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ADVANCED SIMULATION APPLICATIONS USING ROOM

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ABSTRACT

ROOM is a dynamic thermal simulation model that has been continuously developed at Arup over the last 30 years. It remains one of the principal tools used for thermal modelling within Arup. The programme includes detailed representation of complex geometry and building constructions, radiative heat transfer and air movement. ROOM is particularly suitable for determining environmental conditions and heating and cooling loads in spaces such as atria, naturally ventilated buildings and shopping malls.

Arup have developed new bespoke versions of ROOM for specific applications. Examples include comfort modelling of stadia; outdoor microclimate design; and solar towers for power generation. The aim of this paper is to describe how ROOM has been adapted to model these non-standard spaces and give examples of their use.

INTRODUCTION

The need to satisfy the requirements of the Energy Performance of Buildings Directive resulted in the formulation of the National Calculation Methodology for the calculation of energy use to meet the requirements of Building Regulations. Whilst the default approach is a simple software tool (SBEM, 2008) there is also the possibility to use accredited detailed Dynamic Thermal Models (DTMs) (http://www.ukreg-accreditation.org/). This has lead to a significant expansion in the use of these software tools. It has also, probably, affected the direction of new developments. Furthermore, in the United Kingdom, the most commonly used DTMs are 'black boxes'. This means that the user has no control over how the calculations are carried out and so the engineer is effectively handing the technical intellectual input of the design over to the software vendor. Arup has always insisted on some form of control (and so responsibility for) the calculations made by its' engineers. This means that in addition to the use of the tools necessary to satisfy the statutory instruments, Arup has developed tools that compliment the commercial packages and extend the range of issues that can be investigated. In doing so, exactly what happens when the 'run button' is pressed is known and more importantly modifications can be made to order. The Oasys ltd. ROOM program (Holmes and Connor, 1991) is one example.

The original specification for ROOM was 'to predict comfort at any point in a space' (where ROOM was always to be a single zone model). Comfort predictions were to be made using the Fanger (Fanger, 1972) comfort equations. Thus, it was necessary to predict accurately air and surface temperatures, the distribution of transmitted shortwave radiation within the space and air speed. Unlike most other DTMs, ROOM development started with the modelling of the exchange of longwave radiation within a space using the concept of radiosity (Holmes, 1988). The method developed is now the CIBSE reference calculation method (CIBSE, 2006). A fairly standard finite difference approach is employed for the calculation of the response of the surfaces. Although it has always been seen as desirable to make detailed predictions of air temperatures and speeds this aim has not yet been achieved[1], i.e. ROOM is limited to a simple stratified temperature distribution model and a single air speed for the prediction of thermal comfort. The latter is possibly not unreasonable; the assumption is that the designers have already taken steps to ensure that discomfort due to airspeed is not an issue. The type of prediction that can be made is shown in Figure 1. The effect of an internal blind upon occupant comfort is shown in the upper diagram. There are two identical windows on the South wall – the one on the East side has the internal blind lowered. The reduced transmission of direct solar radiation results in a significant reduction in the predicted percentage persons dissatisfied (PPD). The lower diagram shows where the sunlight would fall on the floor of the space if the windows were unobstructed.

Validation of the ROOM software is important in order to ensure the calculations employed are valid. ROOM has been tested against the standards outlined in CIBSE TM33 (CIBSE TM33, 2006. This work was overseen by a CIBSE Committee chaired by

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[1] In theory ROOM could be integrated with a CFD code. This is not seen to be practical if periods of up to one year are to be considered.

Michael Holmes) and was found to comply[2]. Further successful validation has been conducted using the BESTEST framework (IEA, 2002). A summary of these tests results is distributed with the software in the release notes. A task currently being undertaken by the development team is to restructure the program code and to then revalidate ROOM.

