APPLICATION OF THE THREE-DIMENSIONAL NUMERICAL GENERATION OF RESPONSE FACTORS (NGRF) METHOD OF MULTI-YEAR BASED CONDUCTIVE TEMPERATURES IN SOIL AND PASSIVE COOLING EARTH-CONTACT COMPONENTS

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ABSTRACT

The presented paper reports on the application of a method for the numerical prediction of temperatures within and around structural passive cooling components. The recently developed method named the three-dimensional numerical generation of response factors NGRF (Zoras et al., 2009) was claimed to be fast, accurate and flexible as a result of incorporating elements of the response factor method into a finite volume technique based numerical model. Initially, a 'pre-processing' procedure is required to generate a certain number of hours, e.g. 50 hours, for use as a time-series by the response factor technique in the second stage of the method. This method solves the three-dimensional earth-contact temperature profiles, which interact with indoors and outdoors temperature profiles. Once the numerical temperature response factors time series of an earth-contact component's grid node have been generated then its future thermal performance due to any surrounding temperature variation can be predicted fast and accurately. The NGRF method is applied through an intermodel testing procedure to simulate soil and structural earth-contact passive cooling component temperatures for multiple years.

INTRODUCTION

The exact behavior of building earth-coupled systems can, theoretically, be determined by analytical solutions. However, difficulties arise in the application of these solutions that have led to simplifications being made in the treatment of the problem. Analytical methods can however be applied in a fast and efficient way in certain cases (e.g. simple geometry). An important limitation is that, generally, the analytical methods assume constant internal temperature and sinusoidally time varying outdoor temperature, which does not perform efficiently in many cases.

The theoretical determination of thermal response factors can generally only be made analytically in one dimension and for homogeneous systems. However, heat transfer is a multidimensional procedure and in many cases the structural components of the buildings are characterized as heterogeneous. Thus, if the thermal system under consideration includes the ground, the determination of temperature response factors is generally not possible analytically because the ground generally is heterogeneous and the heat transfer takes place via a three dimensional space. The use of experimental methods would not be applicable because it is not possible to control the thermal conditions of the soil in a multidimensional environment like the ground and the earth surface temperature.

Numerical models treat the three-dimensional heat transfer from earth-contact in the most efficient way but they are relatively slow. Three-dimensional numerical methods can deal with 'all' the parameters influencing earth-coupled systems but long computer run times are needed. However, these methods are useful since they provide flexible simulation and accurate results. The addition of numerical methods into general simulation models (e.g. APACHE (Davies, 1994) and TRNSYS (Mihalakakou et al., 1995) for the modeling of the earth coupling yielded tools that can deal with all the aspects influenced in a building (e.g. HVAC components).

There is thus a requirement for a design tool which can offer accuracy, speed and flexibility in terms of the structures that it can address. This design tool should be capable of performing rapid parametric analyses of the structures to determine the design priorities. Numerical models appear to be capable of satisfactorily modelling earth-contact heat transfer in terms of accuracy and flexibility. Such models are however too slow to be considered for use within a design tool especially given the requirements for repeated parametric simulations. It was shown though that numerical methods could be adapted for use in a design tool such that the speed can be dramatically increased whilst still retaining their accuracy and flexibility (Zoras et al., 2009). This adaptation involves the combination of a numerical method (in this case finite volume) with elements of the response factor method which is given the name 'Numerical Generation of Response Factors' (NGRF).

Soil temperature is an important factor for calculating the thermal performance of buildings in contact with the ground. In order for energy-efficient and 'comfortable' buildings to be designed and constructed, an understanding of the dynamic, interactive heat transfer processes, of which earth-contact passive cooling components' temperature is one, must be achieved. Critically, this understanding must be arrived at early enough in the design process for it to have an impact on the final design. Sometimes it is of paramount importance to evaluate the thermal performance of a building at a specific location over a long period of time. If the initial ground field of temperatures is known at the time the simulation starts then the period of simulation shortens. Usually, this is not the case and thus, an initial ground temperature must be assumed and the model run for a longer period (e.g. 3 years), in order to approximate the thermal performance of the earth-contact domain when it reaches equilibrium. Actually, the model needs to run until there are no more significant differences in the heat transfer distribution year after year. The duration of the period that the simulation must be carried out depends on how good the initial ground temperature has been approximated in relation to the meteorological conditions and the location. The NGRF method is proved to work dramatically faster than pure three-dimensional numerical models whilst retaining a high degree of accuracy. Thus, the advantage of the NGRF ground temperature representation is that there is no need for past soil temperature profile data apart from an initial above ground boundary set of conditions. NGRF method would be at its most useful when it is applied in time consuming multiyear simulations and repeated parametric analyses procedures whilst retaining the accuracy and flexibility of three dimensional numerical modeling.

