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Design and low energy ventilation solutions for atria in the tropics

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ABSTRACT

A generic atrium building was designed to incorporate low energy solutions and features of both vernacular and contemporary South Asian architecture. To achieve low energy and comfort within the atrium space, some key design variables were examined by running a dynamic thermal model (DTM) for some representative cases. This DTM model was developed with multiple levels and zones to simulate the heat and air movement throughout the building and validated with the data measured in a real building of similar form. The modelling study was carried out to investigate the effects of two roof forms for the atrium and three low cost ventilation solutions on indoor thermal comfort. It reveals that low cost ventilation and acceptable comfort are achievable in this traditional form of architecture and low energy solutions and careful design can complement well its functional aspects and even enhance its aesthetic and practical qualities.

The solar heat gain, air temperature, and mean radiant temperature in the atrium were used to assess the effectiveness of clerestory windows with opaque rooftop (i.e. side-lit model) as compared to the fully transparent glazed rooftop (i.e. top-lit model). Data on cooling loads, indoor air temperature, and mean radiant temperature were used to evaluate the design options with special consideration on local adaptable thermal comfort criteria. The possible effects of the research outcomes on the incorporation of atria are discussed at the end.

1. Introduction

Atria have become very popular in modern buildings, particularly large commercial buildings, such as hotels, shopping malls and office headquarters (Reid et al., 1994). Often right after the main entrance or as the extension of the entry lobby, an atrium provides a central core circulation area with feeling of space and light as well as a transition zone between the outdoors and the interior for long stay (Saxon, 1994). Moreover, traditional balconies are adopted as walkways above ground level to maximise the use of the atrium space. This is particularly true in buildings like shopping malls, as a linear atrium create a semi-outdoor environment for the long balconies, the key circulation paths in these buildings. Apart from this major attraction, atria have many environmental implications, such as for solar gain, daylight and thermal comfort. They affect the physical environment within the void space and even to the adjacent spaces. These environmental conditions in the atria depend directly on the complex interaction between the buildings' elements (and construction materials), architectural forms and much more the outdoor weather conditions (Atif, 1992).

In cold climate the environmental benefits of such void spaces are obvious as they are used as a sunspace during sunny day and buffer zones between harsh external climatic conditions and the indoor environment (Hawkes & Baker, 1983; Nelson, 1984). In hot climate, however, the environmental effects are not always desirable. A typical example of this is that the glazing cover allows deeper penetration of high level natural lighting, a much welcome feature for an interior space, and strong solar radiation, an adverse factor to thermal comfort (Douvlou & Pitts, 2001; Edmonds & Greenup, 2002). In the tropics, solar radiation penetrating through the large glazed envelope can severely worsen indoor thermal environment of a building during the occupied hours, especially the radiations from the high altitude of the afternoon sun and high temperature in the high level of the atrium space (Pan, Li, Huang, & Wu, 2010).

An example of such poor indoor conditions is best illustrated by Sandra Day O'Connor United States Courthouse, a glass box building. It is well known that the air temperature inside the atrium can easily go beyond 38 °C. Even with Ove Arup's innovative solution the indoor air temperature rises as high as 33 °C on the ground floor of the atrium under the scorching Arizona Sun (Stephens, 2011)

Unfortunately the problem of overheating is not easily seen until the building is actually occupied and the high bill for cooling is incurred. Apparently the benefit from the abundant natural lights often overshadows the adverse effects of excessive solar

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penetration on thermal comfort. The negative sides of solar penetration are often neglected in many building projects involving atrium form in hot regions as the functions of atria are mainly for spatial and aesthetic reasons, which are often justified by the abundant natural lights associated with the atrium form. Moreover there is a misconception among architects that glass technology is now very advanced and unshaded glass would not present any thermal problems. This practice has been best summarised as "architectural designers do not always recognise the high probability of thermal discomfort in glass buildings in hot climate" as reported in ASHRAE (2009), and more and more glass atria are appearing at rapid pace. A recent review on some buildings well-acclaimed among architects and architectural critics shows a significant trend of increase in the use of glazed envelopes even in Southern Asia countries, where the air is hot and solar altitude is low (Welch & Lomholt, 2011) (Fig. 1).

ASHRAE (2009) has also pointed out that glass box buildings are notoriously uncomfortable regardless of a very large, sophisticated, expensive and maintenance-intensive system.

The heat at the top of the atrium can be removed by both wind and stack forces in a naturally ventilated building. Wind drives air movement throughout the building including the atrium well. This force however is often weak for urban buildings due to canyon sheltering effects (Santamouris, Papanikolaou, Koronakis, Georgakis, & Assimakopoulos, 1998). The stack effect can be dominant to draw air from lower part of the building and lift it upward in the atrium and eventually push it out through rooftop openings. Heat collected at a glazed roof top, is beneficial for enhancing the airflow but its radiation also causes discomfort particularly to the users on the higher level balconies.

Excessive solar gain is normally the immediate cause of overheating within the space and solar control becomes essential, such as shading devices or external evaporative cooling (Abdullah, Wang, Meng, & Zhao, 2009; Wang, Huang, & Cao, 2009). These problems could be resolved more easily and less costly during early design process than at later stages (EEBPP, 1996). Hence energy efficiency and environmental strategies are developed in many building projects and considered well starting from the conceptual design stage. However, a recent study points out that these concepts are rarely fully analysed using methods such as quantitative prediction, assessment and optimisation (Pollock, Roderick, McEwan, & Wheatley, 2009). Assessing and optimising solutions needs prediction of thermal performance of each of those proposed designs and quantitative investigation due to the complex nature and intricate relationships among design variables.

This paper presents a study comprising the following three components: designing two generic atrium forms for the tropics; proposing two low energy mechanical ventilation solutions to improve thermal condition within the atrium well, and developing a method of modelling atrium thermal behaviour using commercial software during design stage. As the quantitative analysis was carried out using a popular commercial program, the primary aim was to demonstrate how modelling should be used at early design stage to predict the effects of a number of design options and ventilation solutions for the atrium on its indoor thermal environment. In addition it was to show that low energy solutions and design for an atrium can complement well its functional aspects and even enhance its aesthetic and practical qualities.

2. Methods

The study was carried out in three stages. It began with developing a representative atrium building that bears features to be examined which include two roof forms and key design variables, and also identifying two common ventilation schemes namely natural ventilation and pressurised mechanical ventilation. The next stage was to develop a multi-level and multi-zone modelling technique using a dynamic thermal modelling (DTM) tool and carrying a validation test. The final stage was to apply the DTM to the representative models with differing design variables and to carry out a parametric study to investigate quantitatively the effects of selected parameters that specify the atrium and ventilation solutions.

2.1. The building

The generic office building was developed to contain the following elements of the vernacular architectural features in South East Asia, as identified in a previous review study (Abdullah, 2007) (Figs. 2 and 3):

- Three storey building with rectangular plan of 21 × 30 m and elongated along East–West axis;
- 3.4 m floor to floor height for all three storeys;
- Linear central atrium with ground floor area of 9 × 21 m, four storey high and surrounded by office/shop spaces on three floors;
- Long balconies, or walkways, of 1.5 m wide on first and second floors surrounding the atrium well, serving as main circulation areas as well as platform to enjoy the void and landscape;
- Atrium form with Plan Aspect Ratio of 0.3 (or 1:3) to reflect the smallest linear form;
- The Sectional Aspect Ratio for all the tested models taking into account the height of the atrium well from the ground floor level to the second floor ceiling level was about 1.7 (or 1:0.6);
- The total volume of the below roof space beyond the second floor ceiling level was also kept constant for both representative models, which was about 432 m^3 for models with wall-to-roof void and 270 m^3 for model without wall-to-roof void, respectively;

To examine the impact of some key design variables and solar control measures on the atrium indoor thermal environment, other features were also included in the parametric modelling study. They are two roof forms, side-lit (Fig. 2a and c) and top-lit (Fig. 2b and d) and their variations. Side-lit form is a local traditional response to natural lighting and strong solar radiation, while the top-lit form is an imported solution popularly employed by present day designers.

The variations included the overhangs for the side-lit roof form, extra space beneath atrium roof, and blinds next to the glazing panels. These will be discussed in full details in the section on the parametric study.

2.2. Weather and internal conditions

The 1978 weather data file for Subang, Kuala Lumpur was used as it consisted the representative data generated from those of the months selected from the individual years before and concatenated to form this test reference year or typical meteorological year (The Malaysian Meteorological Service, 1993). The file contained the mean hourly values of all the weather variables including the air temperature, humidity, total and scattered solar radiations, and wind speed and direction for a whole year (Deosthali, 2000).

Studies have confirmed the trend of intensified urban heat island due to recent urbanisation particularly in Asia (Hung, Daisuke, Shiro, & Yoshifumi, 2006; Güneralp & Seto, 2008; Li et al., 2009; Juan-juan Li, Wang, Wang, Ma, & Zhang (2009)). They also report a less significant change in the temperature in rural and suburban area while a significant temperature increase in city centres. Therefore an updated weather data would be needed for modelling prediction. However, the generic building is a low rise one and presumably located in a suburban area. Therefore the weather data were used without any modification.

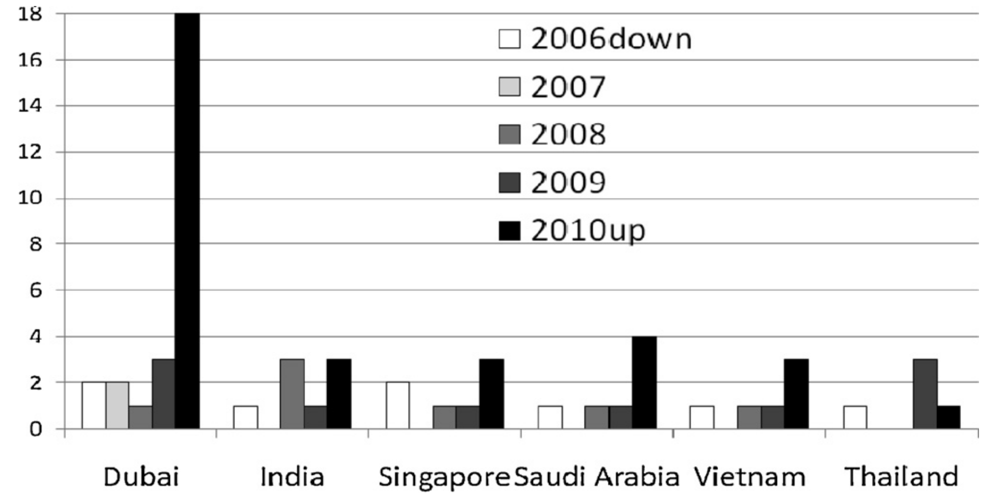


Fig. 1. Gazetteers of notable atrium buildings in hot climate Asian countries.

For simulating the worst case scenario, 21st March (noted as Day 80) was chosen as the design day (i.e. the hottest design day of the year) for Kuala Lumpur as suggested by many authorities (Koenigsberger, Ingersoll, Mayhew, & Szokolay, 1980; Nieuwolt, 1977; Takahashi & Arakawa, 1981). In order to ensure that the reported results for the chosen simulation day are reflective of any thermal mass effects of the structure, all models were 'pre-conditioned' for 10 days. Hence the actual modelling was run for 10 days, and the results of the last day were examined.