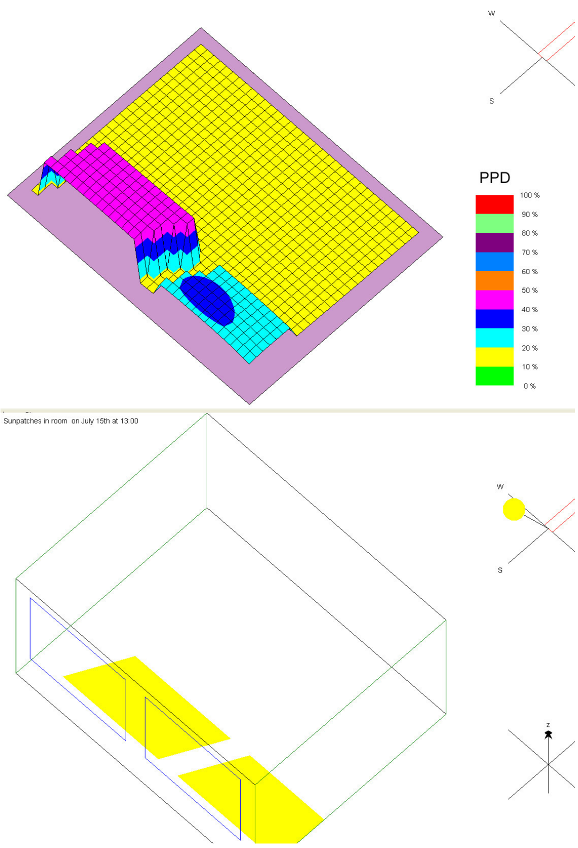

Figure 1: Comfort prediction.

ROOM has been written to enable easy modification by using self-contained, stand-alone subroutines. This facility has been used extensively and the user is able to invoke the more complex versions of the model, such as those described in this paper, through simple inputs in the user interface. This paper presents three examples from Arup projects (the details of which are not provided here due to space limitations):

- The conversion to the assessment of comfort conditions in street canyons where the most significant modification was the addition of an appropriate airflow network.
- Sports stadia in countries with aggressive climates can consume considerable amounts of energy to maintain spectator comfort. This can be reduced by supplying air beneath the seating. The comfort of the spectators will be affected by the way in which this air is supplied and the local radiant field. The densely occupied seating areas differ greatly from those found in offices and modifications were required. In addition the effect of a moveable roof had to be studied.
- Solar chimneys have been proposed as a way to generate electricity. They comprise a tall tower connected to a collector. Figure 2 shows a conceptual tower. The chimney provides a means to generate a significant stack pressure. Turbines at the junction of the collector and chimney are used to generate electricity. ROOM already has a facility to convert a single space into a set of stacked spaces (ROOM façade model) The main requirements here were to introduce compressible gas equations and assess the applicability of common modelling assumptions to large scale buildings.

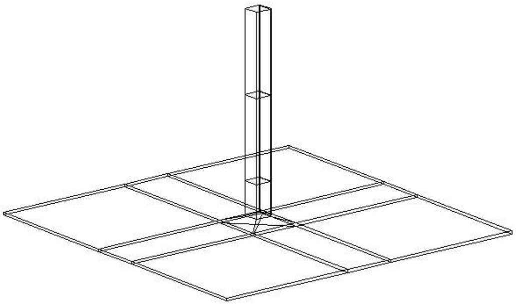

Figure 2: Conceptual solar chimney.

OUTDOOR SPACES

Problem

Arup are consultants to the EPSRC funded LUCID project (LUCID, 2007) for which OutdoorROOM has been developed so that external temperatures and comfort parameters in outdoor spaces such as street canyons can be predicted. The objective is to understand how different surface materials and building massing alter heat fluxes to and from the urban surface and impact on local microclimates and the urban heat island, issues that are coming to the fore internationally.

Theory

The theory implemented in OutdoorROOM is based on that derived in Harman et al., 2004. The flow in a street canyon can take one of three forms depending on the canyon aspect ratio, H/W, where H is the canyon height and W is the canyon width. These flow regimes are shown in Figure 3 where the dashed line indicates the notional boundary between the so-called recirculation and ventilated regions. The

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[2] Some of the tests are intended for multi-zone thermal models therefore some approximations were required to assess ROOM as it is a single zone model.

canyon height, width and length of the recirculation region, L_r, are also shown for case (a).