Thus, the basic concept of this work is to improve the speed of such models without losing accuracy whilst still retaining the flexibility of these models in simulating complex geometries. Therefore, the only applicable method for the determination of thermal response factors would have been numerical models that solve the transient heat conduction equation in three dimensions. This would be the temperature representation of a wall or floor grid node on contact with soil and room air.

REVIEW OF THE METHOD

Response Factor Technique

The response factor technique makes use of the concept of determining the response of each structural element to known perturbations and then using this information to predict the response to other perturbations via a superposition method, where the overall resulting response is the sum of the weighted responses. The implementation of the response factor technique requires a linear and an invariant system. Therefore, any changes in the thermo physical properties of the solids due to changes of the temperature and the moisture content, are considered to cause acceptably small errors. These responses have been analytically calculated and tabulated for a wide variety of wall and floor types (ASHRAE, 1997) in one dimension. Generally, the analytical three-dimensional determination of these factors is not possible, thus, in this study a three-dimensional numerical generation of the response factors (i.e. NGRF) has been proposed. Initially, a numerical model is used to produce two response time series due to changes in the internal boundary conditions for every room of an earth-coupled building corresponding to the air and radiant temperatures and one response time series due to changes in the external boundary conditions. The calculation of temperature for the buried slabs is then given by Equation 1. $T_{ai}^{(N)}$ is the temperature difference between the air point temperature in room N and the base temperature of the pulse (10 deg. C), $T_{ri}^{(N)}$ is the temperature difference between the radiant point temperature in room N and the base temperature of the pulse (10 deg. C), $Z_a^{(N)}$ are the time series response factors due to an air point temperature excitation and $Z_a^{(N)}$-10 is the temperature variation from base in the Nth room's passive cooling component whilst all the other excitations are set at 10 deg. C, $Z_r^{(N)}$ are the time series response factors due to a radiant point temperature excitation and $Z_r^{(N)}$-10 is the temperature variation from base in the Nth room's component whilst all the other excitations are set at 10 deg. C. Note that, in Equation 1 if the temperature base of the pulse was different than 10 deg C then the equation would have been refined accordingly.

$$\begin{aligned} T_t = \Bigg\{ & \sum_{p=0}^{s} T_e(t-p)\big(Y(p)-10\big) + \sum_{p=0}^{s} T_{ai}^{(1)}(t-p)\big(Z_a^{(1)}(p)-10\big) \\ & + \sum_{p=0}^{s} T_{ai}^{(2)}(t-p)\big(Z_a^{(2)}(p)-10\big) + \ldots\ldots\ldots\ldots + \sum_{p=0}^{s} T_{ai}^{(N)}(t-p)\big(Z_a^{(N)}(p)-10\big) \\ & + \sum_{p=0}^{s} T_{ri}^{(1)}(t-p)\big(Z_r^{(1)}(p)-10\big) + \sum_{p=0}^{s} T_{ri}^{(2)}(t-p)\big(Z_r^{(2)}(p)-10\big) + \ldots\ldots\ldots\ldots \\ & + \sum_{p=0}^{s} T_{ri}^{(N)}(t-p)\big(Z_r^{(N)}(p)-10\big) \Bigg\} + 10 \end{aligned} \tag{1}$$

The use of Equation 1 for the calculation of a node's hourly temperature (T_t) for a period of one or more years takes only a few seconds. Thus, any changes in the internal ($T_{ai}^{(N)}(t-p), T_{ri}^{(N)}(t-p)$) or external ($T_e(t-p)$) temperature profiles (i.e. during a parametric analysis in which parameters unrelated to ground coupling, e.g window size/type, were varied) would lead to a full simulation with dramatically improved run time. This assumes that the thermal properties of the three dimensional construction remain unchanged (i.e. $Y(p)$,

$Z_r^{(N)}(p), Z_a^{(N)}(p)$: constant). Any parametric studies specifically related to ground coupling (i.e. changes in thermal soil properties or to the foundation insulation configuration etc.) would require new response factors time series to be generated.