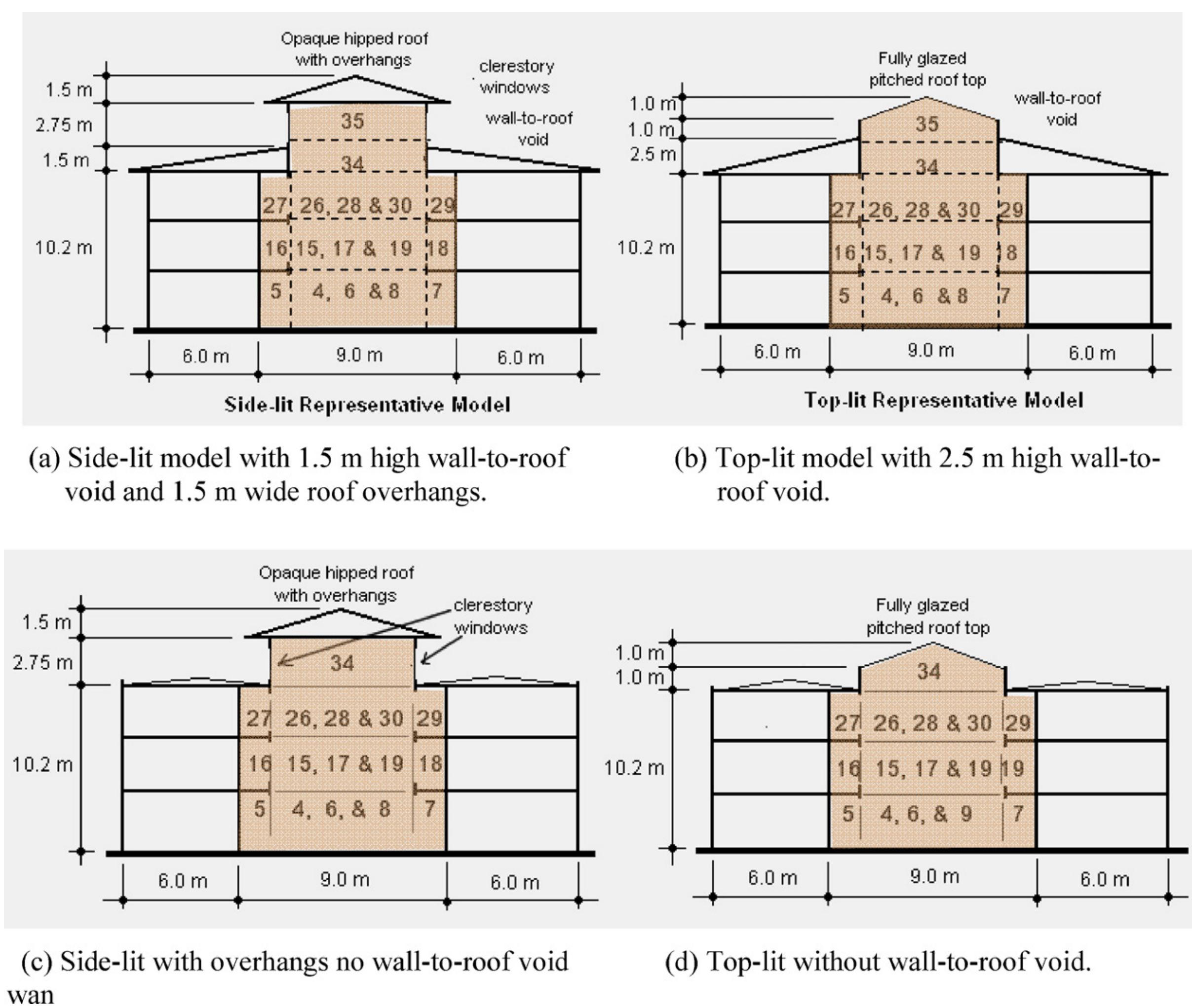


Fig. 2. Schematic cross-sections of representative atrium models. (a) Side-lit model with 1.5 m high wall-to-roof void and 1.5 m wide roof overhangs; (b) top-lit model with 2.5 m high wall-to-roof void; (c) side-lit with overhangs no wall-to-roof void wan; (d) top-lit without wall-to-roof void.

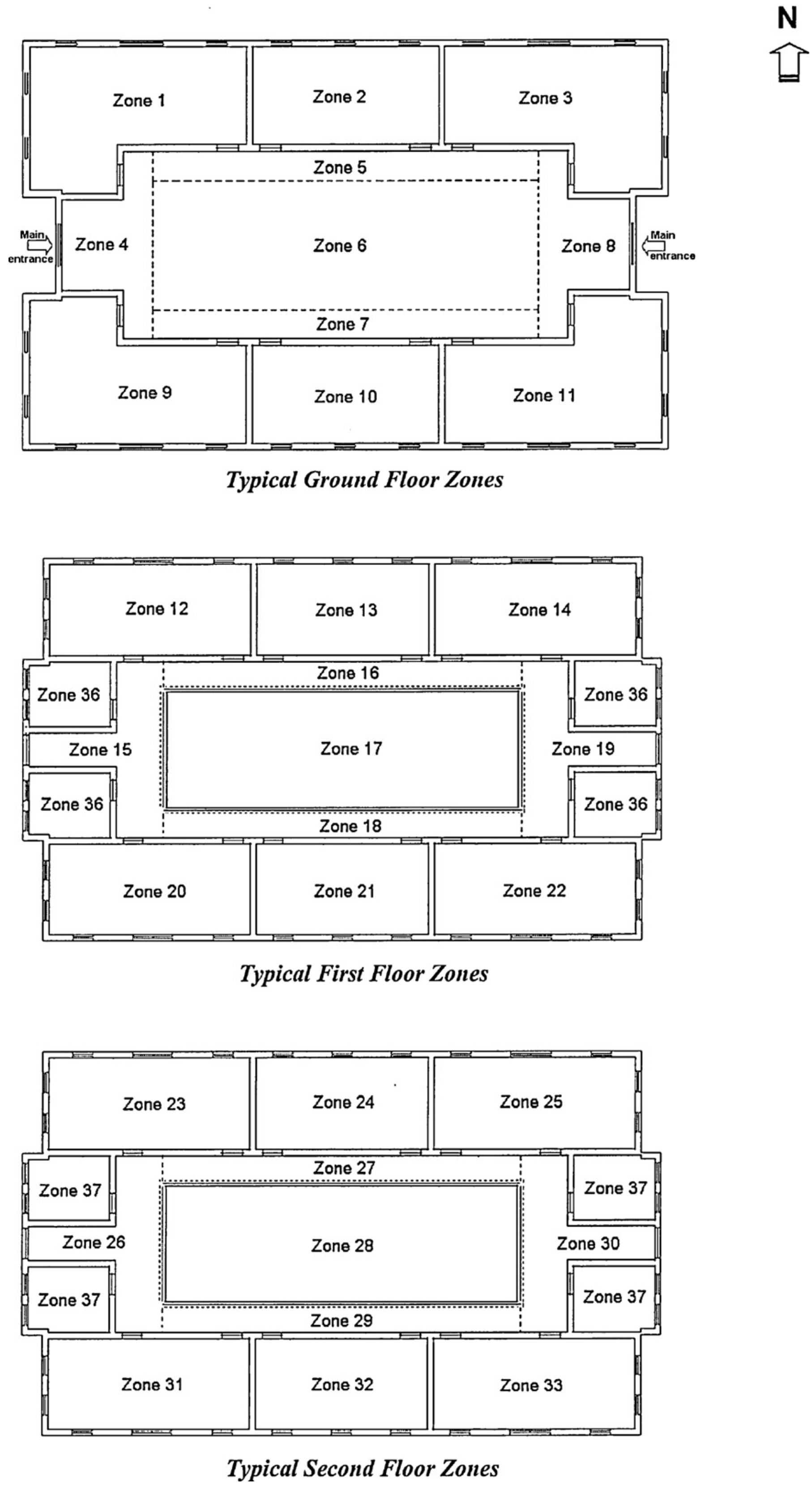


Fig. 3. Typical floor plans of the linear three-storey representative atrium.

In order to investigate the effect of solar penetration on the atrium thermal performance due to seasonal changes, three simulation days including the 21st June, 21st September and 21st December were also used for modelling.

2.3. Ventilation schemes

Two types of ventilation strategies, namely natural ventilation and pressurised mechanical ventilation, were considered to examine how the thermal conditions within the atrium and communal space were affected by the selected design parameters.

2.3.1. Full natural ventilation

To simulate full natural ventilation, the following general assumptions and settings were considered for the two roof forms and their variations:

- The internal conditions were specified accordingly.
- Main entrances on either side (east and west sides) of the linear building were considered as the main low-level openings (ground level) for cross ventilation due to easterly wind. It was assumed that during office hours from 0800 to 1800 h, the opening area of both external doors, west and east main entrances, were maintained equal. The total area of each of the external doors was 5 m^2.
- The high-level (roof level) opening for both top-lit and side-lit models was considered a half (50%) of the total area of low-level openings so that all openings would have the same size. Respectively, the total area was 85 m^2 for clerestory windows and 113.64 m^2 for the glazed roof. These outlets (clerestory window vent for side-lit model and rooftop vent for top-lit model) were set to always open.
- The vents for all windows, internal doors and external doors were set to 100% open starting from 1800 to 0700 h the next morning for night cooling.

2.3.2. Pressurised ventilation

The two representative models were simulated with two types of pressurised ventilation: all occupied floors pressurised and the ground floor only pressurised. The pressurised ventilation is a simple and economical solution primarily because it uses the air from the surrounding air conditioned rooms to cool the atrium and no return air ductwork is needed in the building. It was proposed as a low-energy ventilation scheme to cool the atrium space, as it did not exert extra cooling on the contra cooling plant. This could also save running cost as the outdoor weather in Malaysia is generally warm and humid with low wind velocity for most parts of the year.

To model the pressurised ventilation, the atrium was supplied with the air at 23 °C off the adjacent offices, which were pressurised by supplying 18 °C cool air during office hours. The amount of the supply air was calculated locally to each of the office zones. Each of these zones was specified with the values of casual gains of the lower end of the recommended range in CIBSE guides.

Night cooling was applied for out of office hours.

2.4. Criteria for assessment of indoor thermal performance and comfort

Fanger's theory provides a very sound base for many thermal comfort standards, including ASHRAE (1992) and CIBSE (2006). These standards have been challenged by many surveys carried out in hot climates, as they often result in overcooling and causing discomfort to people (Tantasavasdi, Srebric, & Chen, 2001). A new concept was introduced by Fergus (2004) as adaptive thermal comfort to reflect the local climate and people's preference.

The predicted air, mean radiant temperatures and resultant temperature on the ground floor, the walkways on the first and second floors were used to assess the effects of the design parameters on the indoor thermal performance. Hence in this study, thermal comfort was interpreted with the following special considerations for warm-humid and hot countries:

- In tropical climate thermal comfort is set to a range of temperature from 20.8 to 28.6 °C along with the relative humidity between 40 and 80% in air-conditioned buildings; and a wider range of 20.8–31.5 °C along with relative humidity between 54 and 76% in naturally ventilated building, with the aid of average air movement of 0.15–1.0 m/s; according to Malaysian cases (Abdul Rahman & Kannan, 1997; Sabarinah, 2002) and Thai studies (Rangsiraksa, 2006; Yamtraipat, Khedari, & Hirunlabh, 2005).
- In short stay spaces, such as an atrium, an even wider range of comfort should be applied as the atrium space is normally used as a relaxing and transitional space, the comfort requirement is therefore less stringent. A recent survey over nearly 1150 people using transitional spaces in the tropics reveals that the neutral temperature is between 26.1 and 27.6 °C, although the preferred temperature is slightly lower (Jitkhajornwanicha & Pitts, 2002). A further study shows that a 3° higher than the normal cooling standard can result in 4.8–8.5% reduction in cooling energy in atria under British summer conditions (Pitts & Saleh, 2007). The reduction will be more significant when the outdoors is hotter and for a longer period.

2.5. Modelling tools

The three major approaches commonly employed in predicting thermal conditions inside a building in the design stage are theoretical calculation, physical simulation (either water tank or wind tunnel) and computer modelling. Theoretical calculation shows clearly the quantitative relationships between the key variables such as ventilation rate and other design variables, such as opening areas and height between two set of openings under a limited temperature differences between the indoor and outdoor air (Holford & Hunt, 2003). For a real building it can be very hard to use this method due to the complexity of building geometry and flow paths configuration. Physical modelling is normally very time consuming and expensive, as it involves scaled model tested in a specialised laboratory environment with equipments, such as boundary layer wind tunnels which are normally big in size (Sharples & Bensalim, 2001) and a technique of Planar Laser Induced Fluorescence for quantitative visualisation of flow in a water tank. Hence, it is difficult to be applied to each atrium design.

Computer modelling has been popular recently due to increase in computing power and code capability and availability. In many practices, modelling has been routinely carried out to test design options. Among these computer modelling tools, computational fluid dynamics (CFD) gives more details of a flow field. A recent review on modelling tools reveals that CFD was a favourable choice for most studies on building ventilation performance (Chen, 2009). Particularly its high resolution for flow domain allows detailed representation of the geometry and secures accurate solutions of the pressure and velocities over large openings, the key concern in correctly modelling natural ventilation in atrium with large openings (Li, Pitts, & Li, 2007). The high space resolution also provides accurate account for the contribution to thermal comfort made by long wave radiation from surrounding surfaces (Li & Pitts, 2006). However, due to heavy computation, it is normally used for steady-state modelling. Hence the results are featured with high resolution for space but static in time. Nevertheless, specifying the boundary conditions has to rely on other modelling to provide reasonable values, particularly for modelling natural ventilation in atria (Tan & Glicksman, 2005).

