Thermal Comfort and Environmental Modelling in Atrium Buildings

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ABSTRACT: Atrium spaces are extensively used in modern architecture and are often claimed to offer some passive benefits to the internal environment as well as energy efficiency opportunities. It has also been established over recent years that it is difficult to predict and analyse the internal environments of atria because of the complex nature of their operation and air flows.

The thermal sensation experienced by occupants in a building space is known to be affected by four environmental factors - air temperature, air velocity, humidity and mean radiant temperature (MRT). The calculation of the comfort level in atrium spaces involves two difficulties compared to other spaces. Firstly, solar radiation that can penetrate the atrium skylight has a significant impact influencing thermal comfort and adds to the difficulty of calculating MRT; and secondly, there is strong temperature stratification in the space due to stack effect, which makes it difficult to obtain the air temperature.

This paper, which is part of an ongoing project of a systematic study on the thermal environment of atrium spaces, focuses on the above two issues and presents a tool developed for the evaluation of the comfort level in atrium spaces. For the first issue, CFD analysis is performed and a new MRT calculation method which can take solar radiation into account is used. A platform is then built for the data from the two analyses to communicate and exchange. An application of the tool is presented finally.

Keywords: atrium, comfort, modelling

1. INTRODUCTION

Atrium spaces have been incorporated as a design element with increased frequency over the last few decades. A great many ideas and much enthusiasm have been expressed about this special type of space - they can bring in natural light and natural ventilation, enable more surfaces to be “open” to nature and facilitate the circulation of people [1,2]. Not only can they be adopted in newly-built public buildings as entrance spaces or cafeterias, but they can also be used for the refurbishment of existing traditional and historical buildings. In addition, these kinds of spaces can fulfil various kinds of function – economic, cultural, shelter, accommodation, etc [3]. With the popularity of glass, the atrium space has become a common feature of modern public buildings.

However, one major concern about the use of atrium spaces is their energy consumption. Although atrium spaces can be adopted as ‘buffer zones’ and ‘solar collectors’ offering some passive benefits, the energy and environmental potential of atrium buildings has not been exploited to full advantage and many atrium buildings have been relative energy and financial luxuries. One significant reason for this is that they can easily overheat in warm summers causing thermal discomfort, due to the large glazing usually adopted.

In order to identify the problem of thermal discomfort and hence provide a standard for the design and control of HVAC systems used in atrium spaces, a calculation method which can predict the thermal comfort level of atrium spaces is both essential and desirable. The thermal sensation experienced by occupants in a building space is known to be affected by four environmental factors - air temperature, air velocity, humidity and mean radiant temperature (MRT). In comparison with other spaces, the calculation of the comfort level in atrium spaces presents two difficulties. Firstly, solar radiation that can penetrate the large area of glass envelope of atrium spaces has a significant impact influencing thermal comfort and adds to the difficulty of calculating MRT while this effect is usually ignored for the calculation of other kinds of spaces; and secondly, there is strong temperature stratification in the space due to stack effect, which makes the air temperature difficult to obtain. Furthermore, the internal thermal environment of atrium spaces is not usually uniformly distributed and with strong air stratification. Thus, a single value such as average temperature would not be adequate to describe the whole field.

A pragmatic way of solving this problem is to divide the whole space into small grids and for each of them the property can be considered as uniform. In this way, the environmental parameters for each grid can be studied separately using functions for the calculation of properties of rigid bodies such as mass, momentum, and energy conservation. Due to the large number of grids, it is nearly impossible to manually calculate all the results – usually computer programmes have to be resorted to.

2. MODELLING OF THE ENVIRONMENTAL PARAMETERS IN ATRIUM SPACES

As only the bottom of the space is occupied, only the thermal comfort for this level (1.6m high) is to be studied in this paper. A simple shape of space – hexahedron is chosen for the study and a 16x16 grid is employed for both MRT calculation and CFD analysis for temperature field.

2.1 Calculation of MRT

Traditional MRT calculation methods are based on the absolute surface temperature of the surrounding surfaces and the view factors of the surrounding surfaces from the point of interest, which can be expressed by the following equation –

$$T_{mrt}^4 = \sum_{i=1}^{6} (F_i T_i^4) \tag{1}$$

where T_{mrt} is the mean radiant temperature, F_i is the view factor from the point interested to the surface *I* and T_i is the temperature of surface *i.* This formula does not consider the influence of solar radiation and thus cannot be applied to atrium spaces.

