THERMAL BRIDGE ASSESSMENTS

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ABSTRACT

Thermal bridge (cold bridge) assessment is becoming more important for two reasons: firstly, as legislation and energy awareness lead to increased insulation levels, so losses due to cold bridging form an increasing fraction of building heat losses; and secondly, condensation and mould growth are increasingly a focus for environmental health concern. This paper describes two recent developments aimed at improving thermal bridge assessment. The first is the EUROKOBRA thermal bridge atlas, which was developed with the aim of giving designers an easy to use, flexible, assessment, tool. The second is an extension of the detailed dynamic simulation program ESP-r to 3-D conduction capability, allowing the possibility of thermal bridge assessment within a complete building model.

INTRODUCTION

Traditionally, facilities available to designers for assessing cold bridges have involved either the use of guidebooks or steady state analysis using one of a range of 2-D and 3-D programs. The former suffer from the handicap that the design detail in question does not necessarily match the details in the guidebooks; the latter can be time consuming to set up, are limited to steady state or response to step changes, and are not integrated with other heat transfer processes in the building.

There have been several recent initiatives aimed improving this situation. This paper focuses on two such developments:

The use of improved thermal bridge assessment techniques in the early design stage or for remedial action on retrofits to assess the overall impact of energy losses and condensation risk. This is enabled through an EC-supported development of the EUROKOBRA database of 2-D thermal bridges, in conjunction with a software package for their selection, manipulation and analysis.

2. The ability of existing dynamic simulation programs to undertake detailed studies, by incorporating 3-D conduction capabilities into the existing program structures.

The paper begins with a description of the EUROKOBRA project. It then describes modifications to 1-D modelling which have been used within recent international projects to take into account 3-D conduction, and the deficiencies of this method. Lastly, results of implementation of 2-D and 3-D conduction within the detailed thermal simulation program, ESP-r, are described.

EUROKOBRA THERMAL BRIDGE DATABASE

A number of printed atlases are available which give general guidance on the problems that can result from, and methods for avoiding, thermal bridges in specific construction types. These are inflexible - it may be difficult to decide how closely a specific construction matches the atlas and it will not be possible to investigate the effect of modifications. It is also difficult to obtain quantitative information on energy loss or surface temperatures that are likely to lead to condensation risk from a general catalogue.

At the other extreme, sophisticated finite element software that allows detailed modelling of 3-D heat flow and temperature distribution through complex components has been available for many years. These are complex to use and need considerable input from experienced users before structures can be specified or modified - it is also possible for plausible answers to emerge without their accuracy being clear.

More recently, a committee of the European Standards Organisation (CEN), CEN TC89 WG1, has produced draft European standards on the calculation of thermal bridges. These specify the input meshes, boundary conditions and two types of output:

The Linear Thermal Transmittance or Ψ factor; this is the heat loss per meter length through a structural element containing a thermal bridge minus the heat loss that would occur if the thermal bridge was not present.

2. The temperature factor of the surface,

$$f = \frac{T_s - T_o}{T_i - T_o} \qquad (1)$$

where T_s is the internal surface temperature, T_i is the internal air temperature and T_o is the external air temperature. This gives an estimate of the 'quality' of the thermal bridge independently of the imposed boundary conditions and can be used as an index of the likelihood of mould growth.

KOBRA is a program developed by the Belgian company Physibel to interrogate a database of 2-D thermal bridge details. It provides quantitative information on the linear thermal transmittances and temperature factors, and allows the effect of modifications to be rapidly investigated.

The EUROKOBRA database which can be interrogated by KOBRA was developed under an EC SAVE project by eight participating countries, led by the Belgian Building Research Institute. The database, or atlas, contains the 2-D geometry of the details (the left hand side of Figure 1 shows an example) including the thermal conductivities of each of the materials; a rectangular grid for the calculation is also specified. Within the given topology of the detail, the user can vary the boundary conditions, the horizontal or vertical size of each element and the conductivities of each material. The outputs are calculated within a few seconds on a standard PC. They include, as shown on the right hand side of Figure 1, the temperature factors at key points and warnings on the risks of condensation and the linear thermal bridges based on both the internal and external dimensions of the building. Colour pictures of the temperature and heat flow distributions through the section can also be displayed.