The other type of computer modelling, dynamic thermal modelling (DTM) programs have been routinely used to model smaller spaces regarded as 'rooms' in conventional buildings (Abdullah, 2007). Based on a multi-zonal model, they treat each room within a building as a zone, calculate the heat and air flows moving among these zones through energy and mass balance equations and predict dynamic thermal performance of a building (Megri & Haghighat, 2007). The simulation results have low resolution for space but high in time, normally including hourly figures throughout a typical year. Hence they are often used for overall assessment of thermal performance and energy consumption of a specific design (Chen, 2009). Apart from the whole year performance assessment, DTM method also allows the indoor conditions to be assessed on hourly basis. Hence statistical data can be obtained for natural ventilation assessment at the design stage, such as the percentage of occurrence of overheating or the temperature exceeding a given threshold in all zones of the building (Pollock, 2011).

For buildings with a large and complex multi-level space such as atria, assigning a large single zone or only dividing each level into one zone may not be sufficient to correctly model the space.

In this study, therefore, the atrium space was divided both vertically and horizontally into a group of small zones in order to improve the spatial resolution for the solutions. The vertical division is essential for simulating stratification (Voeltzel, Carrie, & Guarracino, 2001). In addition, each of the two horizontal directions of the space was further divided into at least in three sections to calculate the movement of heat and air flows. Such technique was an attempt to improve spatial resolution of DTM prediction so that a DTM model could correctly model the stratification and other thermal behaviours within a large multi-level space of the atrium. The DTM model for this study was developed using TAS (Jones, 2000).

2.6. Validation

To test whether the DTM technique was suitable to investigate atrium ventilation and stratification, a real building with similar form and features, as well as situated in a similar climatic conditions was modelled and the predicted results were compared against the measured ones.

The selected building shared four key features outlined as follows:

- A linear atrium with retractable fabric blinds right underneath the roof glazing, external spray of evaporative cooling;
- Similar height of the atrium space;
- Internal balconies/walkways to each floor between the atrium well and the standard air-conditioned rooms; and
- Ventilation schemes: natural ventilation, ground floor only pressurised ventilation.

Validation conditions included a hot clear day and a cloudy day to cover two levels of solar impacts and full occupancy, to include high indoor casual gains. Apart from the standard air-conditioned rooms, the atrium space was divided into 31 zones in 6 levels (Fig. 4). The measurement was carried out in previous study (Abdullah et al., 2009).

2.7. The model and parametric study

In the DTM models, the building elements such as floor, roof, wall and glazing constructions were all specified from the TAS Construction Database with reference to common Malaysian practice (Abdullah, 2007). The ground floor was simulated as being constructed on grade without a false floor, and it *U*-value was 0.29 W/m^2 K. Intermediate floors had *U*-value of 0.95 W/m^2 K. The hipped roofs surrounding the wall-to-roof void areas and above the clerestory space were of sloping tile roof construction with a *U*-value of 0.45 W/m^2 K (Fig. 2a and b). The opaque parts of the facade were with *U*-value of 1.93 W/m^2 K, and the internal walls had the *U*-value of 2.12 W/m^2 K. Glazing materials for external walls, main entrance doors, windows, clerestory windows and transparent rooftop were single clear float glass with *U*-values of 5.33 W/m^2 K for windows (including clearstory windows) and 6.23 W/m^2 K for glazed roof, respectively. For side-lit and top-lit models without wall-to-roof void area as shown in Fig. 2(d) and (c), respectively, the concrete 'flat roof' construction surrounding the clerestory and transparent rooftop areas had a *U*-value of 0.27 W/m^2 K.

The atrium was divided over five levels into 35 and 34 zones respectively for the ones with and without the wall-to-roof void, so that the temperature variation over and air movement among various parts of the atrium space could be calculated individually (Tables 1 and 2). Other zones were simulated as offices with typical casual heat gains (Appendix A).

Basically using the TAS weather data for Kuala Lumpur for simulation day 80, parametrical studies to examine the impact of some key design variables on the atrium indoor thermal performance due to full natural ventilation were carried out as follows:

(i) Varying low- and high-level opening sizes – the representative models were simulated to investigate the effect of varying low- and high-level opening sizes on atrium indoor thermal performance. Four opening sizes (i.e. 0.5 m^2, 0.8 m^2, 1 m^2 and 2 m^2) were considered. The hourly wind speed and direction was fixed at 3 m/s and 90° respectively, while the other weather parameters remained unchanged. Analysis of wind conditions for Kuala Lumpur indicates that the wind velocity throughout the year is generally low and the North-easterly wind in March is less than 3.3 m/s (MMS, 2004).

(ii) Varying wind speeds – the representative models were also simulated to investigate the effect of varying wind speeds on atrium indoor thermal performance due to cross ventilation of the easterly wind. Three different wind speeds were considered: 3, 5 and 7 m/s. These are significantly higher than the actual local conditions in order to see the wind cooling effects. For these simulations, the area for each of the low-level openings was maintained at 0.8 m^2, while the high-level opening was kept totally shut. Hence, the hourly wind speed was changed accordingly and the wind direction was fixed at 90° (easterly wind), while the other weather parameters remained unchanged.

(iii) With and without wall-to-roof void area – the representative models with wall-to-roof void (Fig. 2a and b) and without wall-to-roof void (Fig. 2c and d) were simulated and their results were compared to examine the effectiveness of the wall-to-roof void area in improving thermal conditions particularly on occupied levels. For these simulations, the condition and size of openings were similar to number (ii) above.

(iv) With and without roof overhangs above the clerestory area – side-lit models with and without roof overhangs were simulated and their predicted results were compared to examine the contribution of roof overhangs in minimising the effect of solar radiation on the thermal performance within the side-lit atrium. The depth of the roof overhangs above the clerestory areas was 1.5 m, which was calculated to be sufficient to block direct sunlight from entering through clerestory windows (less than 2.75 m height) due to the lowest solar altitude of 63° in equatorial regions in January (Ahmad & Rasdi, 2000); for these simulations, the weather conditions and the size of openings were similar to that of number (iii) above. Apart from simulation for day 21st March, the models were also simulated for 21st June, 21st September and 21st December. These simulation days were particularly considered to examine the effect of Sun's

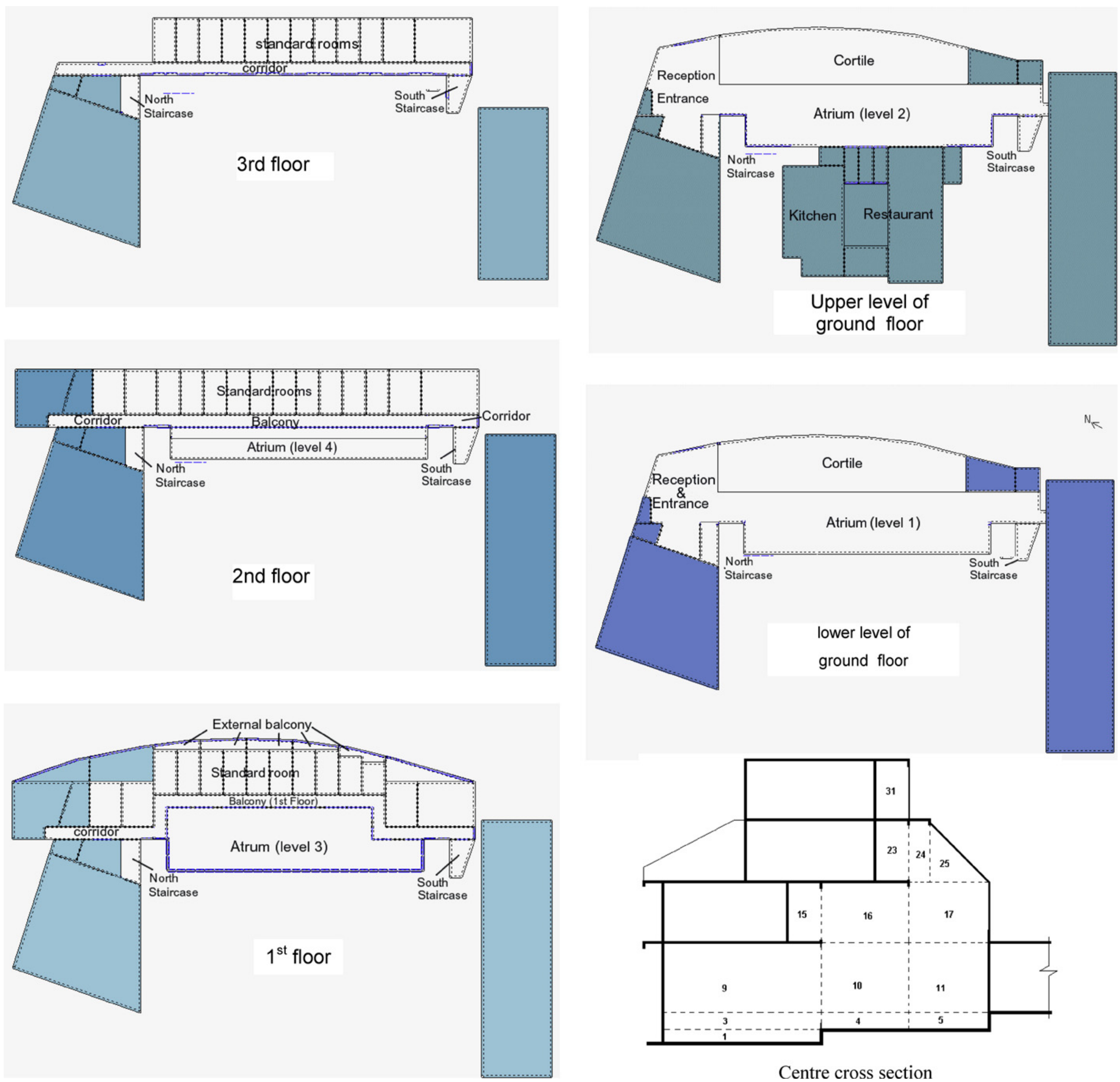


Fig. 4. The TAS model created to represent the validation building. (a) The measured/predicted air temperatures averaged over each level for hot and overcast day (26th of July). (b) The measured/predicted air temperatures averaged over each floor for hot and clear day (27th of July). (c) The measured/predicted resultant temperatures and roof blinds surface temperatures for hot and clear day (simulation day 208). (d) The measured/predicted air and mean radiant temperatures averaged over each level at 1400 h during the clear day.

altitude and solar radiation intensity due to seasonal changes on the atrium thermal performance.

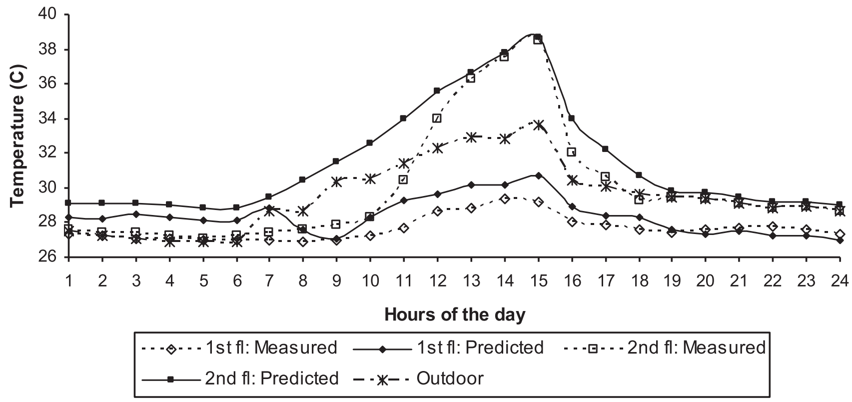
(v) With and without internal solar blinds – the representative models (without internal solar blinds) and models with internal solar blinds were simulated and their results were compared to examine the effectiveness of the solar blinds in improving the atrium's thermal conditions particularly on occupied levels. The same weather conditions and size of openings as that of number (iii) and (iv) were used for these simulations. In order to simulate the atrium thermal conditions when the blinds were extended from 0900 to 1800 h, the new substitute building elements were created to represent both the atrium roof glass with blinds and clear glass windows/walls with blinds at the clerestory facade. These new building elements were specifically put into the substitute building element and substitution schedule columns of the original building elements for both atrium roof glass and clear glass window.

