CONTENTS

| 1. INTRODUCTON                         | 4  |
|--|----|
| 1.1. BACKGROUND                        | 4  |
| 1.2. PROJECT AIM & SCOPE               | 4  |
| 1.3. PROJECT DELIVERABLES              | 4  |
| 2. TEST MODULE description             | 5  |
| 3. METHODOLOGY                         | 8  |
| 3.1. OVERVIEW                          | 8  |
| 3.2. THE ACCURATE/CHENATH GROUND MODEL | 8  |
| 3.3. COMPLEX FOURIER ANALYSIS          | 10 |
| 3.4. HEAT3 3D SIMULATIONS              | 11 |
| 4. RESULTS AND DISCUSSION              | 12 |
| 4.1. HEAT FLUX COMPARISON              | 12 |
| 4.2. STATISTICAL ANALYSES              | 21 |
| 4.3. DISCUSSION                        | 21 |
| 5. CONCLUSIONS                         | 23 |
| ACKNOWLEDGEMENT                        | 23 |
| REFERENCES                             | 23 |
| APPENDIX A                             | 24 |
| APPENDIX B                             |    |
| APPENDIX C                             |    |

# 1. INTRODUCTON

#### **1.1. BACKGROUND**

There are many environmental and economic concerns with regards to the impacts of the current level of energy consumption. As issues such as climate change and rising energy costs continue to be at the forefront of the debate on energy use, adaptation to more efficient energy use for all energy consuming sectors becomes inevitable.

Building heating and cooling energy use constitutes a significant part of total household energy consumption in Australia. During the last decade, the establishment and adoption of the Nationwide House Energy Rating Scheme (NatHERS) has played a critical role in the energy efficiency of the Australian residential building sector.

As National Administrator of NatHERS, the Department of Climate Change and Energy Efficiency (DCCEE) has a strong interest in the ongoing validation and refinement of the benchmark software - made up of a combination of the Chenath calculation engine and the AccuRate interface. As part of the Department's commitment in this area, this project has been undertaken to assess the validity of the current ground heat transfer calculations within the Chenath engine.

Research to validate the ground model is pertinent given the significance of heat flux from the ground in determining the thermal performance of residential buildings, and the widespread use of ground-coupled concrete slab construction in Australian dwelling designs. It is hoped that this work will help to improve understanding and confidence in NatHERS tools by analysing fundamental calculations within the software in order to establish the accuracy of the algorithms and/or to identify any areas for improvement.

# **1.2. PROJECT AIM & SCOPE**

The main purpose of the research is to validate the ground model adopted in the Chenath engine using experimental dataset obtained from test cell modules at the University of Newcastle collected since 2003.

The project aims to compare the actual measured heat flux with the predicted heat flux calculated by the Chenath engine which calculates the whole slab heat exchange.

It is noted that the measured heat flux were obtained only under Newcastle climatic conditions and were generalized for a whole slab area based on a 100mmx100mm sensor located one meter from the centre of the slab towards the eastern corner of the module. These experimental constraints have limited the project to a preliminary investigation. Further research is required to better assess Chenath ground model using measurements with multiple heat flux sensors at different locations.

# **1.3. PROJECT DELIVERABLES**

The project deliverables were:

• A draft report outlining the key findings of the study and providing sufficient data in tabulated and plotted forms to facilitate the discussions.

• A comprehensive final report containing all the essential information given in the draft report together with additional analysis and conclusions arising from discussions with CSIRO and DCCEE.

# 2. TEST MODULE DESCRIPTION

Four test building modules were constructed in the University of Newcastle Callaghan Campus in suburban Newcastle at latitude 33°south. The performance of each module was observed with the interior space being either in a 'free-floating' state (directly influenced by ambient weather conditions), or with the interior artificially heated or cooled to a preset temperature range [1]. The free-floating state, solely influenced by the external weather conditions is considered in this research.

The modules had a square floor plan of 6 m x 6 m and were spaced 7 m apart to avoid shading and minimise wind obstruction. With the exception of the walls and roofs, the buildings were of identical construction following standard Australian practice, being built on a concrete slab-on-ground and aligned in a manner so that the north wall of each building was aligned to astronomical north.