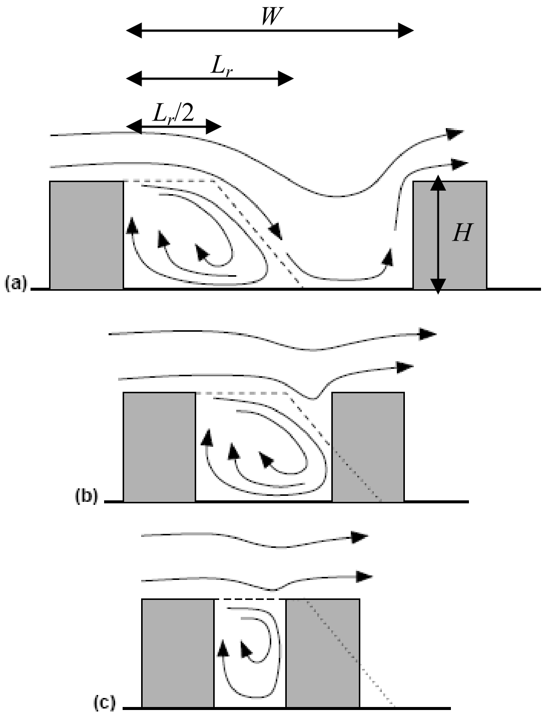


Figure 3: Streamlines in the three flow regimes: (a) Isolated roughness flow regime; (b) wake interference flow regime; (c) skimming flow regime (see also Oke, 1987)

As the wind blows across the street canyon, air is entrained downwards into the street canyon. A recirculation region forms in the near wake of the upstream buildings. If the street is sufficiently wide, a ventilation region also forms, in which air is brought down to street level but escapes the canyon downstream (Figure 3(a)).

In a narrow street canyon (Figure 3(c)), only a recirculation region is formed. Although air is entrained into the canyon, the high level air jet skims over the canyon. This is known as the 'skimming' regime.

Figure 3(b) shows the intermediate 'wake interference' regime. This has both recirculation and ventilation regions, but the high level air jet impinges on the downstream canyon wall rather than the on the street.

These three flow regimes can be characterised by appropriate resistance networks. It is these resistance networks that are employed in OutdoorROOM and their use represents the major distinction from the standard ROOM program.

Examples

Depicted in Figure 4 is the OutdoorROOM representation of a street canyon.

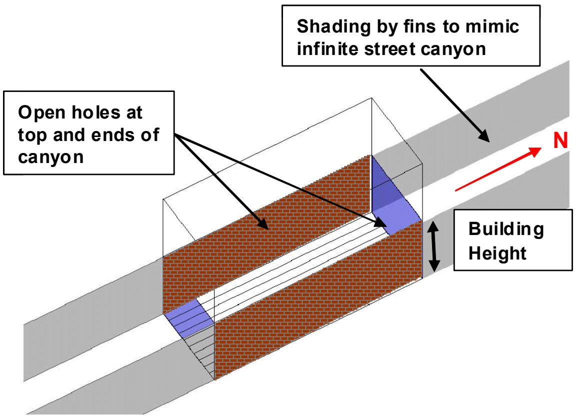
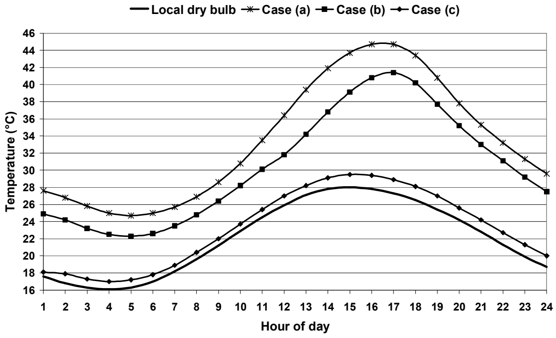


Figure 4: Street canyon representation in OutdoorROOM.

The OutdoorROOM street canyon domain is twice the building height where the upper halves of the boundary walls are set as open holes. All these upper surfaces are external. The side walls of the canyon, representing the buildings, may be constructed from a single fabric element and contain apertures. They can be defined as internal or external. The present theory considers a canyon of infinite length. Therefore, the end walls of the OutdoorROOM canyon are input as windows with no glazing elements, permitting the addition of very long shades to the end wall windows, as indicated by the grey areas in Figure 4. This mimics an infinitely long street canyon in the model and ensures the correct calculation of solar radiation. The floor is divided into strips running along the length of the canyon so as to improve the calculation of the effects of solar radiation, which may vary across the canyon.