3. Results and discussion

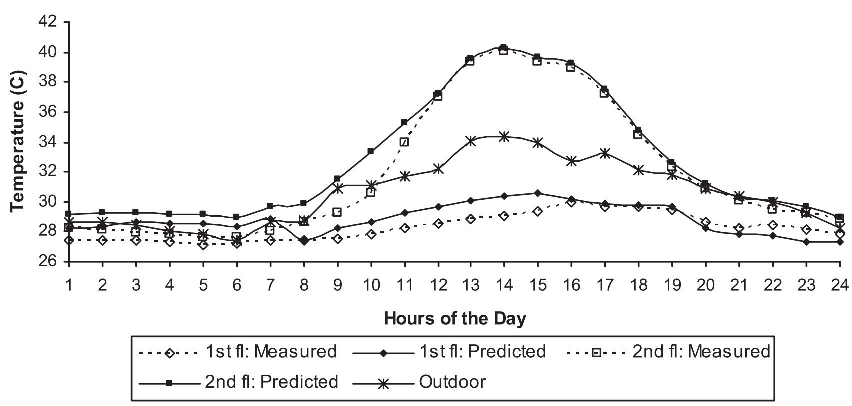
3.1. Result of validation

Fig. 5 (a) and (b) shows that the simulation results tend to be overestimated for both first and second floors. In addition to the dissimilarity in weather conditions, the discrepancies between the measured and predicted results might also be due to the followings:

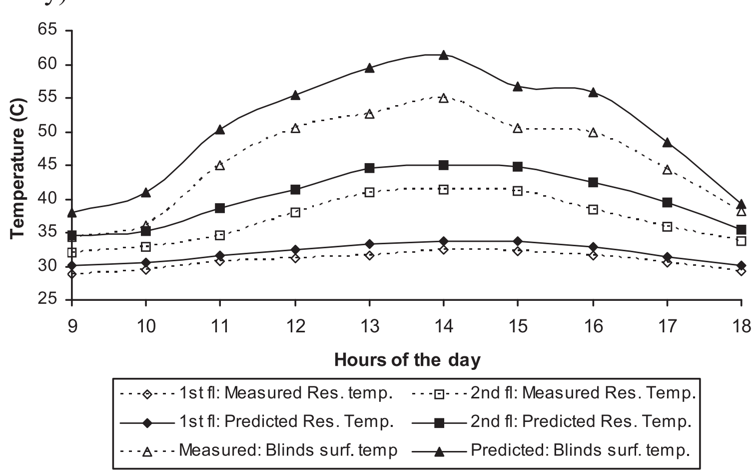
- As a result of uncertainties about the thermal properties of the existing construction materials, the thermal properties of building elements including the glazed openings of the model were estimated and specified using the construction details programmer in building data editor. Inaccurate specifications of thermal property data, particularly for the glazed roof and walls, had led to higher prediction of solar penetration in the model, whereas in the real building solar penetration could be much smaller than that of the model; thus, resulting in higher prediction of the indoor net heat gain in the model.
- In the real building, there were numerous infiltration airflow paths which allowed the indoor heat to be dissipated. However, in the model the infiltration rates were fixed and the values could be much lower than that of the real building. Hence, less heat dissipation in the model led to higher prediction of the indoor heat gain.



a) The measured/predicted air temperatures averaged over each level for hot and overcast day (26th of July).

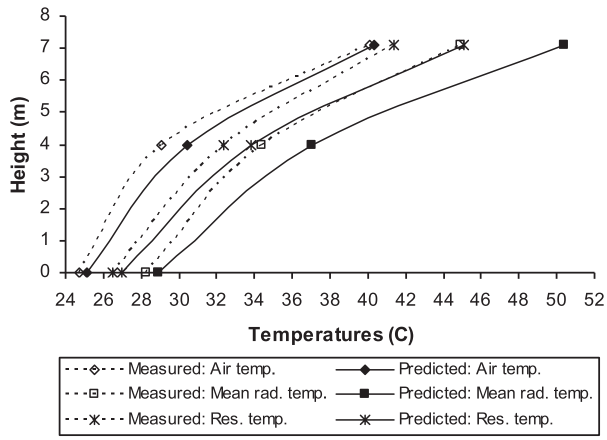


b) The measured/predicted air temperatures averaged over each floor for hot and clear day (27th of July).



c) The measured/predicted resultant temperatures and roof blinds surface temperatures for hot and clear day (simulation day 208)

Fig. 5. Comparison between the predicted and measured data of the validation case.



d) The measured/predicted air and mean radiant temperatures averaged over each level at 1400 h during the clear day.

Fig. 5. (*continued*).

- In the model, the fixed internal conditions were specified based on general assumptions and estimations. There is a tendency for the heat gains from occupants, lighting and equipment to be overestimated in the model since the occupancy pattern and the use of lighting and equipment in the real conditions were somewhat irregular. Moreover, there is also a great possibility that the infiltration rates and conditioned air supply rates were underestimated due to the uncertainties of the actual flow rates and uncontrolled actions of the users in the real building. All these would result in higher prediction of the indoor heat gain in the model.

However, both graphs above show similar trend which indicates that the temperature stratification would occur at high level inside the atrium where the indoor air temperature on the second floor is well above the outdoor air temperature. For overcast day the difference in air temperature between the first and second floors at 1500 h (the hottest hour of the day) was 9.3 K for measured and 8 K for TAS prediction results respectively. For clear day (day 208), on the other hand, the air temperature difference at 1400 h (the hottest hour of the day) was 11 K and 9.9 K for measured and predicted results respectively. These results revealed that during the hottest hour of the day the measured conditions recorded slightly higher air temperature difference between the first and second floors compared to that predicted by TAS. In general for both overcast and clear days the predicted air temperatures on the first floor in the afternoon was comparatively higher than the measured conditions. The difference in air temperature on the first floor in the afternoon between measured condition and TAS prediction was in the range of 0.7–1.5 K for overcast day and 0.2–1.3 K for clear day respectively. Basically the higher air temperature on the second floor was due to the fact that there was no provision of rooftop vent to exhaust the stratified hot air at higher level out of the building.

It was found in Fig. 5(a) that for hot and overcast day, it was not easy to estimate and modify the amount of solar radiation and cloudiness compared to that of the hot and clear day, as there was considerable discrepancies between predicted and measured air temperature on the second floor particularly from early morning to 1200 h where the differences ranged from 1.5 to 4.3 K. On the other hand, the predicted results on the first floor agree reasonably well with the measured air temperatures even though TAS calculations tend to be overestimated.

However, during hot and clear day when the water spray was turned off and the solar blinds were extended, the TAS prediction results show a reasonably good agreement with the measured data as revealed by Fig. 5(b). Similar to the results for hot and overcast day, the discrepancies between the measured and predicted results generally occur from early morning to about noon. An explanation for this could be due to the large thermal storage effect calculated by TAS, which was carried on to the simulation day, as 10-day preconditioning period was considered for these modellings. Therefore the high air temperature due to thermal storage effect of the structure calculated by TAS a few days prior to the simulation day affected the air temperature of the simulation particularly from early morning to about noon. However, as the Sun's altitude gets higher, and since solar radiation is the dominant factor affecting thermal condition within a building with large glazed enclosures, a correct solar prediction could cover all small errors which subsequently led to more reasonable overall results particularly on the second floor.

In general for both simulation days, the predicted and measured air temperatures on the second floor agree considerably well particularly from noon to midnight. However, from late night to around noon the predicted results were generally overestimated, and particularly between 0800 and 1100 h the predicted and measured air temperature show considerably large differences. On the contrary, predicted air temperatures on the first floor are slightly underestimated from 1900 h to about midnight.

The reason for the large discrepancies between measured and predicted air temperatures on the second floor is apparently due to the large overestimation of internal surfaces temperatures by TAS (as depicted by higher prediction of both resultant temperature and blind surface temperature in Fig. 5(c). Therefore, at night when the external air temperature drops, TAS took into account the heat released by the hot internal surfaces, which led to the rise in air temperature within the atrium particularly on higher level. The same situation applies to the first floor level where the predicted air temperature is generally greater than the measured air temperature. However, when the solar blinds were fully retracted at 1800 h, the predicted air temperatures fell below the measured air temperatures starting from about 1900 h to midnight as the effect of blind's surface temperature was not considered.

It can be clearly seen from Fig. 5(c) and (d) that even though the measured and predicted air temperatures on the second floor differ slightly, the TAS prediction of resultant/mean radiant temperatures was relatively higher than the measurement. The reason was that in the DTM model, the blinds were assumed to cover the whole glazed roof area. Whereas in the real building, the roller solar blinds were installed in pieces and each glass panel provides gaps between each blind from which the air in between the glass roof and blinds could move freely. The higher air temperature in between the blinds and the glass roof predicted by TAS led to the increase in the blinds' surface temperature significantly (Fig. 5(c)). Consequently, the resultant temperature on the second floor would also increase as a result of higher mean radiant temperature (Fig. 5d). However, the predicted resultant temperature on the first floor showed a considerably good agreement with the measured data due to slightly lower mean radiant temperature.

Comparison of results of the prediction made by TAS and the results from site measurement has shown that the created TAS model is capable to model thermal stratification within multi-level atrium with reasonably accurate results. Quantitatively, on hot and clear day, considering the average air temperature difference between the second floor and first floor from 0800 to 1800 h, measured data yielded 6.6 K while the predicted result gave 6.7 K. On the other hand, for hot and overcast day, the difference in air temperature between the second and first floor yielded 4.0 K for measured data and 5.0 K for predicted result respectively. This small error in the range of 0.1–1.0 K made by TAS is considered in the acceptable range.

In general, it was found that DTM model overestimated its prediction results. For hot and overcast day simulation, the difference in air temperature over the 24 h between measured and predicted is in the range of 0.1–1.8 K on the first floor and 0.2–4.3 K on the second floor respectively. Whereas for hot and clear day simulation, the difference is in the range of 0.1–1.5 K on the first floor and 0.1–2.7 K on the second floor respectively. The main reason for these differences is due to the dissimilarity between the real weather conditions and the weather data in TAS for the two days in question. Therefore, it is suggested that for better simulation results, the external weather data on solar radiations, relative humidity, wind speed and direction should also be measured and recorded so that the weather data in TAS for the two simulation days can be correctly amended.

The other possible reason for a slightly high air temperature predicted on the second floor is due to the effect of radiant heat from the large predicted surface temperature of the roof blinds. In TAS model solar blinds were assumed to cover completely the whole glazed roof from one end to the other resulting in large prediction of blind's surface temperature, while in the real condition, the roof blinds were actually installed in pieces along each glass panel providing gaps in between each of the blinds for the air to circulate freely which helped to slightly reduce the blinds' surface temperature.

In general it was anticipated that there would be discrepancies between the measured data and TAS prediction results as the measured conditions and the assumed simulation conditions made for the TAS model was not exactly similar. The fixed internal conditions settings made for the TAS model were merely based on general assumptions and estimations. Whereas in the real conditions there were a lot of uncertainties and irregularities in the occupancy patterns, infiltration rates, conditioned air supply rates, etc., as well as uncontrolled actions of the users, which directly influenced the measured parameters recorded. Although there were discrepancies between measured and prediction data, the general trend proves that large unwanted thermal stratification occurs at upper floor causing great thermal discomfort to the occupants.

However, the results from both the field and modelling studies confirm that with no provision of high level or rooftop exhaust vent the air temperature on the second floor (normally above 7 m height) of the three-storey atrium was generally more than 37 °C. Particularly the area below the roof the air temperature could reach 40 °C or more with the presence of internal roof blinds.

Overall the modelling was considered acceptable. The division of the atrium space was sufficient to reveal the movement of heat and air flows throughout the large void. In order to apply DTM for studying large space, it seems that at least 27 zones are needed to ensure a three-zone division on each direction of the 3D space to allow heat and air flows to be distinguished in the directions.

3.2. Natural ventilation

3.2.1. Roof forms

As anticipated, the side-lit form performed better than the top-lit in terms of minimising solar heat received respectively by balcony floors, the wall-to-roof void and space beneath the roof (Fig. 6). The total daily solar heat gain for the side-lit model and the top-lit model was 159.37 kW and 269.99 kW, respectively. Obviously if the two atrium models were to be air-conditioned, the annual energy consumption for top-lit model would be much higher compared to the side-lit model due to the large cooling load required to condition the occupied floors.

The chart shows that the ground floor space of both representative models generally contributed the highest total solar heat gains despite being the lowest level within the atrium well. This was because the typical ground floor zones comprised the largest opaque and transparent surface areas, and the fact that the zones solar gains are the sum of the surfaces solar gains facing into the zones. Most of the solar heat gains on the ground floor came from the zones at the centre and both ends where the large main entrances were of glass materials.