Numerical Model

The numerical model (APACHE, 1994) used for the generation of the response time series is based on Patankar's finite volume method (Patankar, 1980) to solve transient linear multi-dimensional conductive heat transfer, the governing equation being:

$$\nabla^2 T = \frac{\rho c}{\lambda} \cdot \frac{\partial T}{\partial t} \tag{2}$$

The thermal conductivity of solids is used as a constant property. The finite volume model can be solved using either an explicit or an implicit scheme. Details and testing of the model (i.e. APACHE) can be found in the study undertaken by Davies (1994). In the present finite volume model (APACHE), the above system of equations is solved by iterations. The stability of the explicit scheme, used in the present study depends on the size of the time step according to the criterion (Patankar, 1980):

$$\Delta t < \frac{\rho c(\Delta x)^2}{2\lambda} \tag{3}$$

METHODOLOGY AND TESTING

A comparison of the NGRF numerical solution against the results of the standard numerical model (APACHE) has been undertaken for four grid nodes i.e. two on the buried walls, one on the floor and one in the soil domain (Figure 1). The output considered for the testing are the hourly temperatures over a period of three years. Equation 1 was applied for the generation of the full simulation for one room.

Process for the Generation of the Time Series Responses for the Structure

The numerical model (APACHE) was used to generate the temperature hourly time series responses where the initial conditions assumed were 10 deg. C throughout. The procedure included the following two simulations:

1. The time series response (i.e. $Y(p)$) of the grid points' temperatures due to an external pulse of 1 deg. C (from an initial 10 deg. C) for 1 hour was generated. The internal boundary conditions for both the air and radiant temperatures in the room were kept constant at 10 deg. C.

2. The time series responses (i.e. $Z_a^{(N)}(p), Z_r^{(N)}(p)$) of the grid points' temperatures due to an internal pulse of 1 deg. C (from an initial 10 deg. C) for equal air and radiant temperature profiles for 1 hour were generated. More specifically, when a 1 deg. pulse of a specific kind of excitation was assumed in the room, all the other temperature excitations in the system were assumed to be constant at all times at 10 deg. C. The external boundary conditions including the soil temperature for each run were kept constant at 10 deg. C.

A certain number of hours of the time series responses are required to give acceptable simulations. The more hours of the time series that are used, the higher the accuracy (Zoras et al., 2009).

Generation of the Full Simulation

The response factor technique (i.e. Equation 1) was used for variable external and internal boundary conditions, to predict the hourly temperatures for three years. The results were then compared with the results from the numerical model for the same period of time.

THE FOUNDATION TEST FACILITY MODULE

The Fundamental Test Facility Module (FTF module) is a test basement with uninsulated floor and walls located at the University of Minnesota. Only the ceiling is well insulated in order to be considered as an adiabatic boundary (*U-value* of 0.007 $Wm^{-2} K^{-1}$). Two U-shaped electric resistances were used to heat the basement with a controlled minimum set point of 20 deg. C. The floor and walls are both concrete with a thermal conductivity and volumetric heat capacity of 1.82 $W m^{-1} K^{-1}$ and 653 $KJ m^{-3} K^{-1}$ respectively. More specifically, the floor is square (5.89 X 5.89 m^2) and the bottom of the walls is 2.03 m below the ground surface for a total height of 2.49 m. Figure 1 shows a schematic section of the structure. The surrounding soil is composed by 15 different kinds of materials (e.g. sands, soils, silt…. etc.) with different thermal properties each. More details about the structure can be found elsewhere (Adjali et al., 1999). For the simulation of the FTF module approximately 40,000 nodes were used and the scheme of solution was explicit. The selected grid nodes for testing were 24539, 25858, 34944 and 25856 (see Figure 1).