Based on the mechanism of radiation heat transfer, La Gennusa [4] derived a new MRT calculation algorithm taking solar radiation into account, as shown in Equation (2) –

$$T_{mrt} = \sqrt[4]{\begin{array}{l}\sum_{i=1}^{6}(F_i T_i^4) + \\ \frac{C_{dn}}{\varepsilon\sigma}(\alpha_{irr,d}\sum_{j=1}^{M} F_j I_{d,j} + C_s \alpha_{irr,b} f_p I_b)\end{array}} \tag{2}$$

where T_{mrt} is the mean radiant temperature for the position of interest, F_i is the view factor from the position of interest relative to the surface *i*; T_i is the temperature of surface *i;* C_{dn} is day-night coefficient (equal to 1 in the daytime and to 0 in the night time); C_s is the shading coefficient (equal to 1 when the point is hit by the solar beam and to 0 in other cases); ε is the emissivity of the human body; σ is the the Stefan-Boltzmann constant; $\alpha_{irr,d}$ and $\alpha_{irr,b}$ are absorption coefficient for direct and diffuse solar radiation respectively.

It can be seen from the above equation that the radiant heat transfer generally consists of three parts – the radiation from the wall, the direct radiation from the sun that penetrates the glass and the diffuse solar radiation from the glass. The wall part is determined by the view factor and the surface temperature of each wall. The sun part is a little complicated – in order to make clear the values of coefficients C_s and C_{dn}, firstly whether it is daytime or night time and whether the position of interest could directly 'see' the sun should be judged. A diagram for the calculation procedure can be shown as below –

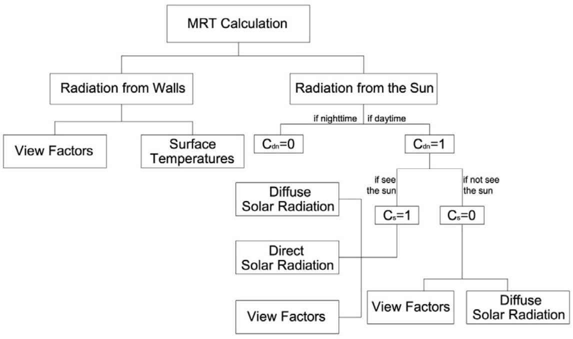

Figure 1: Diagram of MRT calculation procedures

The coefficients should be determined before the calculation is performed. C_{dn} is easy to determine since it only depends on the time. C_s is a little complicated as it is related to the sun position and the position of the glass. With the sun position and space orientation known, a line parallel to the sun rays can be drawn from each grid by basic algebra knowledge. Then whether this line has a intersection with the glass is checked and the value of C_s can be designated accordingly.

The surface temperatures, diffuse and direct solar radiation are related to the weather data and building materials, and they are regarded as already known in the study. Algorithms for the view factors calculation can be found in the work of Hamilton and Morgan [5]. Only two kinds of algorithms are needed – one is for horizontal surfaces, i.e. roof and floor, while the other is for vertical surfaces, i.e. walls.

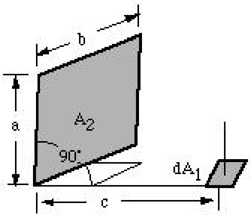

Figure 2: Illustration of the view factor calculation for walls

For the walls, the view factor can be calculated as

$$F = \frac{1}{2\pi}\left[\tan^{-1}\left(\frac{1}{C}\right) - \frac{C}{Y}\tan^{-1}\left(\frac{1}{Y}\right)\right] \tag{3}$$

where $A = a/b; C = c/b; Y = \left(A^2 + C^2\right)^{0.5}$.

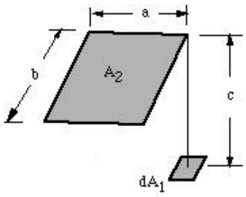

Figure 3: Illustration of the view factor calculation for roof and floor

For the view factors to the roof and floor, the following calculation formula can be used –

$$F = \frac{1}{2\pi}\left\{\begin{array}{l} \frac{A}{(1+A^2)^{0.5}}\tan^{-1}\left[\frac{B}{(1+A^2)^{0.5}}\right] \\ +\frac{R}{(1+B^2)^{0.5}}\tan^{-1}\left[\frac{A}{(1+B^2)^{0.5}}\right] \end{array}\right\} \quad (4)$$

where $A = a/c; B = b/c$.