The EUROKOBRA database, currently containing about 1000 details of all parts of typical European buildings, is now available. Further specialized atlases covering details such as window frames and steel-framed buildings are in preparation, and consideration is being given to extending the capabilities of the system to 3-D.

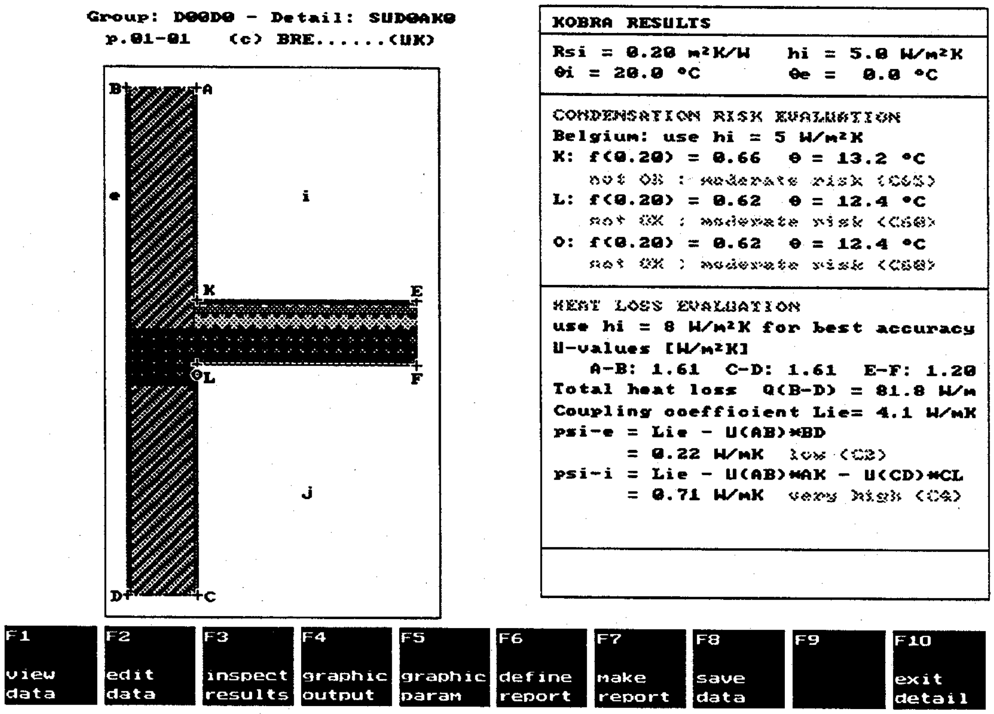
MODELLING OF 3-D GEOMETRY WITH 1-D SIMULATION PROGRAMS

Although the creation of the EUROKOBRA database offers a significant advance in assessing steady state 2-D losses (and potentially 3-D losses), for detailed studies it is clear that these heat losses need to be integrated more fully into dynamic simulation programs which attempt to model the overall building performance.

Although in principle it is easy to formulate the discretized equations for 3-D conduction (Clarke 1985), in practice they have not been implemented until recently. The reasons for this are twofold - with regard to the computational effort, they result in significantly larger program size, much longer simulation times, and time consuming model specification; on the other hand, it was considered that other uncertainties in thermal simulation gave rise to greater errors than those caused by the 1-D conduction approximation. This perspective may be changing, as computing power and user interfaces improve, and thermal bridging and ground modelling assume a more important role within overall building response.

This need for improvement was clearly demonstrated in a major European research programme called PASSYS (Vandaele and Wouters 1994). This programme, in which 10 European countries participated, involved the establishment of a series of test cells throughout Europe. One of the aims of the project was to use the test cells to gather high quality data sets for use in the empirical validation of dynamic simulation programs. Figure 2 shows the test cell structure.

A major difficulty encountered in the work was the (relatively) large 2-D and 3-D conduction losses in the test cells resulting from the thick walls (0. 52m) of the cells. In the case of the test cell fitted with the insulated calibration wall on the south facade, it was estimated that the heat losses were 48% higher than those estimated from a simple 1-D heat loss calculation based on internal dimensions. The idea of the test cell construction was to have highly insulating constructions on the floor, ceiling and all walls except the south wall. Different wall components could be mounted on the south wall - as these would typically have much higher heat losses than the rest of the insulated cell, experimental uncertainty of the south wall performance (the focus of the work) would be minimized.