BOUNDARY CONDITIONS

Each space in the construction has been considered as an individual boundary with its own boundary conditions. Real hourly temperature profiles were applied to the simulations for the air point temperature of the rooms and the outdoor air. The ground was initialized at 10 deg. C during the generation of the time series responses.

Soil External Surface Boundary

The nodes of the ground surface adjacent to the atmosphere are connected to the external boundary via a 'solair' temperature. The testing of the numerical model in previous studies showed good agreement with real experimental data (Davies, 1994; Davies et al., 1995, Adjali et al., 1999) and the same external boundary conditions were applied to both the numerical solution and the modified solution in this study. The following equation is used for the hourly calculation of 'solair' temperatures:

$$T_{SOLAIR} = T_{OA} + SR[(DIR + DIF)\alpha - \varepsilon RADLWS(SLP)] \quad (4)$$

where the surface resistance (SR), the surface absorptivity (α) and the surface emissivity (ε) have the values of 0.06 m^2 K / W, 0.5, 0.9, respectively. Measured data are used for the calculation of the radiation (DIR and DIF) on a sloping surface (Harkness and Mehta, 1978). The external boundary data applied are shown in Figure 2. These have been repeated for the remaining two years.

Internal Floor Boundary

The finite volume method treats the floor nodes adjacent to the slab as though they are connected to both a radiant and an air temperature point, with the use of the binary star radiant-convective scheme as described by (Davies, 1990). For the purposes of this testing, however, the radiant and air points were treated as a single temperature in order to clarify matters. Note that this does not invalidate the testing described later in this paper as identical boundary conditions are applied to both the standard and modified solution methods. For this work, the indoor boundary conditions are predefined temperature profiles which are shown in Figure 2. These have been repeated for the remaining two years.

DISCUSSION AND RESULTS

Results

Three grid points have been selected on the structural components on contact with the room and one in the soil's domain. A three year simulation was carried out to calculate the hourly grid nodes temperatures using both the original numerical method and the NGRF method. The simulations performed using the NGRF method were undertaken utilizing a portion of the time series responses being 1000 hours. The remainder of the time series response for a three year period (e.g. from 1000 hours to 26280 hours) was set to zero. Figures 3 and 4 show the time series temperature responses at the four grid nodes.

A comparison of the predictions of the models

Figures 5 - 8 show the results of the runs. The hourly Root Mean Square Errors (RMSE) and Pearson correlation coefficients (i.e. original model predictions – NGRF model predictions) for the three year period are shown in Table 1.

Discussion

A method (Equation 1) has been applied for estimating the temperatures of earth-contact passive cooling components based on three dimensional response factors time series estimated by the defined NGRF method. An intermodel testing procedure has been followed in comparison to a pure three dimensional finite volume technique based model (APACHE, 1994).

From Figures 5-8 it is concluded that the nodes' hourly temperature profiles during a three year period were predicted, generally, efficiently by the use of the NGRF method. In Table 1 it is illustrated that even 1000 hours of response factors timeseries seemed sufficient to predict future yearly structural temperatures. It is also noted that the accuracy of the NGRF numerical solution reduces the deeper the grid cell under consideration is. In other words more response factors may be needed with increasing depth because heat waves due to the changes of the temperature at the ground's surface die away with depth.

The most important advantage of the NGRF method in relation to the pure numerical solution was that only two numerical simulations have been carried out, of 1000 hours each, instead of 26280 hours that the full numerical simulation required. This becomes even more obvious when the NGRF method is used in a parametric analysis role. Once the response factors have been determined then every subsequent run takes only a few seconds. This assumes that the thermal properties of the earth-contact domain, including structural components, remain unchanged. Note that, even for "one-off" simulations the NGRF method took 10 minutes to generate the full simulation in contrast to the three year numerical simulation which took, approximately, 8 hours on the same computer machine.

It is also emphasised that the simulation of earth-contact domain and structural components temperatures can be achieved in three dimensions using finite volume models without any flexibility problems such as description of geometry and insulation. Here, the NGRF provides an improvement of such models that has been achieved in terms of speed while retaining a high degree of accuracy. The inclusion of other aspects (e.g. moisture transfer, surface evaporation etc.) influencing earth-contact heat transfer while using fast superposition methods (response factors technique) is still an issue.