Based upon above analysis, a code which can perform the MRT calculation is developed by using MATLAB which is a high-level language and interactive environment capable of performing computationally intensive tasks, such as the calculation in relation to matrix, which is the basic need of this part of the study.

2.2 Calculation of air temperature

As stated earlier, the air temperature distribution in atrium spaces is usually not uniform but with strong stratification. To deal with this thermal characteristic, a CFD method, which allows the explicit calculation of the whole temperature and velocity field of a flow by numerically solving the corresponding transport equations, will be performed. The three-dimensional conservation equations describing the transport phenomena for steady flows in free convection are of the general form:

$$\frac{\partial(U\phi)}{\partial x} + \frac{\partial(V\phi)}{\partial y} + \frac{\partial(W\phi)}{\partial z} = \Gamma\nabla^2\phi + S_\phi \quad (5)$$

where ϕ represents the concentration of the transport quantity in a dimensionless form, namely the three momentum conservation equations (the Navier–Stokes equations) and the scalars mass and energy conservation equations; *U, V* and *W* are the components of velocity vector; Γ is the diffusion coefficient; and S_ϕ is the source term. The governing equations are discretised by finite volume scheme following the procedure described by Patankar [6].

The commercially available CFD code FLUENT is employed in the study. For the ease of communicating and exchanging data, the same grid used for MRT calculation is also employed for the CFD analysis.

To achieve a sensible and accurate result, couple implicit is chosen as the solution method and second-order upwind discretisation schemes are used for momentum and turbulence equations. The convergence criterion for all variables is set up as default – 0.001. As the air velocity is very low, the flow can be considered as laminar. The surface to surface model is adopted to model the radiation between the walls.

3. DEVELOPING A NEW METHOD FOR THE EVALUATION OF THERMAL COMFORT LEVEL IN ATRIUM SPACES

The widely used thermal comfort indicator PMV (Predicted Mean Vote) is employed in the study. It can be calculated according to the following function –

$$PMV = \left(0.303e^{-0.036M} + 0.028\right)\left\{\begin{array}{l} (M-W) - 3.05\times10^{-3} \\ \times\left[5733 - 6.99(M-W) - p_a\right] - \\ 0.42\times\left[(M-W) - 58.15\right] - \\ 1.7\times10^{-5} M(5867 - p_a) \\ -0.0014M\left(34 - t_a\right) - \\ 3.96\times10^{-8} f_{cl} \times \\ \left[(t_{cl}+273)^4 - (t_r+273)^4\right] \\ -f_{cl}h_c\left(t_{cl} - t_a\right) \end{array}\right\} \quad (6)$$

where *PMV* is the Predicted Mean Vote; *M* is the metabolic rate; *W* is the external work; I_{cl} is the thermal resistance of clothing; f_{cl} is the ratio of a person's surface area while clothed; t_a is the air temperature; t_r is the mean radiant temperature; h_c is the convective heat transfer coefficient; t_{cl} is the surface temperature of clothing.

From the earlier analysis, the temperature field can be obtained from CFD and the MRT field can be computed from the code developed. However, a platform is still needed in order to integrate the data from the two analyses. FLUENT can export the data from the calculation in ASCII format and then the data can be imported to MATLAB for the further PMV calculation. An application of this tool is shown in the following section.

4. APPLICATION OF THE NEW TOOL

4.1 Case description

The case chosen for the study of the new tool is shown in the figure below. It is an enclosed atrium space surrounded by adjacent parts. The length, width and height of the space are 8m, 10m and 6m respectively. A typical summer daytime, from 9am to 5pm is studied. The air velocity is assumed as 0.1m/s and relative humidity is 50%. Other important data, such as the sun position, solar radiation intensity the surface temperatures for every two hours are obtained from a computer simulation and listed in Table 1.