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KOBRA RESULTS
Rsi = 0.20 m²K/W     hi = 5.0 W/m²K
θi = 20.0 °C         θe =  0.0 °C

CONDENSATION RISK EVALUATION
Belgium: use hi = 5 W/m²K
K: f(0.20) = 0.66   θ = 13.2 °C
   not OK : moderate risk <C65>
L: f(0.20) = 0.62   θ = 12.4 °C
   not OK : moderate risk <C60>
O: f(0.20) = 0.62   θ = 12.4 °C
   not OK : moderate risk <C60>

HEAT LOSS EVALUATION
use hi = 8 W/m²K for best accuracy
U-values [W/m²K]
   A-B: 1.61  C-D: 1.61  E-F: 1.20
Total heat loss  Q(B-D) = 81.8 W/m
Coupling coefficient Lie= 4.1 W/mK
psi-e = Lie - U(AB)*BD
      = 0.22 W/mK  low <C2>
psi-i = Lie - U(AB)*AK - U(CD)*CL
      = 0.71 W/mK  very high <C4>
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Figure 1: Typical output from KOBRA

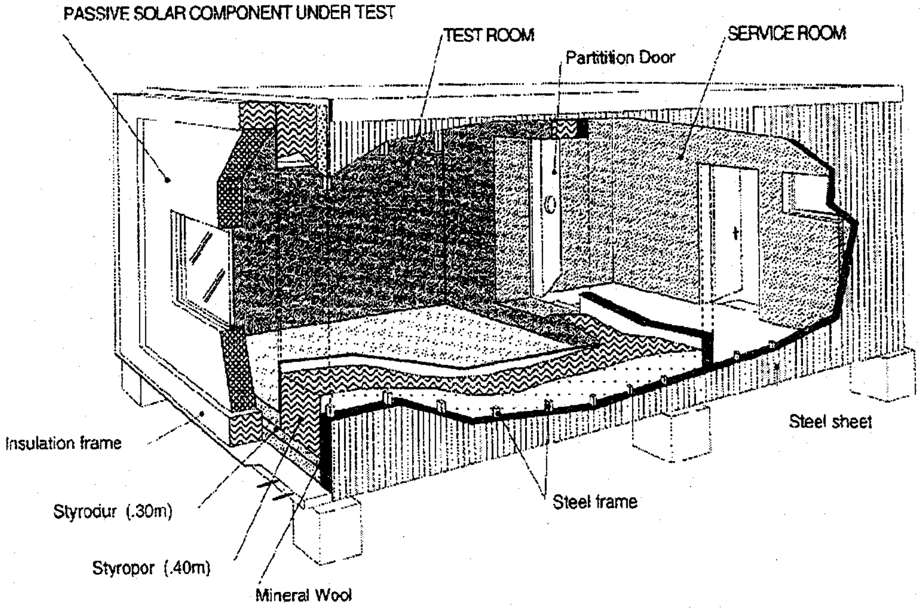

Figure 2: PASSYS Test Cell

The simulation program ESP-r was used within PASSYS. In common with other comparable simulation programs, ESP-r had only 1-D conduction capability and was therefore unable to model explicitly the edge heat losses through the test cell envelope. The edge loss problem was addressed with the use of extra "edge constructions" within the model which attempted to account for the heat transfer in the edges of the test cell. The material conductivity of these constructions were obtained with the use of 2-D and 3-D steady state analyses using the program Trisco (Standaert 1989). A similar procedure using 2-D steady-state analyses was used in the recent IEA Annex 21 empirical validation exercise (Lomas et al, 1994).

In more detail, the technique employed was to keep the same internal geometry of the test cells, but to change the properties of the construction lying within 0.4m of each edge. Beyond this distance from the edge, the 3-D analyses showed that the conduction was essentially 1-D. The resulting model of the test room is shown in Figure 3.