There was only a slight difference in the total solar heat gains between the first and second floors for both side-lit models with and without wall-to-roof void area. With its opaque rooftop, solar radiations could not penetrate deeper into lower levels resulting in this relatively uniform solar heat distribution. In contrast, the top-lit models with and without wall-to-roof void area showed considerably higher differences in the total solar heat gains on both lower and upper levels. This clearly indicates that fully transparent rooftop allowed greater solar radiations to penetrate deeper to lower levels causing higher solar gains within the atrium. And combining both the wall-to-roof void and below roof zones, the solar gains for the top-lit model was double the amount predicted for the side-lit model. The larger glazed roof area of the top-lit model compared to the glazed clerestory area of the side-lit model coupling with the high transmittance and absorptance characteristics for both solar and heat of the glass material causes this great difference in solar gains in below roof area between the two representative forms.

3.2.2. Opening size

In general the prediction results showed that the air temperature stratification within the atrium reduced significantly with the increase in the size of openings. For instance, both Figs. 7 and 8 reveal that with the size of low- and high-level openings of 2 m^2 the difference in air temperatures between the lower level and the next upper level floors was generally about 0.1–0.3 K for side-lit model and 0.2–0.4 K for top-lit model. This small temperature difference was also due to the fact that the incoming easterly wind not only helped the flow of already hot outside air into the building but also enhanced the flow of the supposedly stratified hotter air at upper levels out of the building through the slightly large high-level opening resulting in a relatively stable air temperature within the atrium well. Moreover, both representative models showed that the air temperature on the three occupied levels increased almost linearly regardless of the openings' sizes.

The side-lit model the air temperature on the ground floor remained unchanged with the increase in the size of openings (Fig. 7). Enlarging the openings from 0.5 m^2 to 2 m^2 resulted in

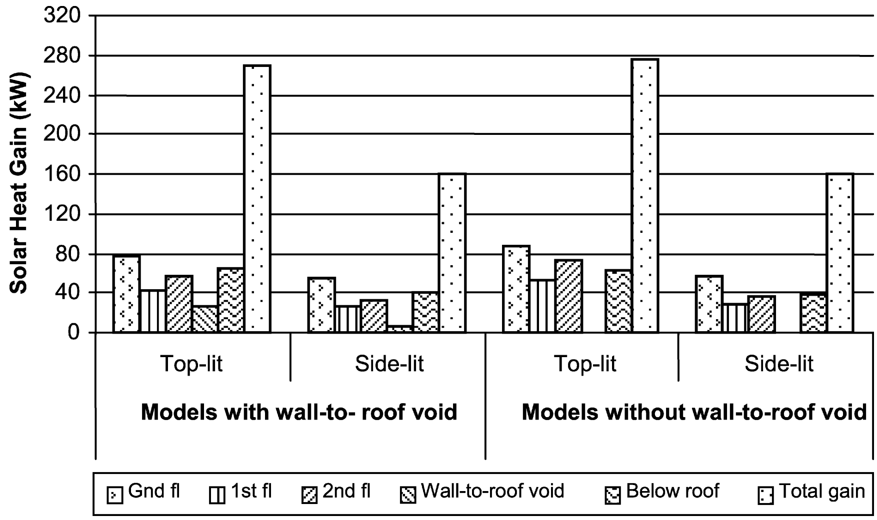


Fig. 6. Total daily solar heat gains: models with vs. without wall-to-roof void.

the reduction of air temperature by about 0.4 K on the first floor (at 3.4 m atrium height), 0.8 K on the second floor (at 6.8 m atrium height), 1.2 K in the wall-to-roof void area (at 10.2 m atrium height) and 1.4 K in the below roof area (at 11.7 m atrium height), respectively. For the top-lit model, it can be seen from Fig. 8 that the increase in openings' sizes led to the decrease in the air temperature by about 0.3 K on the ground floor, 0.9 K on the first floor, 1.4 K on the second floor, 17 K in the wall-to-roof void area and also 1.7 K in the below roof area (at 12.7 m atrium height), respectively. For 0.5 m^2 openings, the difference in air temperature between the second floor and ground floor was 1.1 K for side-lit model and 1.7 K for top-lit model respectively; and for 2 m^2 openings, the air temperature difference between the second floor and ground floor was 0.3 K for side-lit model and 0.6 K for top-lit model respectively. Hence, having larger low- and high-level openings could minimise not only the air temperature within the occupied levels but also the below roof area resulting in a relatively well-mixed atrium indoor air temperature.

However, when the high-level opening was completely closed and low-level openings were only reasonably opened (0.8 m^2) both representative models exhibited greater air temperature stratification within the atrium well. Both Figs. 7 and 8 show that the air temperature difference between the low and upper levels was relatively large. For both representative models, the difference in air temperature between below roof area and the ground floor was 3.7 K. Within the occupied levels, the air temperature difference between the second floor and ground floor was 1.8 K for side-lit model and 2.8 K for top-lit model respectively while the air temperature difference between the first floor and the ground floor was 1.1 K and 1.9 K respectively for both side-lit and top-lit models. In general, both representative models showed that with no provision of high-level opening the air temperature above the second floor level, particularly below roof area of the three-storey atrium was more than 37 °C.

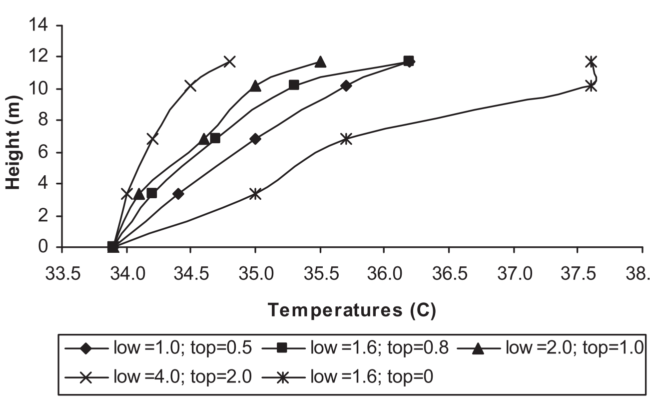


Fig. 7. Average air temperatures in side-lit model at 1400 h due to different sizes of low- and high-level openings (in m^2).

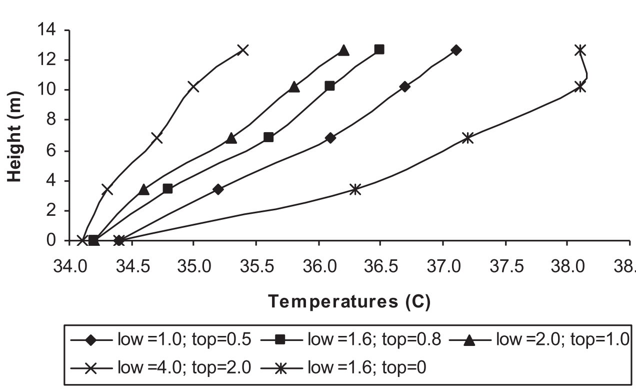


Fig. 8. Average air temperatures in top-lit model at 1400 h due to different sizes of low- and high-level openings (in m^2).

3.2.3. *Wind speeds*

Increasing wind speed from 3 to 7 m/s resulted in the decrease of air temperature by about 0.3 K on both the first and second floors for both representative models (Fig. 9). Within the below roof area, similar increase in wind speeds led to the reduction of air temperature by about 0.5 K for side-lit model and 0.6 K for top-lit model respectively. Even with the wind speed of 7 m/s, unusually high in the location, the air temperatures on the occupied levels within the atrium for both representative forms were generally beyond the comfort temperature of 31.5 °C (with air movement of 0.15–1.0 m/s) for naturally ventilated indoor space recommended for Malaysians (Sabarinah, 2002). This is clear evident that full natural ventilation system could not be used for building with large glazed areas such as atria particularly in hot-humid climate of Malaysia where the outdoor air temperature and relative humidity during the day are generally high with relatively low wind speed throughout the year. This is also true for other countries with similar weather conditions.

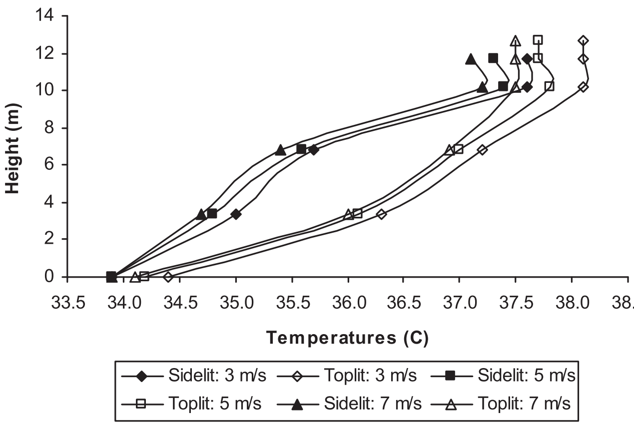


Fig. 9. Average air temperatures within representative models at 1400 h due to different wind speeds.

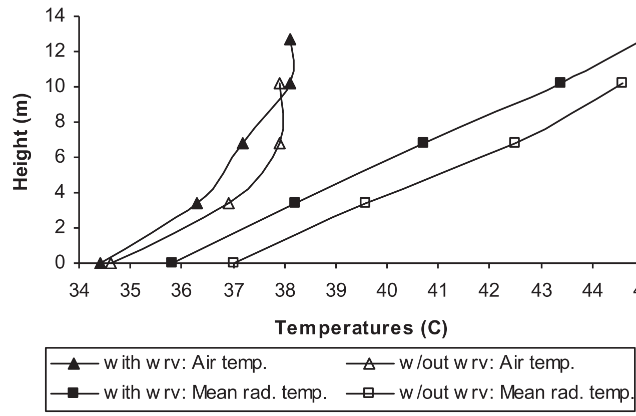


Fig. 11. Average air/mean radiant temperatures at 1400 h within top-lit models with and without wall-to-roof void.

3.2.4. *Wall-to-roof void*

Without wall-to-roof void area, the top-lit atrium model exhibited a substantial increase in the total solar heat gains in occupied levels (Fig. 6). The second floor of both top-lit and side-lit models presented the largest increase which was about 15.52 kW for top-lit model and 3.74 kW for side-lit model respectively. In general, the difference in solar gains between the side-lit model with wall-to-roof void and the side-lit model without wall-to-roof void was relatively small. The effect of wall-to-roof void seemed insignificant for the side-lit atrium model because the prediction results were based on weather data for Kuala Lumpur for simulation day 80 (March 21st) where the hot afternoon sun altitude is generally high. This evidence demonstrated the effectiveness of the side-lit atrium forms with opaque roof in reducing the heat gains from solar radiations during the hottest day of the year in hot humid equatorial regions.

It is evident that the wall-to-roof void area did help to improve thermal performance within the atrium by reducing air and mean radiant temperatures on occupied levels particularly on the second floor for both representative models (Figs. 10 and 11). For the side-lit model, the presence of 1.5 m high wall-to-roof void area helped to reduce air and mean radiant temperatures on the second floor by about 0.3 K and 0.5 K respectively. Apparently the higher wall-to-roof void area would further reduce the air and mean radiant temperatures on the second floor. As such, the 2.5 m high wall-to-roof void area of the top-lit model dramatically reduced the air and mean radiant temperatures on the second floor by 0.7 K and 1.8 K, respectively. The reduction in both air and mean radiant temperatures would also lessen the resultant temperature within the space, thus improving the thermal comfort condition of the occupants.

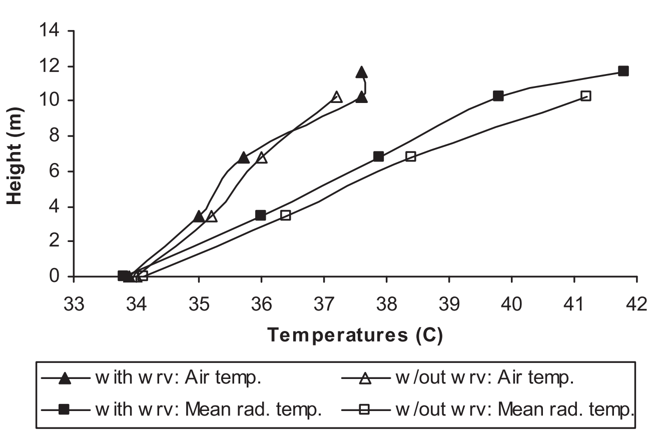


Fig. 10. Average air/mean radiant temperatures at 1400 h within side-lit models with and without wall-to-roof void.