Usually, it is of paramount importance to evaluate the thermal performance of a building at a specific location over a long period of time. Usually, an initial ground temperature must be assumed and the model run for a long period (e.g. 3 years), in order to approximate the thermal performance of the earth-contact domain when it reaches equilibrium. Actually, the model needs to run until there are no more significant differences in the heat transfer distribution year after year. The duration of the period that the simulation must be carried out depends on how good the initial structural and ground temperatures have been approximated in relation to the meteorological conditions and the location. Therefore, the application of the NGRF in multiyear simulations would have reduced run times dramatically.

A whole building simulation model could be applied based on this approximation. The temperature of the solid passive cooling component would be predicted by the use of the far more accurate three-dimensional numerical simulation, rapidly, with just an initial outdoors and indoors set of temperatures available.

CONCLUSION

The advantage of the NGRF grid node temperature representation is that there is no need for past soil temperature profile data apart from an initial indoors and outdoors air temperature set of measurements. In addition, NGRF is at its most useful when it is applied in time consuming multiyear simulations and repeated parametric analyses procedures whilst retaining the accuracy and flexibility of three dimensional numerical modeling.

The NGRF methodology applied in this work would be able to simulate earth-contact heat transfer or conductive temperatures with the use of any multi-dimensional linear heat conduction tool. Generally, whole building simulation models solve the problem of earth-contact heat transfer in one dimension because of run time inefficiency, especially for repeated simulations. Thus, this new method (in either two or three dimensional format) could be integrated into such models to improve accuracy.

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NOMENCLATURE

C	specific heat capacity (J kg^{-1} K^{-1})
DIF	diffuse radiation incident on a surface (W m^{-2})
DIR	direct radiation incident on a surface (W m^{-2})
p	position in time series response
RADLWS	function which calculates the longwave radiation from a surface of slope SLP (W m^{-2})
s	the number of time steps of the time series response to be determined
SLP	slope of a surface (deg.)
SR	surface resistance
t	time (s)
T	temperature (C)
Y	time series of response factors of temperature due to unit excitation (c.f. ref. temp.) at external boundary (determined by the numerical model)
Z	time series *of* response factors of flux due to unit excitation (c.f. ref. temp.) at internal boundary (determined by the numerical model)
Greek Symbols	
α	absorptivity of external surface
ε	emissivity of external surface
λ	thermal conductivity (W m-1 K-1)
ρ	density (kg m-3)
Subscripts	
a	air point temperature (i.e. mean air temperature of an entire space)
r	radiant point temperature (i.e. mean radiant temperature of an entire space)
i	summation over the nodes that compose the grid
OA	refers to outside air
SOLAIR	refers to solar air temperature
Superscripts	
N	number of rooms

Table 1: Root mean square errors (RMSE) and Pearson correlation coefficients between the numerical and the modified predicted temperatures at the four grid nodes

Grid node	**34944**	**24539**	**25858**	**25856**
RMSE (deg C)	0.065	0.710	0.683	0.941
Correlation coefficients	0.99	0.95	0.95	0.92