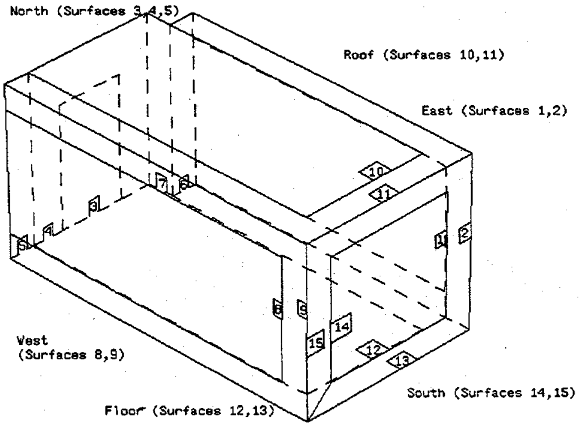

Figure 3: Test Cell Model with Edge Constructions

The conductivities of the edge constructions were then modified to take account of the extra edge losses, i.e. those obtained from the difference between the 3-D and 1-D steady-state analysis for the particular edge or corner. To allow for the changing area through the thickness of the cell, use was made of the "developed area" (see Figure 4 for an example). Each edge construction was subdivided into a number of strips. The inside layer corresponded to the actual material in the test cell, the other layers had artificial conductivity values, increasing in value from inside to outside so that:

(a) the conductivity was proportional to the developed area of the layer, and

(b) the overall conduction losses were in agreement with the steady state analyses.

With regard to capacity of these edge constructions, the capacity of the edge region was sized to approximately match the time taken for the effect of a step heat pulse to propagate from the internal surface to the external surface of the edge (as the primary interest was in the dynamic response resulting from internal changes in temperature).

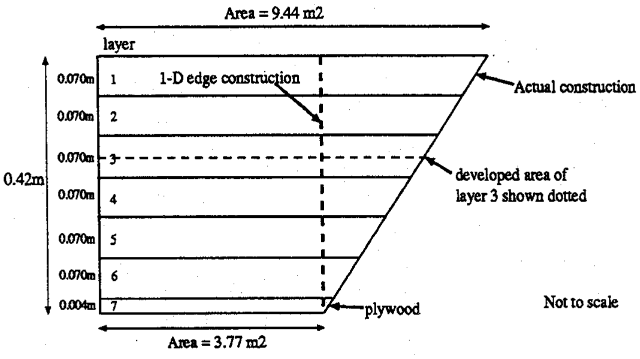

Figure 4: Geometry of the Developed Area

The method and the results are written up fully in (Jensen 1993). In summary, the results of comparing predicted data from a model with these edge constructions with measured data for the calibration-walled test cell showed:

- The steady state model predictions were in reasonable agreement with the measured data when measurement and prediction uncertainties (in particular with respect to internal convection and temperature-dependent conductivities) were taken into account.
- The dynamic response was poor.

Figure 5 shows the measured results for a calibration-walled test cell, together with 1-D simulation results based on internal cell dimensions, and the results after adding edge constructions ("modified 1-D").

Within PASSYS, the results from the calibration experiments were used to calibrate the ESP-r model of the test cell. In particular, the capacity derived from the results of the application of system identification techniques was used to adjust the capacities of the edge constructions to obtain satisfactory agreement for the calibration-walled test cell (Clarke et al 1993). This calibrated model was then used for further comparisons of different test walls.

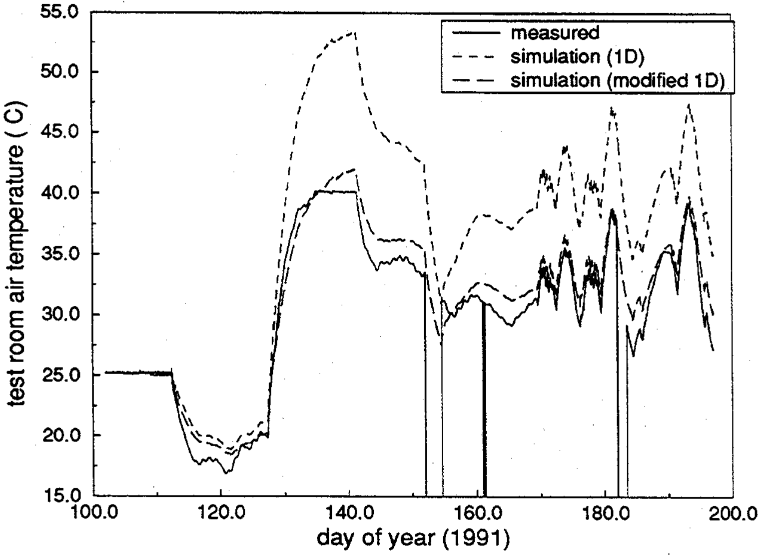

Figure 5: Measured, 1-D and Modified 1-D Air Temperatures

DEVELOPMENT AND IMPLEMENTATION OF 3-D MULTIGRIDDING ROUTINES

Although successful in the case of the PASSYS programme, it is clear that the use of separate 3-D steady state programs and/or the use of detailed experimental data and analysis is not a useful general tool for dynamic modelling. Although the PASSYS test cell is an extreme example of the importance of 3-D conduction heat flow, there are many other cases where full 3-D modelling capability would be useful, e.g. ground modelling and where it is required to predict surface temperatures near the corners of rooms.