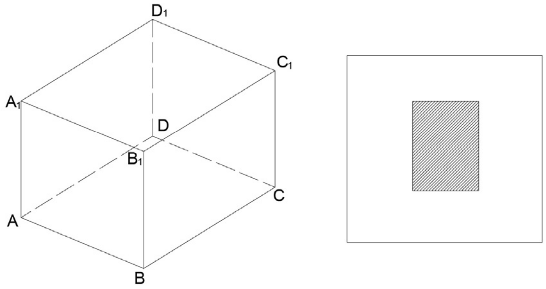

Figure 4: The shape and plan of the atrium

Table 1: Data relevant to the case study

	Surface temperatures (^oC)					
	top	bottom	left	right	back	front
9am	21.2	25.3	24.2	23.1	23.8	22.6
11am	35.6	27.2	27.8	26.9	28.2	25.8
1pm	48.7	29.0	32.6	30.7	33.5	28.7
3pm	40.2	28.0	29.3	30.3	31.7	27.6
5pm	36.8	27.2	26.8	28.7	27.8	25.9

	Solar radiation incident on the roof (Wm^{-2})		Sun position	
	direct	diffuse	Azimuth	Altitude
9am	353	102	113.7	43.5
11am	443	186	153.8	56.3
1pm	443	186	-154.7	56.5
3pm	353	102	-115.3	43.8
5pm	86	20	-88.4	26.4

4.2 MRT simulation

The results of the MRT calculation for each time are shown in the following figures.

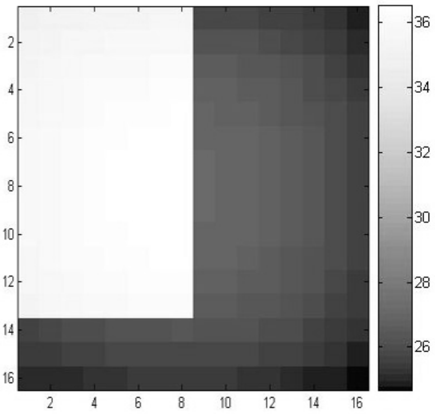

Figure 5: MRT distribution of1.6m level at 9am

The major findings from the MRT calculation study are –

1. The MRT of the area that the sun can irradiate is much higher than that of the area that the sun does not irradiate – usually 10ºC or even higher depending on the radiation intensity and surface temperatures. If the whole surface is not irradiated (i.e figure 9), the MRT distribution is with very small variation – only 2 degrees.