OutdoorROOM calculates the orientation of the street canyon relative to the wind direction and identifies the upwind and downwind sides. The wind is decomposed into along and across canyon components, essential for computing the turbulent heat transfer coefficients.

Figure 5 shows the ventilated and recirculation region air temperatures resulting from OutdoorROOM simulations of each of three flow regimes.



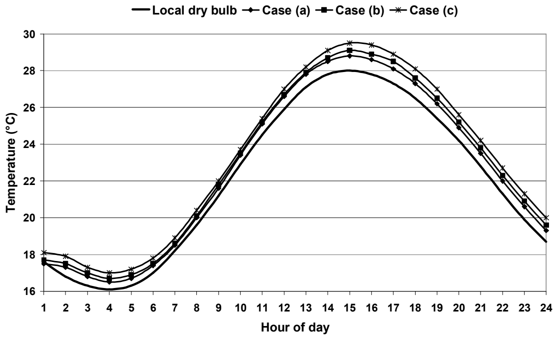


Figure 5: Canyon air temperatures in the ventilated region (top) and recirculation (bottom) for each of the three flow regimes.

The temperatures in the ventilated (and recirculation) region decrease as the canyon aspect ratio, H/W, increases. As described in Harman et al., 2004 this is due to reductions in wind speeds due in part to changes in the boundary layer and changes in the flow regime type. The decrease in wind speed produces a corresponding decrease in heat flux from the surfaces, hence the lower air temperatures.

Another reason for the temperature decrease is due to a decrease in direct solar radiation since as the canyon width decreases, a larger proportion of the canyon will be shaded by the surrounding buildings.

STADIA

Problem

StadiumROOM provides an assessment of the performance of a stadium and includes an optional comfort cooling system where air is supplied under the seats. Modifications to ROOM include allowing solar radiation to pass by seats and onto the lower surface of the slab in order to represent seat spacing. It is also capable of modelling empty and occupied stadia and the effect of air supplied over people is represented using the Fanger (Fanger, 1972) comfort model with a convective model for the supply air.

Theory

Figure 6(a) shows a section of stadium seating in which there is a comfort cooling system supplying air beneath the seats. The darker shades indicate lower temperatures. The underseat jets have a cooling effect around the legs and backs of the occupants. A schemtaic of how this system is represented in StadiumROOM is shown in Figure 6(b).

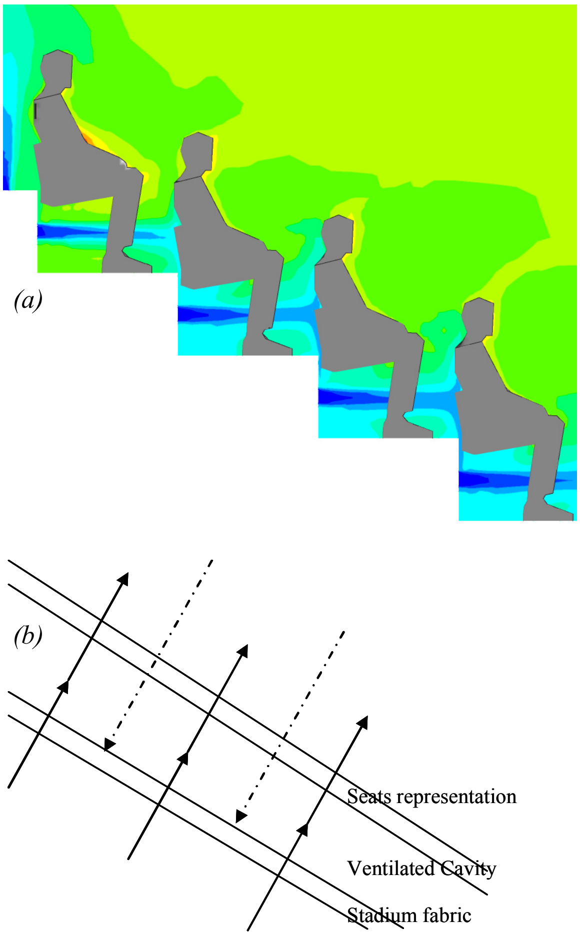


Figure 6: (a) Indicates the stadium to be modelled (shown here in a CFD simulation) and (b) schematic of the ROOM implementation where the solid arrows indicate air flow and the dashed arrows incident solar radiation.