The discretized finite difference approximations for 3-D conduction to be used within ESP-r have been formulated (Clarke 1985). The major problem to be overcome for implementation was the development of an efficient gridding scheme. Since there is no one best grid generation technique for all purposes, a study was carried out to develop an adaptive 3-D grid generation technique for transient heat conduction simulation in buildings. It was a combined study of grid generation techniques and numerical solution methods for partial differential equation of heat conduction. Accordingly, a scheme for 3-D gridding and modelling was developed. Unstructured meshes are generated by the gridding process for each zone element in insolation. This allows flexibility in the resulting model, for example allowing one particular part of the building, such as the ground, to be modelled in 3-D, with the rest of the building in 1-D and/or 2-D.

The flexibility was obtained by adopting the control volume approach. That is:

$$V \rho C_p \frac{\partial T}{\partial t} = - \int_s \vec{q} \cdot \vec{n} \, dS + V g \qquad (2)$$

where $\vec{n}$ is the unit vector in the direction of the outward normal to the surface, g is the energy generation rate per unit volume V, and q is the heat flux per unit area. If the control volume surface area S is divided into (*m*) plane segments Equation (2) becomes

$$V \rho C_p \frac{\partial T}{\partial t} = \sum_{i=1}^{m} A_i \lambda \left(\nabla T_i \cdot \vec{n}_i \right) + V g \qquad (3)$$

where

$$\vec{q} \approx - \lambda \nabla T$$

Although this method ensures energy conservation, with no limitation at the gridding level, the accuracy of the simulation is strongly dependent on the generated mesh. For example, steep mesh spacing changes will magnify the local truncation (and hence the simulation) error.

There are several possible schemes for the positioning of control volumes and their associated grid points (see Figure 6). For the 3-D grid generation, Approach 4 in the Figure was adopted. This gives continuity of heat capacity and density throughout the control volume, and continuity in the boundary conditions throughout each control volume surface. The grid points are located at the geometric centres for each control volume, which is expected to give the best representation of the average temperature over the control volume. In addition, massless nodes are located at the construction boundaries and layer interfaces in order to ensure continuity in the thermal conductivity between grid points and a better dynamic response to excitations at the construction boundaries.

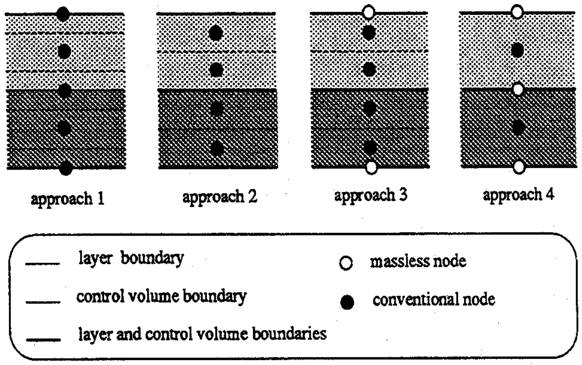

Figure 6: Control Volume Nodal Schemes

There is a price to pay for the grid flexibility - more storage is required for an unstructured mesh than for an equivalent structured mesh. In addition, the number of coefficients (connections) for each node is not constant, and there is a potential for some nodes to have a relatively large number of coefficients. Thus, convergence of the iterative solution methods is expected to be more difficult. Also, some relatively fast direct solution methods for structured grids (such as the Alternating Direction Implicit (ADI) or Explicit (ADE) methods) are not applicable. It should be noted that even for structured meshes, the internal surface nodes are expected to have a relatively large number of coefficients due to the internal longwave radiation process. For the present implementation, storage and speed problems were reduced by introducing sparse storage and matrix solution techniques. However, solution times are still restrictive (although this problem should in time be reduced with increased computing power).