Heat flux sensors were placed on the walls, ceilings and concrete slab (see Figure 1). Thermocouples were placed on the surface of the slab at various locations between the window and the centre of the room. In total, 105 data channels were scanned and logged every 5 minutes for the module (see Figure 2).



Figure 1 Heat Flux sensor fixed to the slab for the Brick Veneer module.



Figure 2 Thermocouple and Heat Flux Layout for the Brick Veneer module.

All temperatures were read using Type T thermocouples connected to three, 30 channel expansion modules. To minimise any cold junction compensation errors, all the thermocouple inputs were maintained at uniform temperature through the use of a thick wall aluminium box as shown in Figure 3. The thermocouples recording air temperatures were placed inside shields to reduce the influence of radiation effects. All other thermocouples were glued onto the solid surface and profile thermocouples were drilled into the masonry units. The temperature recording system (thermocouple wire characteristics, cold junction compensation etc) was calibrated using a Prema Precision Thermometer within the controlled space of the guarded hot box and the corresponding temperature offsets were programmed for automatic adjustment during the logging process.



Figure 3 Data Logging System, Internal Air and Window Radiation Sensors

Heat flux profiles were measured using 100x100mm ultra-thin sensors with typical sensitivities in the order of  $25 \mu V/W/m^2.$ 

# **3. METHODOLOGY**

## 3.1. OVERVIEW

The methodology adopted in the research forms a preliminary validation of the Chenath engine ground model which calculates the dynamic heat exchange between the ground underneath a dwelling and the inside air. Heat transfer between the building's indoor air and the ground underneath the floor is a complex three-dimensional heat conduction and convection process which can account for 15% - 45% of annual thermal loads for slab-on-grade buildings.

The heat transfer between the indoor air and the ground is primarily driven by the temperature differences between indoor air, outdoor air and the ground, and is mediated by the capacitance and conductance effects of the floor. The main challenge in the ground heat transfer calculation is due to its dynamic three-dimensional nature and the significant thermal mass effect which must be taken into account for ground heat transfer modelling. In this study, the total heat transfer rate through the indoor surface of the slab floor is taken as the most appropriate physical measure for validation purposes. The total heat transfer rate can be calculated by multiplying the average heat flux with the floor area. The heat flux refers to the rate of heat transfer through a unit surface area (in this case the surface of the slab) measured here in Watts per m<sup>2</sup>.

The method proceeds by first establishing actual localised heat flux by reference to measured values recorded by the heat flux sensor and logging equipment as shown in Figure 1. Fourier analysis was then performed to establish surface flux relationships with key variables such as indoor and outdoor temperatures based on the heat transfer formula used in the Chenath engine.

The heat transfer results derived from real measurements are then compared with predictions produced by the Chenath ground model algorithm, enabling empirical evaluation of the algorithm. To provide an independent theoretical check for both sets of results, a 3<sup>rd</sup> set of values were generated using commercial thermal modelling software (Heat3) and plotted alongside both Chenath-predicted values and empirically-derived values.

It is noted that due to the significant difference in the heat flux expected between the core and edge of the slab surface, the heat flux measurements which were taken at only one location on the slab surface are limited in capacity for precise comparison with Chenath predictions which calculates heat transfer for the entire slab.

# **3.2. THE ACCURATE/CHENATH GROUND MODEL**

The purpose of the AccuRate/Chenath ground model is to quantify the amount of heat gained or lost between a dwelling's internal environment and the ground below it (via the slab) for each hour of the annual simulation. The model estimates total surface heat transfer rate (Q) for the entire slab area.

In 1983, Delsante *et al* [3] gave a 3D steady-state analytical solution for the slab-onground heat transfer problem with rectangular building geometry. This important study was quickly highly recognised by the building simulation society. It is the only 3D analytical solution currently available for validating the slab on ground heat transfer calculation within the IES BESTEST ground coupling test procedure. However, this 3D analytical solution is only for steady state ground heat transfer scenarios.