The area below roof was extremely hot due to the coupling of the high mean radiant temperature and stratified hot air. The wall-to-roof void area helped to distance the top occupied level from the area underneath the roof, thus effectively lessening the effect of this high radiant heat energy from the hot surrounding surfaces on the occupants within the atrium particularly those on the second floor balcony area.

3.2.5. *Overhangs*

In order to examine the effect of roof overhangs on the thermal performance of side-lit atrium models, the clerestory windows were added to the east and west clerestory facades in addition to the existing clerestory windows on the north and south facades. These additional glazed windows would allow more solar radiations to penetrate into the atrium, thereby addressing the worst possible conditions.

During vernal equinox (21st March) and autumnal equinox (21st September) the effect of roof overhangs was not very significant as the hot afternoon direct solar radiations were generally from the top (Fig. 12). Therefore, in these two seasons, the amount of solar gains within each atrium level for both side-lit models with and without roof overhangs were almost constant. Whereas during summer solstice (21st June) and winter solstice (21st December), when the altitude of the hot afternoon sun was relatively low, the total solar gains for model without roof overhangs were considerably higher than that with roof overhang. In these two seasons, summer and winter solstices, side-lit model without roof overhangs generally exhibited higher solar gains within all atrium levels particularly the area below the roof (clerestory area) due to the lower sun positions over the course of the day. In summer solstice, total daily solar gain in the below roof area was 72.64 kW for model with roof overhangs and 79.54 kW for model without roof overhangs respectively. While the total daily solar gain in below roof area in winter solstice was 46.29 kW for model with roof overhangs and 52.41 kW for model without roof overhangs respectively. Hence, the incorporation of roof overhangs to the side-lit model during these two seasons greatly improved the thermal and energy performance within the atrium space particularly on occupied levels (see Fig. 13).

Moreover, incorporating 1.5 m deep roof overhangs above the clerestory areas did help to improve thermal performance within the atrium. In summer solstice (21st June), the presence of roof overhangs slightly reduced the air and mean radiant temperatures by 0.3 K in the below roof area and 0.2 K on the second floor (Fig. 13).

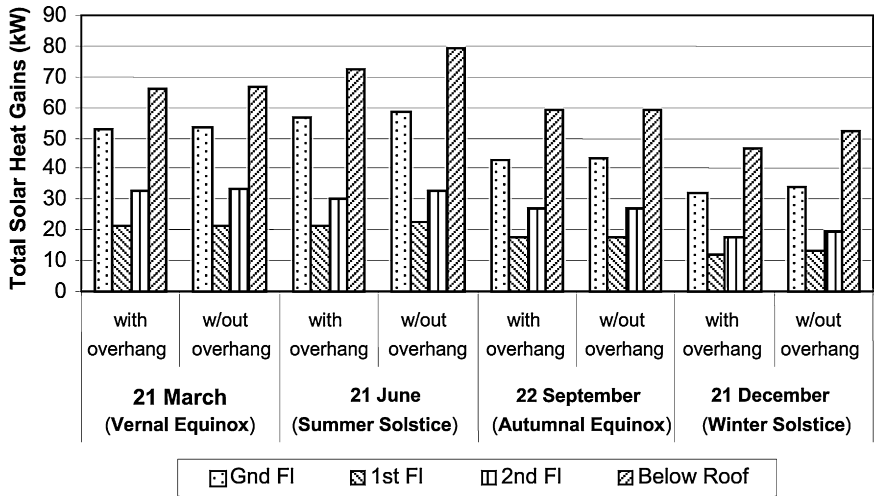


Fig. 12. Seasonal daily solar heat gains: side-lit models with and without roof overhang.

The reasonable decrease in the height of clerestory windows would possibly further decrease the solar gains; thereby lessening the air and mean radiant temperatures within the atrium particularly on upper levels.

3.2.6. Internal blinds

Extending internal roof blinds (top-lit model) and clerestory window blinds (side-lit model) from 0900 to 1800 h greatly improved the atrium thermal performance, as the modelling results show models with solar blinds depicted substantial reductions in the solar heat gains especially in the occupied levels (Figs. 6 and 14).

Comparing both charts (Figs. 6 and 14), by extending the internal solar blinds the solar heat gains in the occupied atrium floors dropped considerably from 178.55 kW to 93.33 kW for top-lit model and from 94.28 kW to 83.04 kW for side-lit model respectively. Undoubtedly the presence of blinds prevented direct and diffuse solar radiations from penetrating deeply to lower levels; thus lowering the temperatures of the surrounding internal surfaces. However, with the presence of internal blinds the solar heat gains in the below roof area tended to increase remarkably, which rose from 91.44 kW to 124.28 kW for top-lit model and from 45.09 kW to 53.8 kW for side-lit model respectively. This dramatic rise in solar gains in the below roof area for both models was due to the high surface solar gains of both the glazed roof/clerestory windows and the blinds, which also eventually led to the rise in air and mean radiant temperatures in the area. Generally, Fig. 14 also reveals that the difference in solar heat gains on occupied levels between the top-lit model with internal roof blinds and the side-lit model with clerestory windows blinds were relatively small. In the below roof area, on the other hand, the top-lit model exhibited significantly higher solar gains compared to that of the side-lit model. This was due to the fact that top-lit model had larger glazed roof surface area and wider solar blinds which absorbed more solar energy from the top.

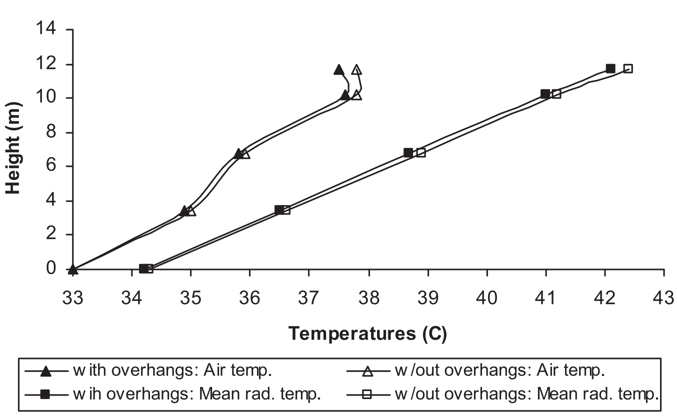


Fig. 13. Average air/mean radiant temperatures at 1400 h within side-lit models with and without roof overhang (day 172, 21st June).

Both side-lit and top-lit models with solar blinds exhibited better thermal performance particularly on occupied levels (Figs. 15 and 16). For side-lit model, the presence of high-level blinds helped to reduce air temperature by 0.2 K on the ground floor, 0.7 K on the first floor and 0.8 K on the second floor, respectively. Likewise, for top-lit model, extending the blinds resulted in the decline of the air temperature by 0.6 K on the ground floor, 1.7 K on the first floor and 1.9 K on the second floor respectively.

The figures also reveal that the difference in air temperatures between the below roof area and the second floor atrium level for both side-lit and top-lit models were significantly large. By extending the blinds, the air temperature difference between the below roof area and the second floor rose from 1.9 to 6.5 K for side-lit model and from 0.9 to 10.7 K for top-lit model respectively. These results indicate that the high surface temperatures of the glazing and blinds led to the rise in its radiant temperature. With contribution of radiant energy from other surrounding internal surfaces due to higher solar gains, the air and mean radiant temperatures in this area would also increase and further enhance the stratification at the high level. For both side-lit and top-lit model with internal solar blinds, it is also interesting to note that for the area directly below the roof the air temperature was generally higher than the mean radiant temperature. This is another evidence which shows that the extremely high temperature of the surrounding internal surfaces within this area due to solar gains led to the substantial increase in the air temperature.

3.3. Pressurised ventilation

3.3.1. Overall effects of pressurised ventilation on atrium thermal performance

As expected, both representative models the total daily plant loads to condition the offices for all atrium floors pressurised was significantly greater than that required for the ground floor atrium only pressurised (Fig. 17). It also reveals that the required cooling loads for the ground floor only pressurised was more than half of that needed for the all floors pressurised. This was because the ground floor offices for both representative models required more

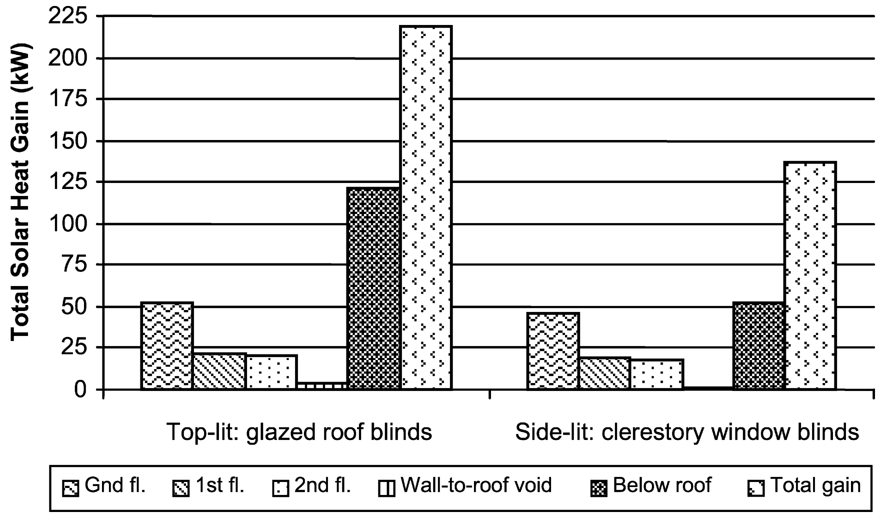


Fig. 14. Solar heat gains for models with internal solar blinds.

sensible cooling loads than that of the combined offices on the first and second floors.

In general the predicted total plant loads for top-lit model was slightly higher than the side-lit model. The difference in the total daily cooling loads between the top-lit model and the side-lit model was 27.5 kWh for modelling with all floors pressurised and 15.8 kWh for modelling with the ground floor only pressurised. Even though the difference in the daily energy required for cooling between the two representative models was rather small but when taking the annual energy consumption into account the top-lit model would obviously cost more than the side-lit model. Similarly the annual energy cost for all floors pressurised would be far greater than that of the ground floor only pressurised.

However, for both representative models, it is interesting to note that modelling with the ground floor only pressurised exhibited slightly higher total daily latent removal loads than modelling with all floors pressurised. This indicates that when only the ground floor was pressurised to ventilate the atrium, slightly more loads were required to remove the air moisture.

Pressurising 23 °C cooled air into the atrium space during office hours (0800–1800 h) improved the atrium's thermal environment particularly on the occupied levels (Figs. 18 and 19).

When all floors were pressurised, the indoor air on all occupied levels were well-mixed as shown by the relatively small vertical air temperature difference (Fig. 18). The average air temperatures on all occupied levels for both representative models were in the range of 24.2–25.1 °C.

On the other hand, with the ground floor only pressurised together with the effect of solar gains from the top, the air temperature on upper occupied levels for the both models increased considerably leading to a higher the vertical temperature gradients (Fig. 19). The presence of the high-level opening enhanced the

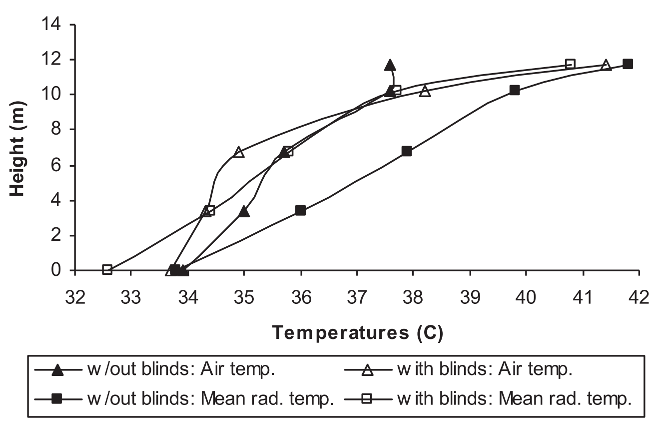


Fig. 15. Average air/mean radiant temperatures at 1400 h within side-lit models with and without internal solar blinds.