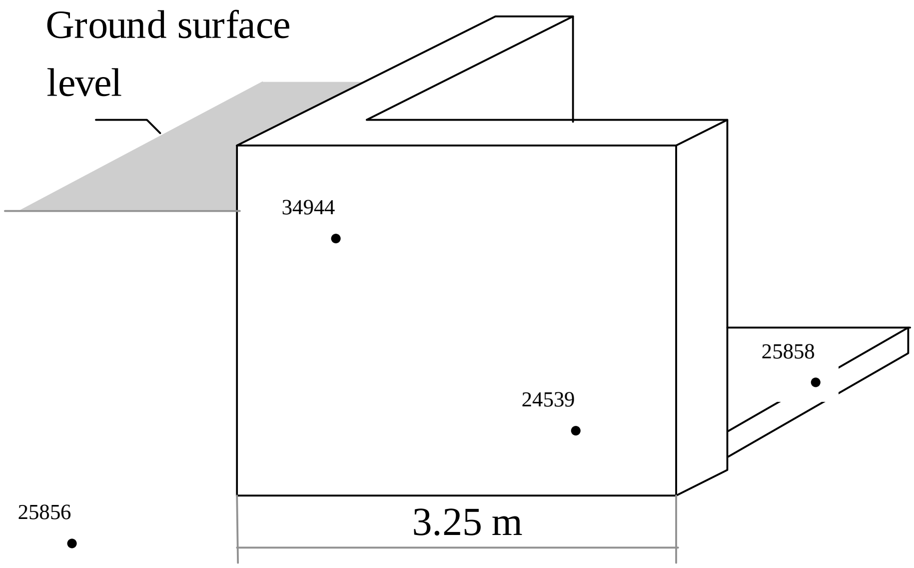

Figure 1 Schematic section of the FTF module.

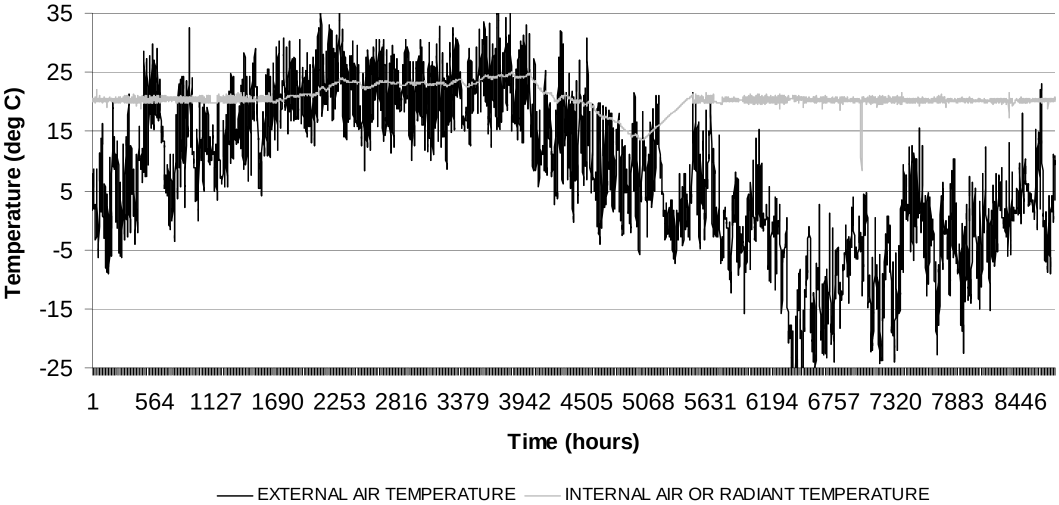

Figure 2 Boundary temperature conditions

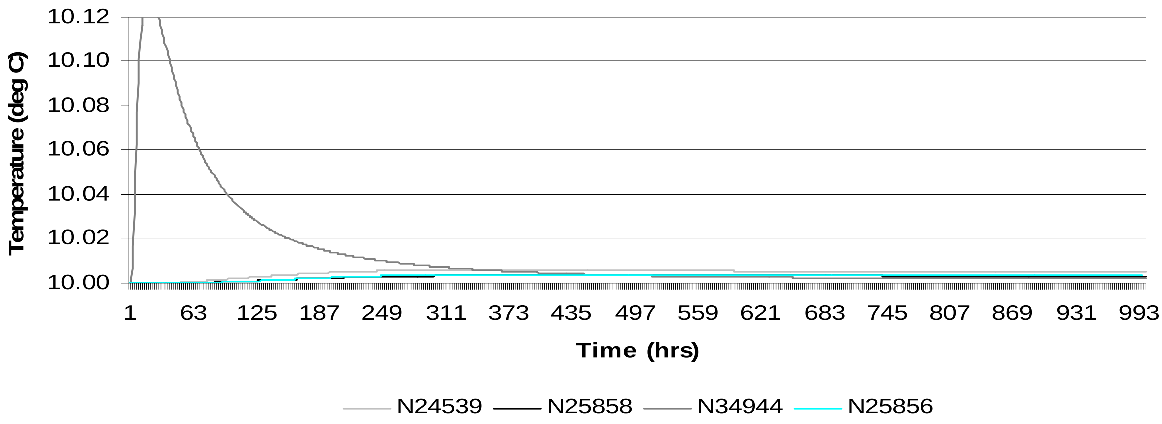

Figure 3 Temperature response factors at the four grid nodes due to an external temperature excitation