An approximate 3D transient heat transfer equation was later constructed by Dr Delsante based on his 2D transient analytical solution in the same paper [3]. Delsante's steady state 3D analytical solution and the approximate 3D transient heat transfer equation form the core of the current ground model in the Chenath engine.

For steady state, Chenath engine uses Eq. (1) for the ground U-value

$$U = Q/LB = (2k/\pi Wx)(\ln(1+x) + x\ln(1+1/x))$$
(1)

where U = Q/LB is the ground U-value, and x = LB/(W(L+B)) or in general  $x = 2 \cdot Area/(W \cdot Perimeter)$ ; k is the thermal conductivity of the ground; W is the wall width; L and B are the length and the width of the slab.

For 3D transient ground heat transfer, the Chenath engine uses the approximate ground heat transfer Eq. (2) as shown below

$$\widetilde{Q} = \left\{ \frac{k(T_i - T_o)P}{\pi a W} [\pi / 4 - Ki_1(aW) + Ki_3(aW) - Ki_1(2Aa/P) + Ki_3(2Aa/P) + Ki_1(a(2A/P+W)) - Ki_3(a(2A/P+W))] + kaLBT_i \right\} \exp(j\Omega t)$$

$$(2)$$

where Q is the heat flow amplitude and  $T_i$  and  $T_o$  are the indoor and outdoor temperature amplitude respectively.  $a = (j\Omega/\alpha)^{1/2}$  where  $\Omega$  is the angular frequency and  $\alpha$  is the ground thermal diffusivity.  $j = \sqrt{-1}$  and t is time.  $Ki_1 \, dn \, Ki_3$  are the repeated integrals of the modified Bessel function  $K_0$ .

In the Chenath engine, the frequency response of the building is first calculated over a range of frequencies. The response to a transient pulse is then derived from the frequency response via linear system theory. In the existing Chenath engine, frequency response at 59 frequencies, given by  $(2\pi/24) \cdot 2^{(n-39)/2}$  (n =1,2,...,59) radians per hour are evaluated.

Considering the transient nature of heat transfer via the ground, the initial condition (temperature distribution) in the ground can have some impact for the first several

years after the house is built, with the effect diminishing over several years. The average annual ambient temperature is generally regarded as a good estimation of the average ground temperature prior to construction of a building above, and is used by Chenath to estimate the initial ground condition. After a house is built, the ground temperature underneath will change slowly and will normally require several years to re-stabilize.

#### **3.3. COMPLEX FOURIER ANALYSIS**

To establish and check values for validation, Complex Fourier Analysis was used to calculate the amplitudes of driving temperatures (based on test cell environmental data) and associated total surface heat flux (see Appendix A, Appendix B and Appendix C). The time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat is flowing. Local heat flux density (the amount of energy that flows through a unit area per unit time) is equal to the product of thermal conductivity, and the negative local temperature gradient.

Temperature and surface heat flux can be expressed in complex Fourier expansion as:

$$T_{in}(t) = T_{in0} + \sum_{k=1}^{N} T_{ik} e^{j\omega_k t}$$
(3)

$$T_{out}(t) = T_{o0} + \sum_{k=1}^{N} T_{ok} e^{j\omega_k t}$$
(4)

$$Q(t) = Q_0 + \sum_{k=1}^{N} Q_k e^{j\omega_k t}$$
<sup>(5)</sup>

In which T is the temperature, t the time variable,  $\omega_k$  the angular frequency,  $\alpha$  the thermal diffusivity  $(k/\rho C_p)$ , Q the heat flux.  $T_{ok}$ ,  $T_{ik}$  and  $Q_k$  are the amplitudes of the complex Fourier expansions for outdoor and indoor temperatures and surface heat flux, respectively at the specified angular frequency  $\omega_k$ . T, Q,  $T_{ik}$ , and  $Q_k$  are all complex numbers and j is the unit imaginary part of the complex numbers.