The jets are modelled in StadiumROOM by deploying a ventilated cavity. Air flows along this cavity and through notional holes in the upper surface that represent the jets. Solar radiation is permitted to pass through this upper surface and warm the cavity in order to model the fact that radiation can pass between the seats.

Figure 7 shows the heat flux paths within a ventilated cavity represented as flows through a resistive network. The resistances R_c, R_r and R_a are those to convective heat flow, radiative heat flow and to convection along the cavity respectively. The temperature t_{ai} is that of the supply air and t_{ao} is the air temperature at a point inside the cavity (and therefore the jet air temperature).

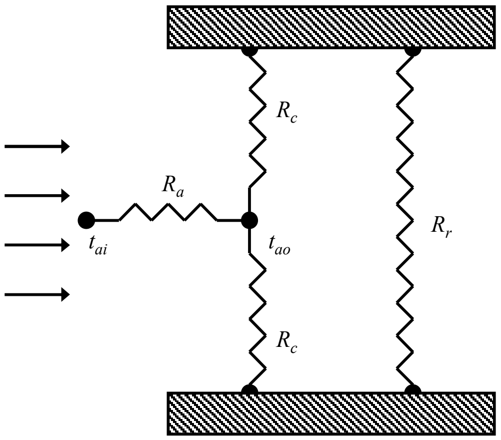


Figure 7: Ventilated cavity thermal network.

This thermal network can be converted into a star network, shown in Figure 8.

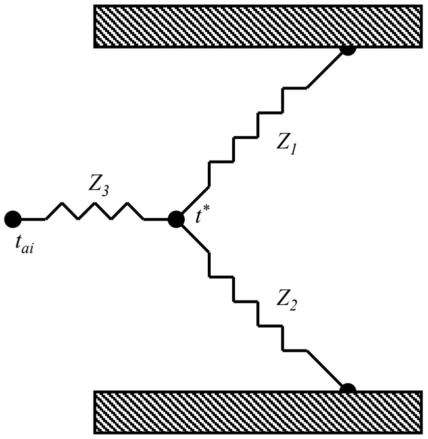


Figure 8: Ventilated cavity star network.

The impedances are given by

$$Z_1 = Z_2 = 1/(h_e + 2h_r),$$

$$Z_3 = (h_r/h_e)/(h_e + 2h_r) + x/m_a c_p \ ,$$

where h_e and h_r are the convective and radiative heat transfer coefficients, x is the distance along the cavity in the direction of air flow, m_a is the air mass flow rate and c_p is the specific heat capacity of the air. From these the jet temperature can be found, i.e.

$$t_{ao} = t_{ai} - \frac{(t_{ai} - t^*)}{(m_a c_p Z_3)},$$

where

$$t^* = \frac{(t_{ai} Z_1 Z_2 + t_{s1} Z_1 Z_2 + t_{s2} Z_2 Z_3)}{(Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1)},$$

and t_{s1} and t_{s2} are the surface temperatures on either side of the slab.

A further modification was to allow the stadium roof to open. This was affected simply by changing the roof material to a hole at the appropriate time.

Examples

A simple stadium as modelled in ROOM is shown in Figure 9.

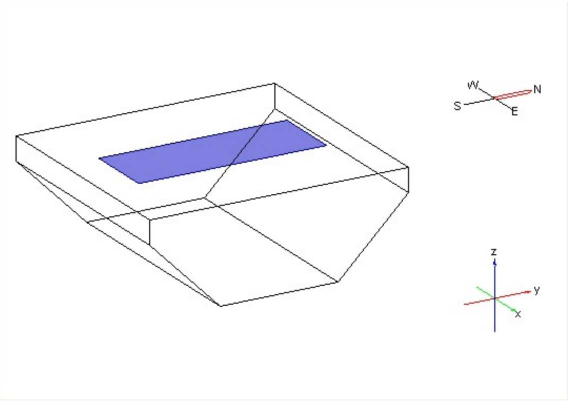


Figure 9: Simple stadium as modelled in ROOM. The spectators are located on the sloping surfaces and the shaded region represents the roof which can be opened.