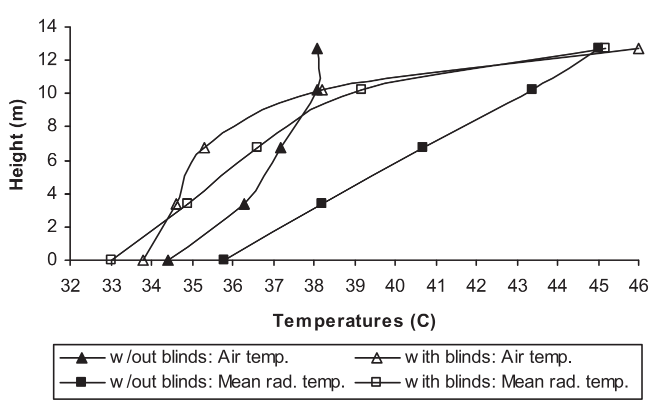


Fig. 16. Average air/mean radiant temperatures at 1400 h within top-lit models with and without internal solar blinds.

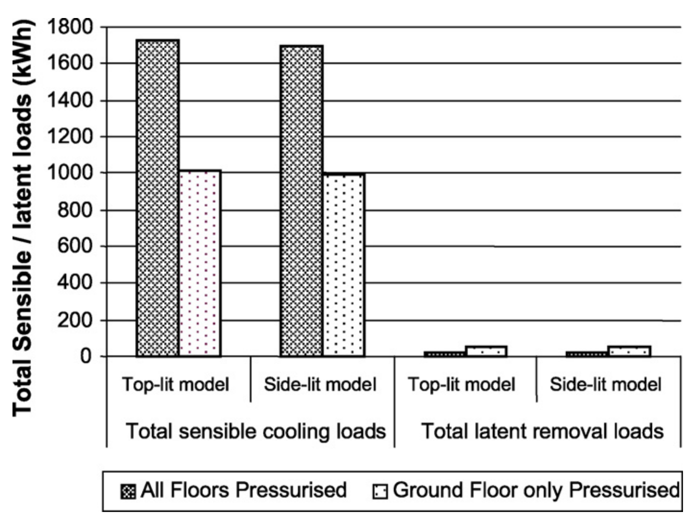


Fig. 17. Total daily sensible/latent loads: 'all floors pressurised' vs. 'ground floor only pressurised'.

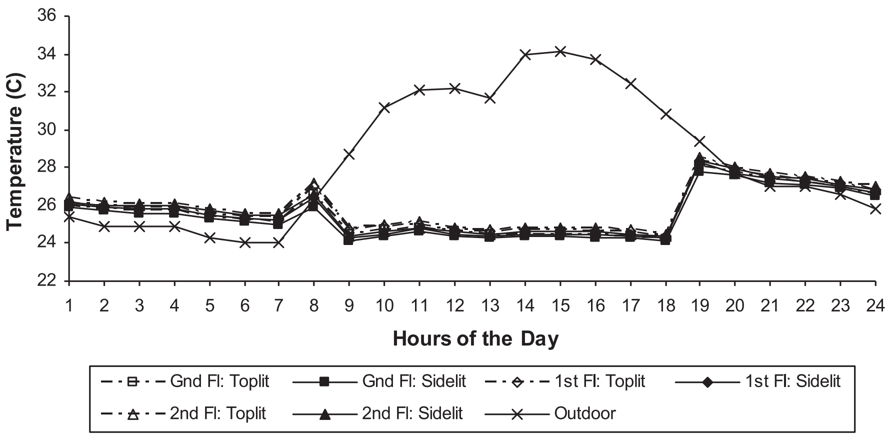


Fig. 18. Average air temperatures on occupied levels due to 'all occupied floors pressurised' ventilation.

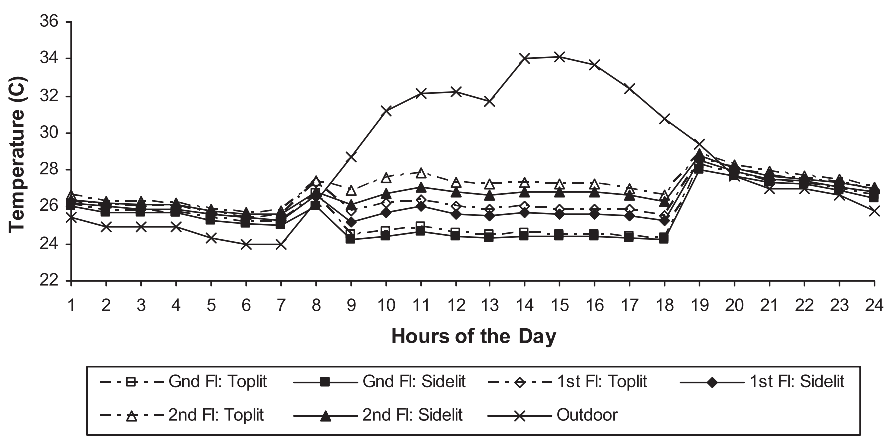


Fig. 19. Average air temperatures on occupied levels due to 'ground floor only pressurised' ventilation.

upward flow of cooler air from ground floor level due to thermal buoyancy effect which effectively helped to lessen the impact of the thermally stratified hot air in the below roof area particularly on the top occupied level.

During early morning, the indoor air temperature was about 1–3 K hotter than the outside. This suggests that night cooling could be applied to cool the atrium space. Although there were vents above external doors and windows, the airflow did not seem to remove the indoor heat easily. The main reason can be due to the insufficient size of low-level openings (generally from the grilles above the external doors and windows) to allow inward flow of outdoor air, following the stack effect and escaping through high-level openings. With the provision of large low-level openings, it is important to equip the building with high security measures.

3.3.2. Full pressurisation

In general, the prediction results from the modelling of all floors pressurised unveiled that the thermal performance within the side-lit model was slightly better than that of the top-lit model. The

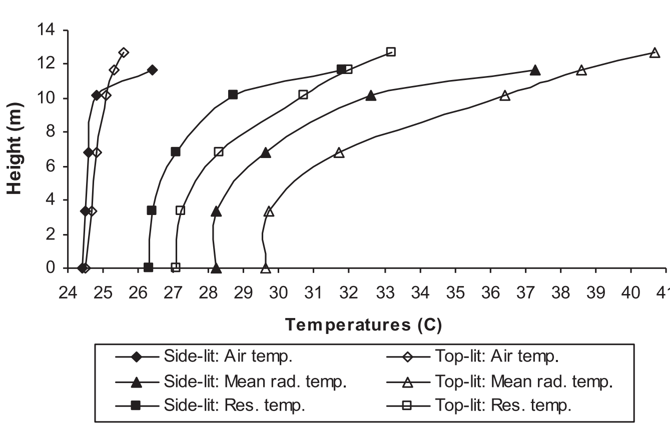


Fig. 20. Average air, mean radian and resultant temperatures at 1400 h due to 'all floors pressurised' ventilation.

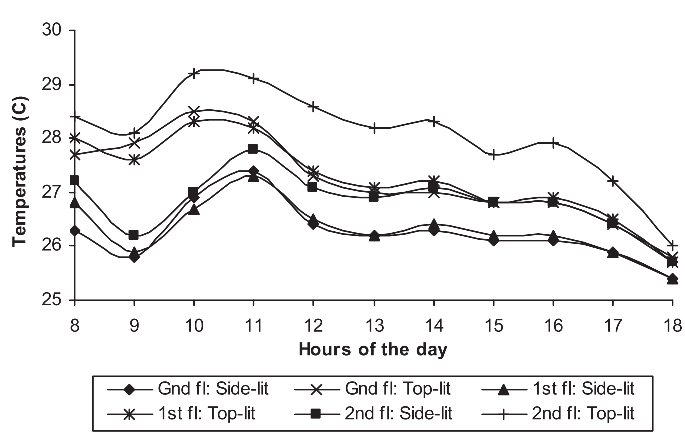


Fig. 21. Average resultant temperatures during office hours due to 'all floors pressurised' ventilation.

Table 1
Cooling load and supply air flow rate for office zones in side-lit model.

Categories	Zones	Sensible cooling load (kW/h)	Sensible heat load (kW)	Volume flow rate (m^3/s)	Mass flow rate (kg/s)
Office Type A	1	43.98	4.06	0.65	0.78
	3	39.64	3.60	0.59	0.70
	9	43.92	3.99	0.65	0.78
	11	39.58	3.60	0.59	0.70
Office Type B	12	40.30	3.66	0.60	0.71
	14	35.63	3.24	0.53	0.63
	20	40.24	3.66	0.60	0.71
	22	35.56	3.23	0.53	0.63
	23	41.33	3.76	0.61	0.73
	25	36.86	3.35	0.55	0.65
	31	41.30	3.75	0.61	0.73
	33	36.80	3.35	0.55	0.65
Office Type C	2	27.89	2.54	0.41	0.49
	10	27.80	2.53	0.41	0.49
	13	29.79	2.71	0.44	0.53
	21	29.68	2.70	0.44	0.52
	24	31.13	2.83	0.46	0.55
	32	31.03	2.82	0.46	0.55

Table 2
Cooling load and supply air flow rate for office zones in top-lit model.

Categories	Zones	Sensible cooling load (kW/h)	Sensible heat load (kW)	Volume flow rate (m^3/s)	Mass flow rate (kg/s)
Office Type A	1	44.63	4.06	0.66	0.79
	3	40.39	3.67	0.60	0.71
	9	44.54	4.05	0.66	0.79
	11	40.29	3.66	0.60	0.71
Office Type B	12	40.90	3.72	0.61	0.72
	14	36.29	3.3	0.54	0.64
	20	40.81	3.71	0.60	0.72
	22	36.18	3.29	0.54	0.64
	23	41.76	3.80	0.62	0.74
	25	37.77	3.43	0.56	0.67
	31	41.79	3.80	0.62	0.74
	33	37.67	3.42	0.56	0.67
Office Type C	2	28.52	2.59	0.42	0.50
	10	28.4	2.58	0.42	0.50
	13	30.52	2.77	0.45	0.54
	21	30.39	2.76	0.45	0.54
	24	32.10	2.92	0.48	0.57
	32	31.99	2.91	0.47	0.57

difference in air and mean radiant temperatures between the occupied atrium levels at 1400 h was generally about 0.1 K and 0–1.4 K respectively for side-lit model, and 0.2 K and 0.1–2 K respectively for top-lit model (Fig. 20). Clearly the side-lit model effectively prevented the solar radiations from penetrating deeply into lower levels; thus lowering the air and mean radiant temperatures on occupied levels.

Figs. 20 and 21 both indicate that the cooler air introduced into the atrium space also effectively helped to reduce the temperatures of both the hot indoor air and the surrounding internal surfaces in the occupied levels. This is demonstrated by the generally low air temperature of less than 25.1 °C and also acceptable

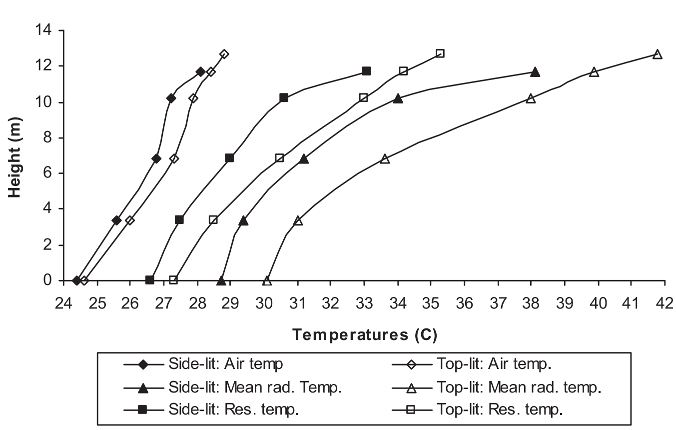


Fig. 22. Average air, mean radiant and resultant temperatures at 1400 h due to 'ground floor only pressurised' ventilation.

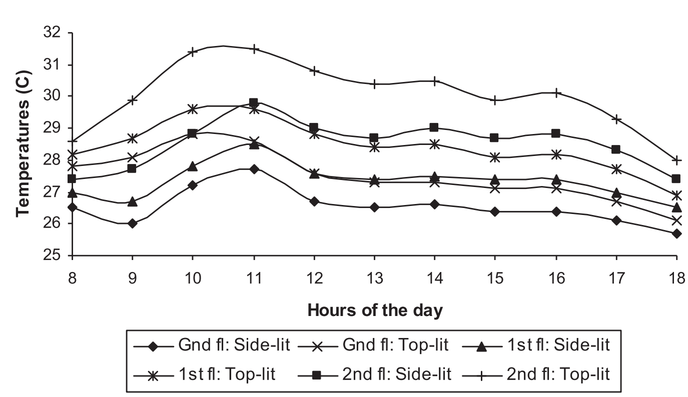


Fig. 23. Average resultant temperatures during office hours due to 'ground floor only pressurised' ventilation.