With the complex Fourier analysis method, the following steps were undertaken to enable predicted heat flux over time to be compared with actual measurements:

- 1. Calculate the  $T_{ok}$  and  $T_{ik}$  (amplitudes of the complex Fourier expansions for outdoor and indoor temperatures) from the time history of the indoor and outdoor temperature through the complex Fourier analysis
- 2. Input the parameters for calculation of the amplitudes of heat conductance through surface to ground.
- 3. Calculate the  $Q_k$  (surface heat flux) using Equations 1 and 2
- 4. Calculate the  $Q_{(t)}$  (heat flux through time) using Equation 5

5. Compare calculated  $Q_{(t)}$  with measurements.

#### 3.4. HEAT3 3D SIMULATIONS

In order to provide an independent check to assist in analysis and validation, simulations were also carried out using 3-dimensional finite difference simulation software, HEAT3. HEAT3 is a general purpose heat transfer calculation software and it is not specifically intended for house energy simulation. However, for a well defined slab on ground heat transfer problem, it is expected that HEAT3 should give reasonably accurate predictions with adequate boundary conditions and grid settings. This software has been internationally validated against several theoretical solutions, specified under ISO 10211.

Figures 4 and 5 show the HEAT3 representations of the slab on ground model. For modelling purposes, the ground is spatially represented as a 20 m cubic. The slab was modelled at a quarter of its actual size to take advantage of mathematical symmetry of this rectangular slab heat transfer problem.



Figure 4 HEAT3 3D representation of the slab on ground (a quarter size)



Figure 5 Schematic vertical section view of the Heat3 slab on ground model

Simulation was conducted to provide predicted heat transfer results for a 10 year period, allowing for the time taken for ground temperature stabilisation. It was noted that the heat transfer and temperature field were still not completely stabilized after HEAT3 simulation for 10 years. This simulation using HEAT3 took over 24 hours computer processing time. By comparison, the Chenath engine took approximately 5 minutes to simulate heat flux for the same 10 year period.

# 4. RESULTS AND DISCUSSION

# 4.1. HEAT FLUX COMPARISON

Table 1 below shows the common parameters used.

| Parameter                                | Value | Unit            |
|--|-------|-----------------|
| Slab length                              | 6.0   | m               |
| Slab width                               | 6.0   | m               |
| Slab perimeter                           | 24.0  | m               |
| Slab area                                | 36.0  | m <sup>2</sup>  |
| Indoor surface heat transfer coefficient | 9.17  | $W/m^2 \cdot k$ |
| Wall width                               | 0.25  | m               |
| Ground thermal conductivity              | 0.7   | W/m·k           |

Table 1 Parameters used in the ground model validation study

|  | Ground thermal diffusivity | 4.44×10 <sup>-7</sup> | $m^2/s$ |
|--|----------------------------|-----------------------|---------|
|--|----------------------------|-----------------------|---------|

As shown in Figure 1C - 7C in Appendix C, the comparison between the heat transfer predictions using Fourier analysis and the measurements are not very satisfied. It is should be noted that the frequency range in the current Fourier analysis is from 1 hour to 1 month. For proper ground heat transfer modelling, a much wider frequency range, especially much lower frequency limit should be used such as that used in the Chenath engine.

Heat flux results as predicted by both Chenath and HEAT3 were plotted against measured results. Results were graphed for a number of months, as shown in Table 2. Observations from Figure 12 suggest that a problem occurred to the test system around 28th November 2003 (following replacement of a sensor) leading to a sudden drop in the heat flux measurements for some months thereafter. For this reason, comparisons were limited to months with reliable data quality.

| Months    | Year |
|-----------|------|
| March     | 2003 |
| April     | 2003 |
| May       | 2003 |
| August    | 2003 |
| September | 2003 |
| October   | 2003 |
| November  | 2003 |

 Table 2. Months heat flux measurements are available for comparison

The measured total slab floor heat losses were calculated by multiplying heat flux measurements (obtained from the sensor located one meter from the centre of the slab towards the eastern corner of the module in Watts per  $m^2$ ) with the slab floor area of  $36 m^2$ . Some variation in heat flux between the centre of the floor and the slab edge is expected due to the greater temperature gradients near the slab edge. For example, the heat loss at the edges could be around 25% greater than the average heat flux of the entire slab., However, the variation in the heat flux along the slab surface is not linear which complicates efforts to resolve the problem precisely. The need for floor area scaling to enable comparison therefore introduces a degree of uncertainty and is a noted limitation of this study.