Figure 10 shows the dry bulb temperature in the occupied zone of this simple stadium model (sloping surfaces) on a summer day in the UK where the roof remains open. Jet flow rates of 0 l/s, 6 l/s, 12 l/s and 18 l/s were switched on between hours 14 and 18.

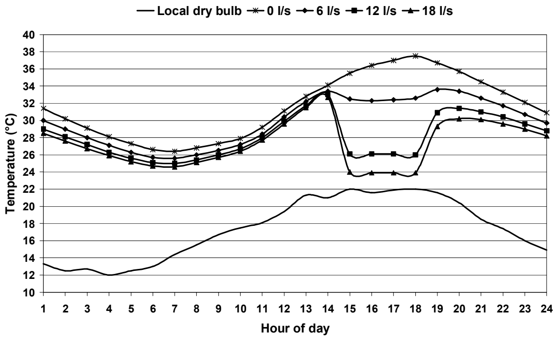
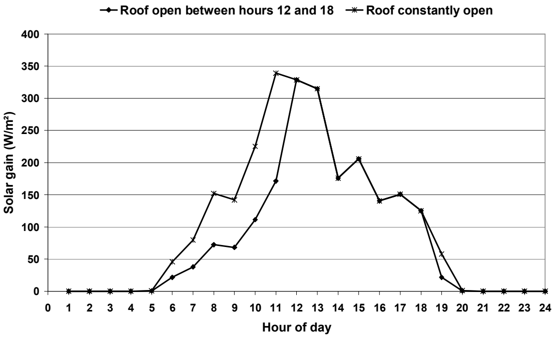


Figure 10: Dry bulb temperature in stadium occupied zone for different flow rates.

It can clearly be seen that if there were no flow, the temperature would be uncomfortably warm. With a flow of 12 l/s or higher the temperature becomes more agreeable (~25°C).

Figure 11 shows the effect of opening the stadium roof.



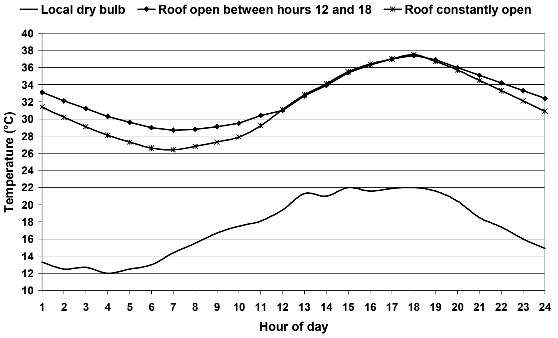


Figure 11: Comparisons of solar gain (top) and dry bulb temperature in stadium occupied zone (bottom) for the simple stadium model with the roof open constantly and open only between hours 12 and 18.

There are higher solar gains when the roof is open, i.e. during the morning. However, opening the roof has other implications (change of heat transfer coefficients, increased solar retransmission) that cause the temperatures inside the stadium to be lower than when the roof is closed for the majority of the 24-hour cycle, as expected.

SOLAR TOWER

Problem

This application was stimulated by a request to investigate the potential for a large scale solar powered generator (see Figure 2) based upon the test tower at Manzanares (Haaf, 1984) in Spain. Although the designers were aware of the existence of consultants offering design advice, they felt they required a better understanding of the factors that could affect the performance of the tower than that offered by what would be a black box approach. Arup Building Physics were contacted, and after considering a bespoke tool it was concluded that the façade version of ROOM could be modified to meet the designer's needs. The façade model is a standard ROOM version that converts a single space into a number of linked vertical zones. The boundary conditions to these zones can be either the external environment or specified internal space temperatures. Ventilation may be by wind or buoyancy, each zone is treated separately as a stirred tank and in this way it is possible to calculate the vertical temperature distribution within the façade. The model can be used to look at the effect of blind position and reflection and shade from obstructions within the façade.