VALIDATION OF 3-D CONDUCTION IMPLEMENTED IN ESP-r

This section describes the first stages of the validation necessary to check on the implementation. As far as possible, the validation methodology described in the EC PASSYS programme was adopted (Jensen 1993), namely a thorough review of the theory and code implementation, followed by application of analytical, inter-model comparison and empirical validation elements.

For the analytical test, the ESP-r results from the default 1-D nodal scheme and the new 3-D nodal scheme (Approaches 1 and 4 respectively in Figure 6) were compared with the analytical solution for a 1-D transient heat conduction problem. The test domain was a slab with an adiabatic boundary at one side and a convective boundary at the other side. The effect of a step change from 50°C to 0°C in the ambient temperature was monitored. The convective boundary surface temperature was selected as the validation variable, as maximum error is expected at that location. The measured and predicted results when plotted on the usual linear time basis are very close; for this reason they are plotted in the format of Figure 7 to accentuate the differences. The predictions from the 3-D scheme are considered acceptable; the 3-D scheme with massless boundary nodes has a better response for the surface temperature, but the default 1-D scheme prediction became slightly more accurate as the rate of temperature variations decreased. This is probably due to the effect of a higher heat storage term for the neighbouring control volume in the 3-D scheme. These simulations were undertaken with 1 hour timesteps; agreement with the analytical solution is improved if smaller time steps are used.

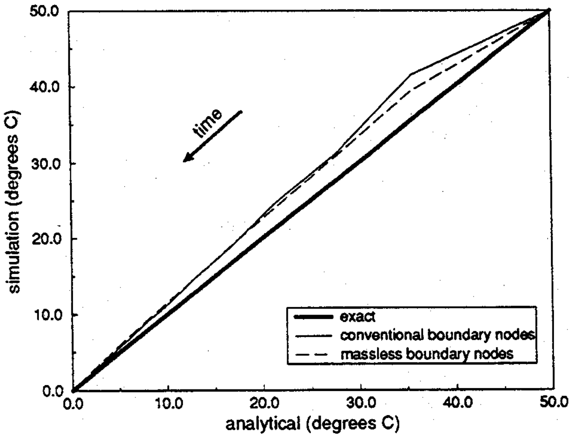

Figure 7: Analytical Comparison:
Decay from Step Change

Two inter-model comparisons were performed. In the first one, a comparison was made between the default 1-D scheme for ESP-r and the new 3-D scheme on a 1-D zone model. Minor changes were required within the 3-D code so that the same nodal scheme (Approach 1) was used in both cases. The predicted temperatures were in agreement to better than 0.001°C. In the second inter-model comparison, ESP-r 3-D results were compared with results obtained using the conduction modelling facilities within the computational fluid dynamics package PHOENICS (Spalding 1991). A cubic room with a homogeneous one layer construction was used. The thermophysical and geometrical symmetry was required to cancel the effect of internal longwave radiation effects which are treated in ESP-r but not in PHOENICS. Due to the symmetry only one eighth of the room was modelled by PHOENICS. The effect of step excitation in the indoor air temperature was examined. The predicted nodal temperatures with ESP-r and PHOENICS were in agreement to better than 0.001°C.

Finally, results from PASSYS test cell experiments were used for empirical validation. Figure 8 shows the measured results, with the modified 1-D and then full 3-D simulations. A portion of the graph is displayed at higher resolution to show shorter period dynamics. At lower temperatures the 3-D simulation results are in much better agreement with the measured data, and in general the dynamic response is better. At high temperatures, the measured and predicted temperatures still differ. This is thought to be mainly due to the effect of temperature on the thermophysical properties, particularly conductivity, for which the model inputs were based on measured conductivity at the standard 10°C. Currently, the ESP-r 3-D scheme is not capable of considering the temperature dependence of thermophysical properties. However, for the default 1-D simulation, the impact of adopting a linear temperature dependence for thermal conductivity for the insulating materials in the test cell is shown in Figure 9. Application of such dependence would improve agreement with measured data at high temperatures.

CONCLUSIONS

Two important recent developments have been described. Firstly, there now exists a comprehensive electronic database of 2-D thermal bridges which can be selected, modified as necessary and the resulting linear thermal transmittance and condensation risk evaluated. This should permit a rapid assessment of thermal bridges within buildings, and possible remedies for unsatisfactory performance.