Figures 6 to 12 show the comparisons of the total slab floor heat losses for each month. In the figures, positive Ground Heat Loss means heat lost from the indoor air to the ground. Negative Ground Heat Loss means heat gained from the ground to indoor air.



Figure 6 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for March 2003



Figure 7 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for April 2003.



Figure 8 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for May 2003.



Figure 9 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for August 2003.



Figure 10 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for September 2003.



Figure 11 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for October 2003.



Figure 12 Comparisons between slab floor heat loss measurements, Chenath predictions and HEAT3 predictions for November 2003

# 4.2. STATISTICAL ANALYSES

Basic statistical parameters such as minimum, maximum, average and standard deviation analysis was undertaken to evaluate discrepancy between measurements and AccuRate predictions for every month considered as shown in Table 3. The analysis was based on the same data presented in the figures in Section 4.1.

|                  | Max   | Min    | Average | STDEV |
|------------------|-------|--------|---------|-------|
|                  | [W]   | [W]    | [W]     | [W]   |
| March (2003)     | 322.1 | 0.2    | 36.4    | 66.9  |
| April (2003)     | 218   | 5.5    | 12.1    | 49.4  |
| May (2003)       | 335.7 | 1      | 1.7     | 65.7  |
| August (2003)    | -1.6  | -510.8 | -20.3   | 64.1  |
| September (2003) | 209.4 | 0.1    | 9.1     | 60.9  |
| October (2003)   | 504.4 | 0.2    | 17      | 53.9  |
| November (2003)  | 637.8 | 0.3    | 38.6    | 146.4 |

**Table 3** Residual difference between the AccuRate formula and measurement

Extremes represented by the maximum and minimum differences for one day in every monthly period are significant, reaching 500 Watts, however averages are minimal or even close to zero. This highlights that AccuRate over predicted peaks for certain days; however standard deviation analysis showed reasonable predictions for the analysed monthly periods (see Figure 13).



Figure 13 Discrepancy between measurements and AccuRate predictions for annual data.

#### 4.3. **DISCUSSION**

All graphs from Figure 6 to Figure 12 demonstrated reasonable correspondence between actual heat flux measurements and the predictions generated by the Chenath ground model. In

general it can be seen that the Chenath engine predictions correlate well with the measurements in terms of the trends in curve gradients and the timing of daily phase shifts.

Most of the discrepancy is apparent at the peaks of positive ground heat loss (heat lost from the dwelling indoor air to the ground) where AccuRate seems to be significantly overpredicting the quantity of heat lost at these phase shifts. This general pattern of the Chenath engine predicting higher-than-measured amplitudes of the diurnal heat flux may be explained by the location of the heat flux measurements, which were taken one meter from the centre of the slab towards the eastern corner of the module. As previously discussed, the Chenath engine calculates the sum of the slab edge as well as the core region heat transfer. Considering that measurements were only taken in one location the comparisons between the measurements and the Chenath predictions are encouraging.

It was also found that the heat losses predicted by the Chenath engine are close to the HEAT3 simulation results which were obtained after simulation for 10 years. It is understood that there is currently no precise analytical solutions for 3D transient ground heat transfer.

It is noted that Eq. (2) is an extrapolation of an exact 2D solution by Delsante et al [3]. Using the responses from 69 discrete frequencies in Chenath to represent the real stepwise driving forces (the indoor and outdoor temperatures) can also give rise to inaccuracy to a certain extent. Consequently, although the comparisons presented in Figure 6 to Figure 12 are encouraging, further investigations are needed for validating and improving the Chenath engine ground model in the future.

The test module used for the current validation study did not have windows on the walls. When windows are presented, the heat transfer from the indoor air via the slab and the ground underneath it becomes more complex due to uneven solar exposure on the slab surface. The complexity of the heat exchange between the slab, exposed to the direct solar radiation, the internal air and the ground can be indicated by the temperature distribution on the slab as presented in Figure 14. So far, there are no building simulation tools which consider such uneven solar exposure. The Chenath engine treats solar exposure through windows to be evenly distributed across the slab floor of a room as a simplification of the real situation. Further investigation is required to quantify the implication of such simplification.