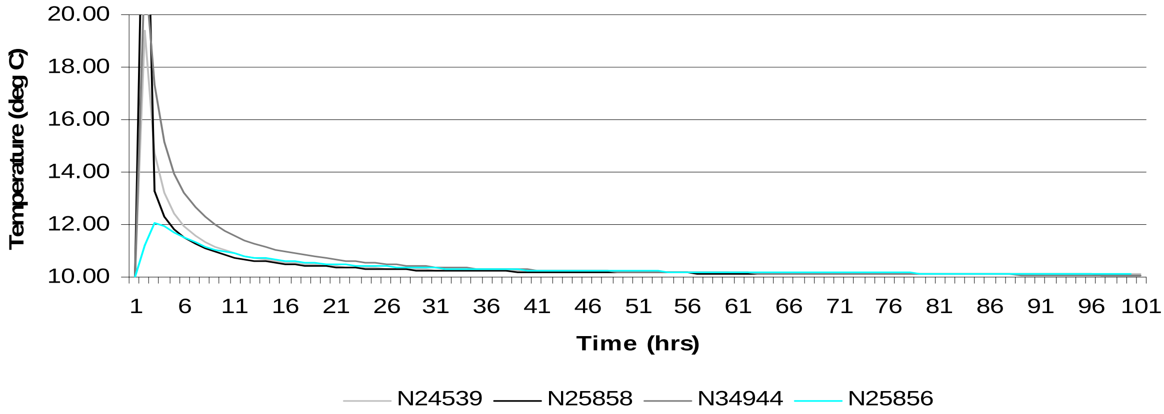

Figure 4 Temperature response factors at the three grid nodes due to an internal radiant or air point temperature excitation

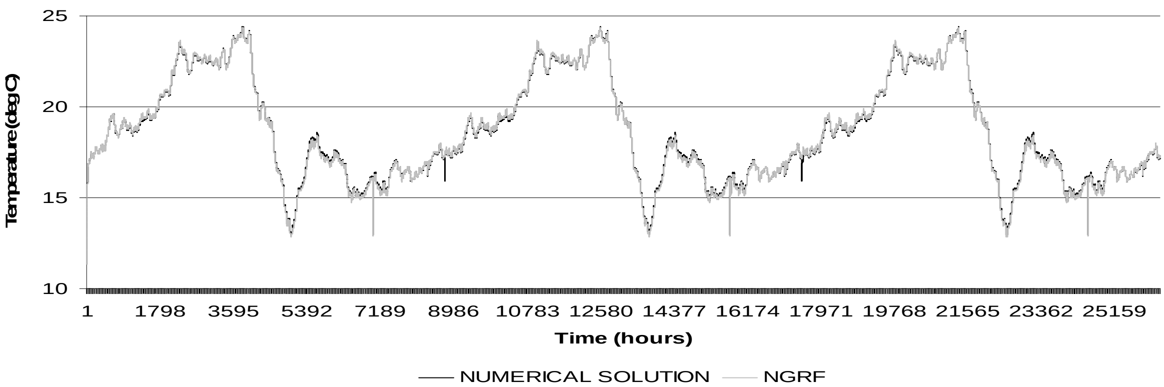

Figure 5 Temperature prediction at grid node 34944 with the use of 1000 hours of the time series responses