Theory

Initially it was assumed that the only modification required would be to add the resistance of a turbine into the façade pressure loss calculation. However, it was later established that the tower could be almost 1km high. In such cases, it is not possible to ignore compressibility effects. Furthermore, the size of the tower could invalidate many of the assumptions used in conventional building models. Other factors that do not have a very significant effect on conventional builds but could be important in this case. This section of the paper looks at the issues that were considered to be important in the model; it is not intended to stimulate a debate on the performance of solar towers. The following issues were felt worthy of investigation:

1. Compressible flow.

In buildings it is usual to calculate the buoyancy pressure from densities calculated using the perfect gas equation. Where there are large height differences it may be necessary to take compressibility into account. In this case for an unconstrained fluid (the external atmosphere) the difference in pressure, ΔP, at height H from that at ground level is

$$\Delta P = \rho_0 R T_0 \left(1 - \left(1 - \frac{aH}{T_0} \right)^{g/aR} \right),$$

where R is the specific gas constant (287 J kg^{-1} K^{-1}), ρ_0 and T_0 are the density (kg m^{-3}) and temperature (K) at ground level, a is the lapse rate (0.0065 K m^{-1}) and g is the accelation due to gravity (9.81 ms^{-2}).

The effect internally was considered by Backstrom (Backstrom, 2003). The average density, ρ_{ave}, in each section of the chimney (façade) is given by

$$\rho_{ave} = \rho_1 \frac{1}{\frac{\gamma}{\gamma-1}} \frac{1}{1-\frac{T}{T_1}} \left(1 - \frac{T^{\frac{\gamma}{\gamma-1}}}{T_1} \right),$$

where γ is the specific heat ratio (1.4), ρ_1 and T_1 are the density (kg m^{-3}) and temperature (K) at the bottom of the zone, and

$$T = T_1 - \frac{gH}{c_p},$$

is the temperature at the top of the zone, where c_p is the specific heat (1004 J kg^{-1} K^{-1}).

The lapse rate determined from the above is 0.00975K m^{-1} which means that the driving pressure will be less than that determined assuming incompressible flow. This difference was considered to be significant.

2. Convection Heat Transfer Coefficients.

Surface convection coefficients at the large Reynolds numbers that might be applicable were investigated. It was considered likely that forced convection will be significant both inside and outside the solar tower. The overall size of the collector is of the order of kilometres and so there were significant doubts as to the validity of the relationships used in conventional building thermal modelling. Computational fluid dynamics (CFD) could have been used to make an estimate but it would have been necessary to model the detail of the boundary layer (the standard wall functions would probably not apply). In this case the validity of CFD is questionable. It was therefore decided to carry out a set of sensitivity studies, an example of which is given in Figure 12. In this case the solar efficiency[3] of the collector is plotted against the internal convection coefficient. There is great sensitivity at low values of the convection coefficient. Typically for forced convection the relationship between the convective heat transfer coefficient, h_c, air speed, V, and scale, D, is

$$h_c = K\frac{V^{0.8}}{D^{0.2}},$$

where K is a constant dependent upon application. Therefore, as size increases, the value of the coefficient decreases. Given that the solar towers are large, it is probable that the internal convection coefficient will be small, suggesting that the solar efficiency will be difficult to determine (see Figure 12).

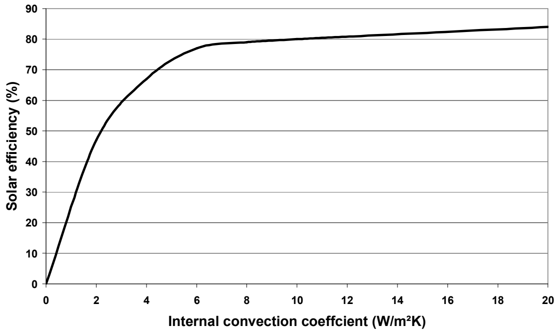


Figure 12: Sensitivity of solar efficiency to variation of convection coefficient.

In practice it is the power generated that is of interest. A simple analysis of performance suggests that power is proportional to solar efficiency. This issue has not yet been resolved.