**Figure 14** Temperature distributions throughout the slab exposed to direct solar radiation for eastern (left) and western (right) part of the module with a window faced towards North. Note: pictures were taken with an Infrared camera.

# 5. CONCLUSIONS

Conclusions drawn here are based on the validation of the ground model adopted in the Chenath engine using experimental measurements and finite difference numerical model HEAT3.

- 1. The research indicated reasonable consistency between the predictions of Chenath ground model with actual measured values.
- 2. The research indicated that the Chenath ground model produced results consistent with commercial 3-dimensional modelling software, HEAT3.
- 3. In general, the predictions of Chenath fell between the bounds of the measured results and the HEAT3 results, demonstrating its validity as a reasonable model of the complex dynamics of ground heat transfer.
- 4. The issue of whether the ground model requires fine tuning was unable to be resolved due to the limits of the current methodology. Further investigation is required to validate the ground model at a higher degree of resolution.

## ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support provided by the Department of Climate Change & Energy Efficiency. Mr Ian Swain and Mr Paul Nagle from DCCEE are gratefully acknowledged for their support, inputs and fruitful discussions during the duration of the project.

#### REFERENCES

- [1] Page A. W., Moghtaderi B., Alterman D. and Hands S., A Study of the Thermal Performance of Australian Housing, Priority Research Centre for Energy, the University of Newcastle, 2011, (available on http://www.thinkbrick.com.au/thermal-performanceand-climate-design).
- [2] HEAT version 3.5. http://www.buildingphysics.com/index-filer/Page548.htm.
- [3] Delsante A.E., A.N. Stokes, P.J. Walsh. (1983). Application of Fourier Transforms to Periodic Heat Flow into the Ground under a Building. International Journal of Heat Mass Transfer, 26(1): 121-132.
- [4] Dong Chen, Chenath Engine Ground Model Validation Study, Urban Systems Program, CSIRO Ecosystem Sciences, 2012

## **APPENDIX A**

Outdoor temperature profiles validation (between the ground and the outdoor air) using Complex Fourier Analysis for the Brick Veneer module is shown in Figures 1A-7A.



Figure 1A: Outdoor temperature amplitude validation for March 2003



Figure 2A: Outdoor temperature amplitude validation for April 2003



Figure 3A: Outdoor temperature amplitude validation for May 2003



Figure 4A: Outdoor temperature amplitude validation for August 2003



Figure 5A: Outdoor temperature amplitude validation for September 2003



Figure 6A: Outdoor temperature amplitude validation for October 2003



Figure 7A: Outdoor temperature amplitude validation for November 2003

### **APPENDIX B**

Indoor temperature profiles validation (between the ground and the dwelling indoor air) using Complex Fourier Analysis for the Brick Veneer module is shown in Figures 1B-7B.



Figure 1B: Indoor temperature amplitude validation for March 2003



Figure 2B: Indoor temperature amplitude validation for April 2003



Figure 3B: Indoor temperature amplitude validation for May 2003



Figure 4B: Indoor temperature amplitude validation for August 2003



Figure 5B: Indoor temperature amplitude validation for September 2003



Figure 6B: Indoor temperature amplitude validation for October 2003



Figure 7B: Indoor temperature amplitude validation for November 2003

## **APPENDIX C**

Surface heat flux comparison between Fourier analysis method based on CSIRO formula Eqs. (1) and (2) and measurements for the Brick Veneer Module Note: measurements here are given for the heat flux sensor at a size of 10x10cm.



Figure 1C: Surface heat flux measurements for March 2003



Figure 2C: Surface heat flux measurements for April 2003



Figure 3C: Surface heat flux measurements for May 2003



Figure 4C: Surface heat flux measurements for August 2003



Figure 5C: Surface heat flux measurements for September 2003



Figure 6C: Surface heat flux measurements for October 2003



Figure 7C: Surface heat flux measurements for November 2003