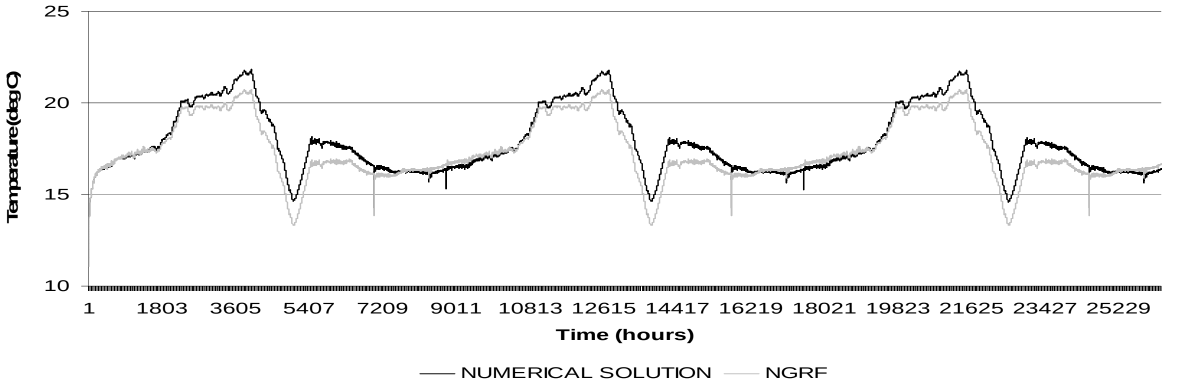

Figure 6 Temperature prediction at grid node 24539 with the use of 1000 hours of the time series responses

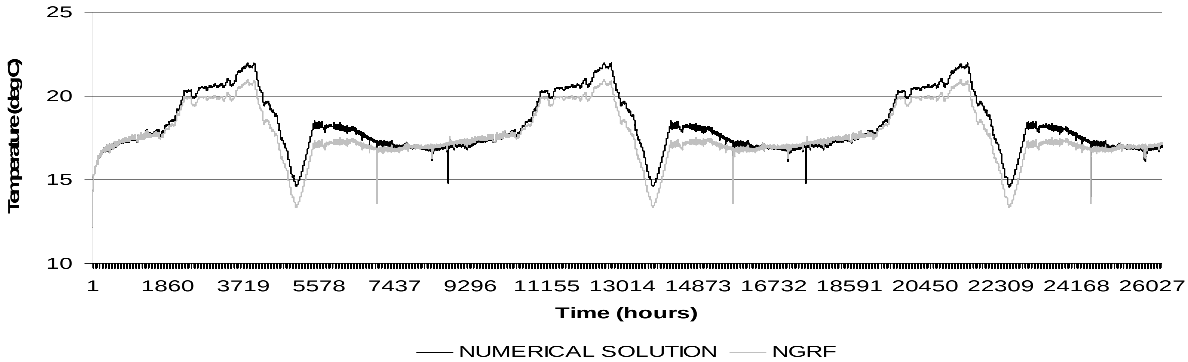

Figure 7 Temperature prediction at grid node 25858 with the use of 1000 hours of the time series responses

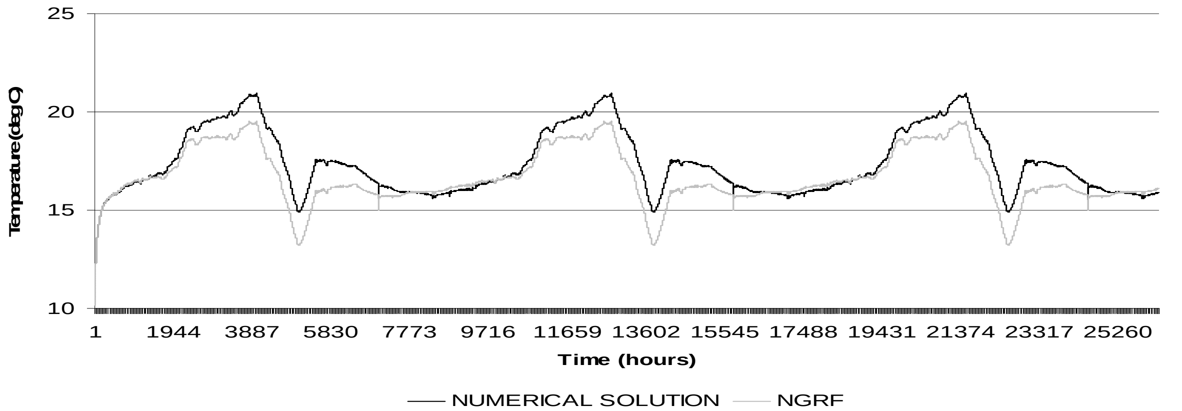

Figure 8 Temperature prediction at grid node 25856 with the use of 1000 hours of the time series responses