When detailed simulations of whole building performance is required, it is sometimes necessary to take 2-D and 3-D effects into account. The method, and limitations, adopted in two recent international projects has been outlined. An attempt has now been made to provide a more fundamental treatment of 3-D conduction within the dynamic thermal simulation program ESP-r. Results from some validation exercises applied to the new code show that 3-D conduction can now be successfully applied, although further improvements in solution speed (or computing power) and ease of problem specification is required before it can be routinely applied.

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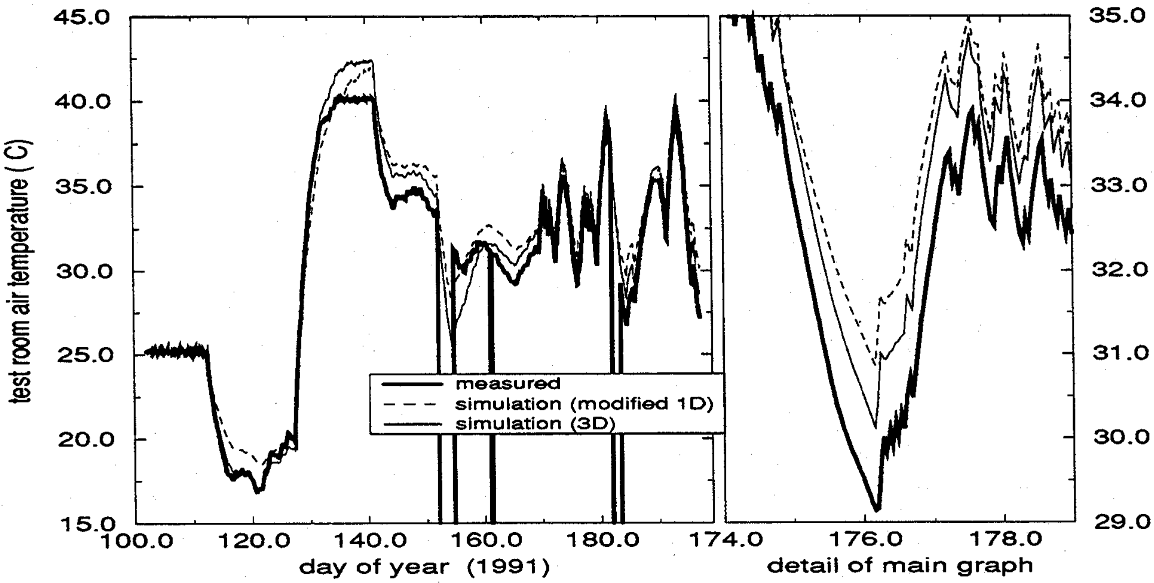

Figure 8: Measured, Modified 1-D and 3-D Air Temperatures

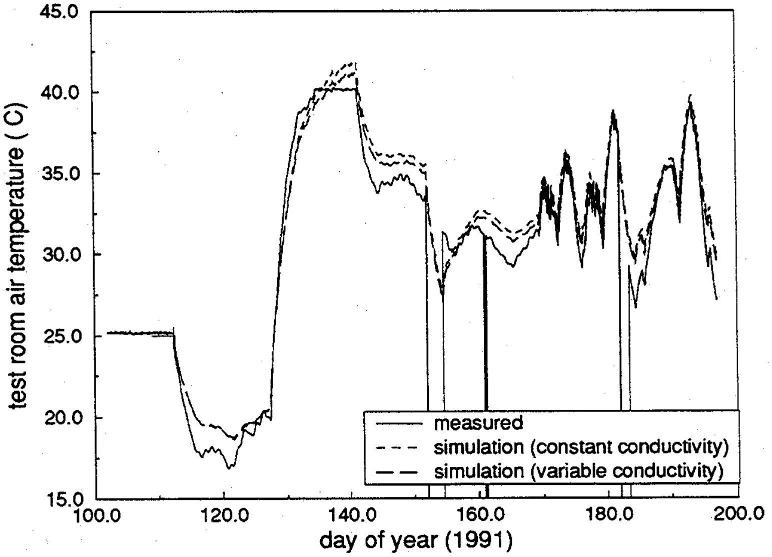

Figure 9: Effect of Conductivity Temperature Dependence