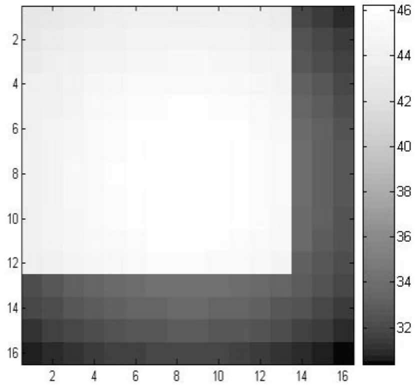

Figure 6: MRT distribution of1.6m level at 11am

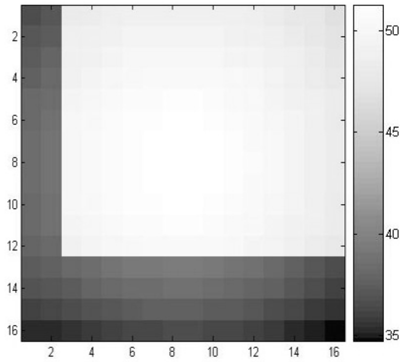

Figure 7: MRT distribution of1.6m level at 1pm

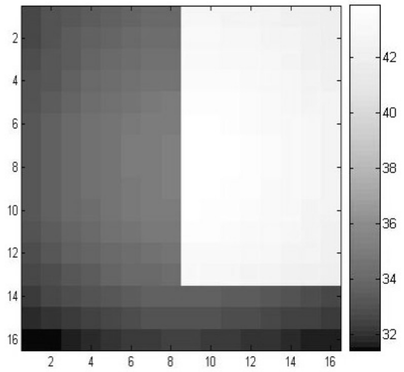

Figure 8: MRT distribution of1.6m level at 3pm

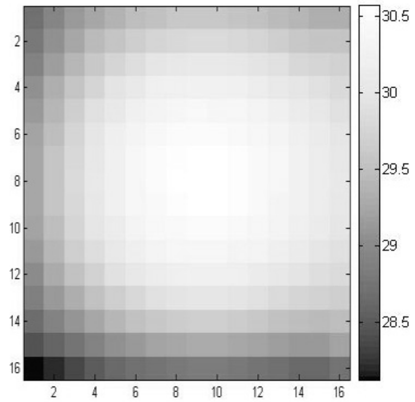

Figure 9: MRT distribution of1.6m level at 5pm

2. Solar radiation has a more significant contribution to the MRT than the surface temperatures. By comparing the MRT distribution at 9am and 3pm (or 11am and 1pm) when the solar radiation for both is the same, the increase of MRT is generally much smaller than that of roof temperature; and when there is no solar radiation, the MRT reduces significantly.
3. The position with the highest MRT is usually in the middle – this is because is has the largest view factor to the roof surface at this level of height. The position with the lowest MRT is located at the shaded corner between two walls with the lowest surface temperatures.

4.3 CFD simulation

The results of the CFD simulation for each time are shown as below.

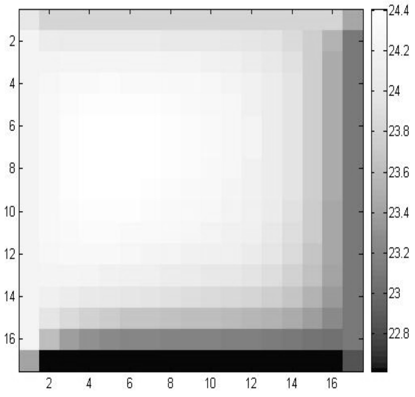

Figure 10: Temperature field of1.6m level at 9am

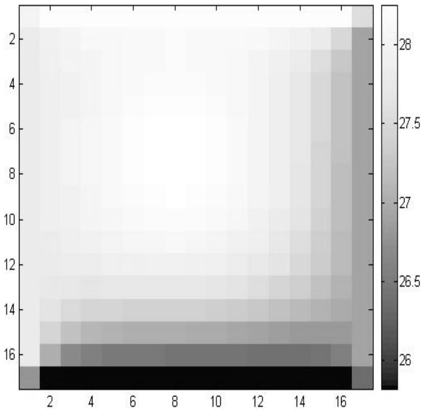

Figure 11: Temperature field of1.6m level at 11am

The findings from the study of air temperature stratification at the height of 1.6m could be summarised as following –
1. The temperature of the roof does not have a significant influence on the air temperature at occupants' level. Even if the temperature rises to nearly 50 degrees at 1pm, the highest temperature of the occupants' level is 34ºC, which is very high compared with the surface temperatures at that time.
2. Temperatures of those grids at the periphery are generally determined by the nearest surface temperatures, while the temperatures of those in the centre of the space are significantly influenced by the surface temperature of the bottom.