3. Ground modelling.

The collector will probably be a transparent cover over bare ground. Ground modelling in thermal models is generally considered to be of second order importance. However, for the solar tower, the ground effects may not be negligable. The large size of the collector means that the ground can probably be represented by a simple one dimensional slab. A simple approach using a fixed value of temperature at some depth beneath the tower was therefore considered appropriate. The depth of ground modelled and the thermal properties of that ground might be expected to affect the performance of the tower. It was also thought that the presence of the tower might result in a long term change in the temperature of the ground. Modelling periods greater than one year is not a problem in ROOM. This long term effect has not yet been studied. For current purposes it might be assumed that the deep ground temperature is close to the average annual temperature in the collector. A sensitivity study was undertaken to examine the relationship between temperatures in the collector and the average deep ground temperature for varying ground depth (the distance between the collector floor and a fixed deep ground temperature. Values considered were 1, 2 and 3m), ground soil type (light dry and heavy dry) and convective heat transfer coefficient (5 W m^{-2} K^{-1} to 15 W m^{-2} K^{-1}).

The results, an example of which is presented in Figure 13, suggest a weak relationship between the assumed soil temperature and the annual average collector temperature. The results for peak collector temperature show a range of about 6K.

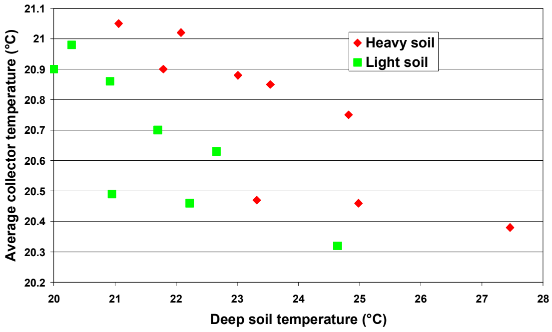


Figure 13: Example ground modelling sensitivity test result.

4. Heat loss to the sky.

The collector is essentially horizontal so the loss to the sky could be important. A number of correlations can be used to calculate sky temperature (and therefore the heat loss). In some cases the calculation of sky temperature only requires knowledge of the ambient dry bulb (Swinbank, 1963) in others (CIBSE, 2004; Berdhal and Fromberg, 1982) knowledge of the thermodynamic state of the air is necessary. The predictions can be quite different, as shown in Figure 14. In calculating the sky temperature for Figure 14 the cloud cover was used to modify the correlations. Unfortunately, the only climate files available for the site of the

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[3] Calculated as the percentage of the incident solar energy picked up by the air.

proposed tower did not contain any humidity data and so the Swinbank (Swinbank, 1963) correlation was used, assuming a clear sky – another uncertainty is introduced.

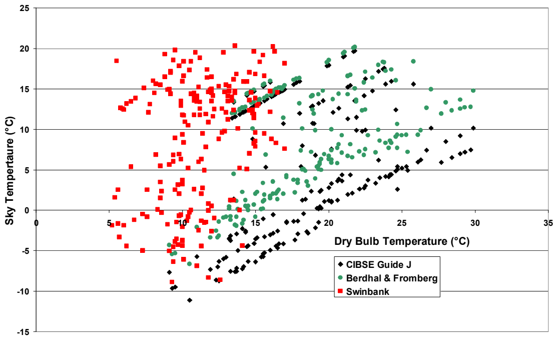

Figure 14: Example of sky temperature calculations.

5. Appropriate weather data.

The climate at 1km might be very different from that at 0km. Weather files used for building modelling may not be appropriate. It was decided that this problem could only be addressed by the introduction of a standard temperature lapse rate and wind speed profile and so did not offer much difficulty.

This investigation has not yet been completed. What might be concluded is that with so many uncertainties a probabilistic approach to the analysis may be more relevant than the single prediction scenario so often used for most building thermal modelling.

CONCLUSION

Three examples in which the ROOM dynamic thermal model has been modified for a specific purpose have been presented: OutdoorROOM for modelling street canyons; StadiumROOM for assessing comfort cooling in stadia; and the Solar Tower. This demonstrates the versatility of the ROOM model.

Through maintaining and developing an in-house model it is believed that Arup gain a significant advantage over relying on commercially produced software alone. That is, the ability to easily introduce new concepts into the ROOM model allows the representation of specific building types that would otherwise have to be approximated.

ACKNOWLEDGEMENT

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