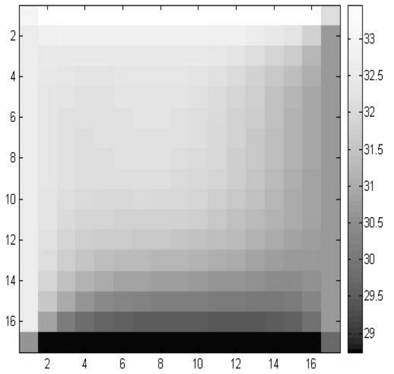

Figure 12: Temperature field of1.6m level at 1pm

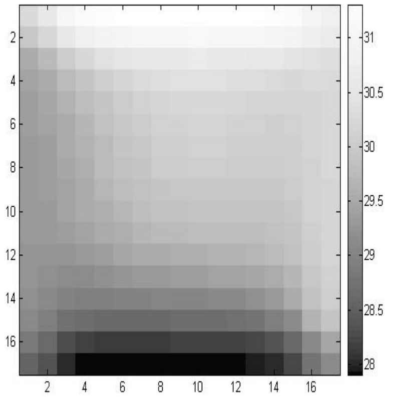

Figure 13: Temperature field of1.6m level at 3pm

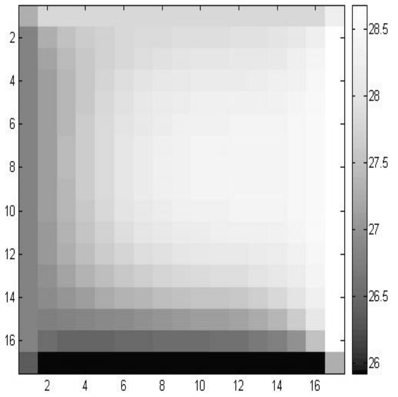

Figure 14: Temperature field of1.6m level at 5pm

4.4 PMV Simulation

The two human factors that can influence the evaluation of thermal comfort level are assumed to be constant – both the activity level and the clothing level are taken as a value of 1. Below are results from the simulation by the tool developed in the study.

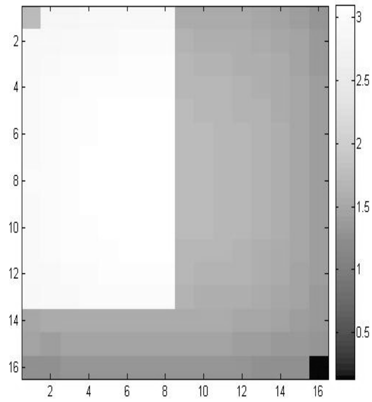

Figure 15: PMV distribution of1.6m level at 9am

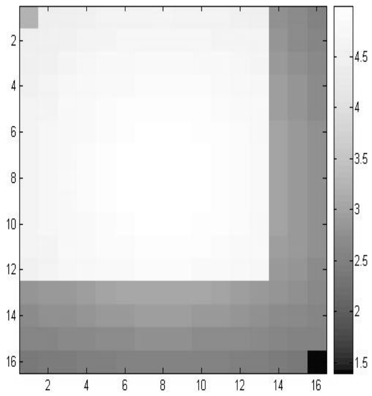

Figure 16: PMV distribution of1.6m level at 11am

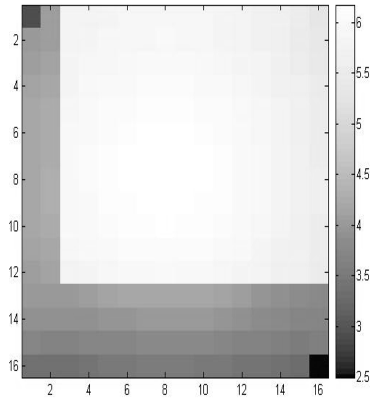

Figure 17: PMV distribution of1.6m level at 1pm

It can be seen from the results that the PMV distribution has the same pattern as the MRT distribution, which confirms that solar radiation that comes into the building through the glass has the most significant impact. This also questions the main cause of overheating of atrium space: the greenhouse effect used to be considered as the biggest problem, as it raises the internal air temperature, but this study shows that the mean radiant temperature is a more influential contributor to discomfort.

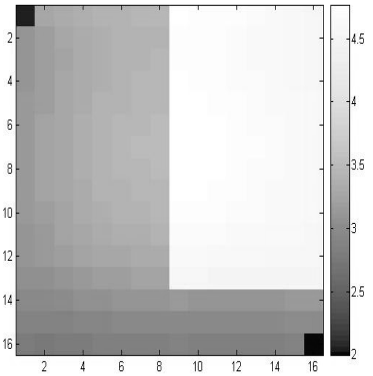

Figure 18: PMV distribution of1.6m level at 3pm

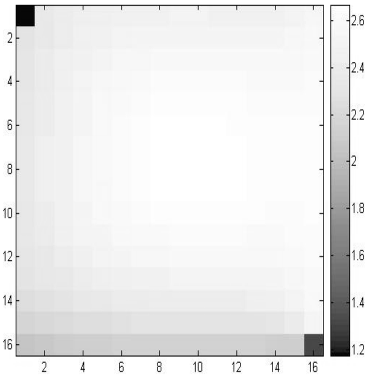

Figure 19: PMV distribution of1.6m level at 5pm

5. CONCLUSION

A tool for the evaluation of thermal comfort level in atrium spaces is developed in this study. The temperature field is obtained from CFD and a code is developed for MRT calculation based upon the combination of solar radiation and radiant heat transfer from the walls. Finally, an application of the tool is demonstrated.

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