Table 3
Inter-zone air movement for side-lit model: all floors pressurised.

Airflow to from office zones atrium zones			Airflow within atrium zones			Remarks
From zone	To zone	Mass flow rate (kg/s)	From zone	To zone	Mass flow rate (kg/s)	
1	4	0.780	4	6	1.482	(i) Total airflow to zone 4 = 1.56 kg/s; assumed 5%
2	5	0.490	5	6	0.490	(0.078 kg/s) infiltration loss due to flow to outside.
3	8	0.700	7	6	0.490	(ii) Total airflow to zone 8 = 1.40 kg/s; assumed 5%
9	4	0.780	8	6	1.330	(0.070 kg/s) infiltration loss due to flow to outside.
10	7	0.490	6	17	3.792	(iii) Total airflow to zone 15 = 1.42 kg/s; assumed 15%
11	8	0.700	15	17	1.207	(0.213 kg/s) infiltration loss due to flow to outside and
12	15	0.710	16	17	0.530	toilets.
13	16	0.530	18	17	0.520	(iv) Total airflow to zone 19 = 1.26 kg/s; assumed 15%
14	19	0.630	19	17	1.071	(0.189 kg/s) infiltration loss due to flow to outside and
20	15	0.710	17	28	7.120	toilets.
21	18	0.520	26	28	1.241	(v) Total airflow to zone 26 = 1.46 kg/s; assumed 15%
22	19	0.630	27	28	0.550	(0.219 kg/s) infiltration loss due to flow to outside and
23	26	0.730	29	28	0.550	toilets.
24	27	0.550	30	30	1.105	(vi) Total airflow to zone 30 = 1.30 kg/s; assumed 15%
25	30	0.650	28	34	10.566	(0.195 kg/s) infiltration loss due to flow to outside and
31	26	0.730	34	35	10.566	toilets.
32	29	0.550	35	Outside	10.566	
33	30	0.650				

resultant temperatures throughout the day. Particularly during office hours from 0800 to 1800 h the resultant temperatures on the occupied level were in the range of 25.4–27.8 °C for side-lit model and 25.8–29.2 °C for top-lit model respectively. Therefore, in the case of all floors pressurised the resultant temperatures within the occupied levels for both representative models were within the comfort range suggested for Malaysians, which should be around 29 °C for air-conditioned atrium.

3.3.3. Ground floor only pressurised

In general, in the case of ground floor only pressurised, the side-lit model exhibited even better atrium thermal performance when compared to the top-lit model. The difference in air and mean radiant temperatures between the occupied atrium levels at 1400 h was generally about 1.2 K and 0.7–1.8 K, respectively for side-lit model (Fig. 10) and 1.4 K and 0.9–2.6 K, respectively for top-lit model (Fig. 22). These slightly large temperature differences reveal that there was greater stratification in the atrium with a top-lit roof. The cooler pressurised air driven from surrounding rooms on the ground floor atrium effectively cooled down the air and internal surfaces resulting in generally low resultant temperatures within lower atrium levels. As the hot stratified air in the below roof area flew out through the high-level outlet opening, it also enhanced the upward flow of cooler air from ground level to upper levels. This thermal buoyancy effect also contributed to the lowering of air and resultant temperatures on the upper occupied floors.

During office hours from 0800 to 1800 h the air and resultant temperatures on the occupied level were in the range of 24.2–27.1 °C and 25.7–29.8 °C respectively for side-lit model, and 24.3–27.8 °C and 26.1–31.5 °C respectively for top-lit model (Fig. 23). The resultant temperature exceeded 29 °C only occurred once at 1100 h on the second floor of side-lit model. In general, this indicates that thermal comfort within the occupied floors of the side-lit atrium can be easily achieved by introducing cooler air on the ground level.

For top-lit model, however, the resultant temperatures on the ground and first floors were generally in the acceptable comfort range except at 1000–1100 h when the resultant temperature reached 29.8 °C. Whereas the resultant temperatures on the second floor were generally exceeded 29 °C comfort range for Malaysians in air-conditioned space. Since the upper levels of both representative models were naturally ventilated and also the fact that the atrium space is normally used as a relaxing transitional space, the comfort temperature range can be relaxed and extended up to 32 °C

Table 4
Inter-zone air movement for top-lit model: all floors pressurised.

Airflow to from office zones atrium zones			Airflow within atrium zones			Remarks
From zone	To zone	Mass flow rate (kg/s)	From zone	To zone	Mass flow rate (kg/s)	
1	4	0.790	4	6	1.501	(i) Total airflow to zone 4 = 1.58 kg/s; assumed 5%
2	5	0.500	5	6	0.500	(0.079 kg/s) infiltration loss due to flow to outside.
3	8	0.710	7	6	0.500	(ii) Total airflow to zone 8 = 1.42 kg/s; assumed 5%
9	4	0.790	8	6	1.349	(0.071 kg/s) infiltration loss due to flow to outside.
10	7	0.500	6	17	3.850	(iii) Total airflow to zone 15 = 1.44 kg/s; assumed 15%
11	8	0.710	15	17	1.224	(0.216 kg/s) infiltration loss due to flow to outside and
12	15	0.720	16	17	0.540	toilets.
13	16	0.540	18	17	0.540	(iv) Total airflow to zone 19 = 1.28 kg/s; assumed 15%
14	19	0.640	19	17	1.088	(0.192 kg/s) infiltration loss due to flow to outside and
20	15	0.720	17	28	7.242	toilets.
21	18	0.540	26	28	1.258	(v) Total airflow to zone 26 = 1.48 kg/s; assumed 15%
22	19	0.640	27	28	0.570	(0.222 kg/s) infiltration loss due to flow to outside and
23	26	0.740	29	28	0.570	toilets.
24	27	0.570	30	28	1.139	(vi) Total airflow to zone 30 = 1.34 kg/s; assumed 15%
25	30	0.670	28	34	10.779	(0.201 kg/s) infiltration loss due to flow to outside and
31	26	0.740	34	35	10.779	toilets.
32	29	0.570	35	Outside	10.779	
33	30	0.670				

Table 5
Inter-zone air movement for side-lit model: ground floor only pressurised.

Airflow tofrom office zone atrium zone			Airflow within atrium zones			Remarks
From zone	To zone	Mass flow rate (kg/s)	From zone	To zone	Mass flow rate (kg/s)	
1	4	0.780	4	6	1.482	(i) Total airflow to zone 4 = 1.56 kg/s; assumed 5%
2	5	0.490	5	6	0.490	(0.078 kg/s) infiltration loss due to flow to outside.
3	8	0.700	7	6	0.490	(ii) Total airflow to zone 8 = 1.40 kg/s; assumed 5%
9	4	0.780	8	6	1.330	(0.070 kg/s) infiltration loss due to flow to outside.
10	7	0.490	6	17	3.792	
11	8	0.700				

Table 6
Inter-zone air movement for top-lit model: ground floor only pressurised.

Airflow from office zone to atrium zone			Airflow within atrium zones			Remarks
From zone	To zone	Mass flow rate (kg/s)	From zone	To zone	Mass flow rate (kg/s)	
1	4	0.790	4	6	1.501	(i) Total airflow to zone 4 = 1.58 kg/s; assumed 5%
2	5	0.500	5	6	0.500	(0.079 kg/s) infiltration loss due to flow to outside.
3	8	0.710	7	6	0.500	(ii) Total airflow to zone 8 = 1.42 kg/s; assumed 5%
9	4	0.790	8	6	1.349	(0.071 kg/s) infiltration loss due to flow to outside.
10	7	0.500	6	17	3.850	
11	8	0.710				

air temperature depending on the surrounding air movement (i.e. about 0.15–1.0 m/s). However, the less comfortable balcony area on the second floor of the top-lit model is only suitable to be used as transitional space.

For the purpose of comparison and discussion of results for all the simulated cases, the predicted air and mean radiant temperatures at 1400 h (i.e. the hottest hour of day 80, where the outdoor dry-bulb temperature is 34 °C) were used as the basis to evaluate the resulting atrium thermal environmental performance.

3.4. Other comments

Although top-lit form is not a favourable choice from thermal point of view, it certainly provides better daylight for the space immediately underneath, such as the walkways and adjacent spaces. This is currently seen as the major attraction particularly in shopping malls and other commercial buildings (Kim & Kim, 2010). In these atria, mobile shading devices such as retractable blinds and fabric rollers, the lower surfaces facing downwards can be polished and light coloured to avoid direct solar and strong longwave radiations during sunny days. During cloudy days, the effects on daylight should be quantified using a modelling tool at the design stage to achieve a good balance between daylighting and thermal comfort, particularly in designing atrium buildings for tropical climates.

Similarly large overhangs are preferable option for solar shading, but obviously not for daylight. They should be sized properly to maximise the solar shading during the sunny days and daylight during overcast days. Variable overhangs are the better alternative but can be expensive to build as well as high maintenance cost.

The atrium was assessed on a few representative days of the TRY. For a real project assessment, a design should be modelled over the whole year so that the statistical data can be obtained, such as the percentage of occurrence of overheating or the temperature exceeding a given threshold in all zones of the building. This can be critical for the decision making for a passive building, and this assessment has been more of a standard practice (Pollock, 2011).

The resultant temperature was used to assess thermal comfort, the effect of air movement was not properly considered due to limitation of DTM modelling. Ideally for a closer examination, the calculation method for mean radiant temperature (Li & Pitts, 2007) should be used together with CFD to properly assess thermal comfort at least for some of the hottest hours identified by the DTM modelling for the whole year.

4. Conclusion

The conclusions drawn from this DTM investigation are three-folds which include the modelling techniques, the atrium design, and ventilation solution. It is evident from the validation exercise that as the entire space of the atria was divided into more than dozen zones, both the heat and air flows could be individually calculated and temperature distribution and bulk air movement throughout the whole building were effectively simulated in the hour-by-hour fashion under the worst weather conditions during a typical year. Such dynamic simulation could reveal in details the thermal features of the atrium and how they were affected by the key design parameters that designers would like to determine in order to achieve acceptable thermal comfort and a solution affordable in hot humid climate. To apply DTM for study large space it seems that at least 27 zones are needed to ensure a three-zone division on each direction of the 3D space to allow heat and air flows to be distinguished in the directions.

The hourly prediction for indoor thermal conditions by DTM should be used to calculate the probability of indoor overheating or the percentage of occurrence of the thermal variables exceeding the given standards when designing a passive or energy-efficient building at the early design stage, as these data provide the building designers and owners quantitative data for decision making.

The roof form is critical for the atrium when thermal comfort and low running cost are concerned. This modelling study has revealed that the three-storey linear side-lit atrium form utilising clerestory windows was generally more effective in terms of providing better thermal performance in the atrium space than the fully transparent top-lit atrium form. Not only the solar heat gains but also the resultant temperatures in the occupied levels in the atrium space are considerably lower. In addition, these modelling studies have also proven that with full natural ventilation, the air temperatures in the atrium are higher than the outside air temperatures, which are also well above the indoor comfort temperature range for hot countries like those in South Asia. Therefore, since the hot and humid climate has almost stable hot external air temperatures with generally low wind speed throughout the year, it is not viable to use full natural ventilation to ventilate the atrium space.

Modelling natural ventilation has unveiled that having wall-to-roof void area for both representative atrium forms as well as the roof overhangs above the clerestory areas for the side-lit form can improve the atrium thermal performance particularly in the occupied levels. The wall-to-roof void area helped to distance the top occupied level from the below roof area. Although the thermal condition in the below roof area would be extremely hot due to the coupling of the high mean radiant temperatures and stratified hot air, the effect of this high radiant heat on the top occupied level is marginally lessened due to the presence of the wall-to-roof void area. Likewise, the roof overhangs for the side-lit form reduced the effect of diffuse and direct solar radiations particularly during summer and winter solstices where the positions of the sun over the course of the day are generally low.

Installing and extending internal solar blinds also have greatly improved the thermal environment on the occupied level inside the atrium for both representative forms. The solar blinds effectively cut the diffuse and direct solar radiations from penetrating deeply to lower levels, resulting in the lower air and mean radiant temperatures in occupied levels. Due to the presence of blinds, the thermal condition underneath the roof would be extremely hot. Hence, the presence of wall-to-roof void area helped to lessen the effect of high radiant heat and stratified hot air within the below roof area on the top occupied levels. Light coloured or other low-emissivity surfaces would be the best choice for these blinds, as they can reduce the re-emission of longwave radiation from these blinds.

Simulation results indicated that thermal and energy performance of the side-lit model is generally better than the top-lit model. The difference in the total daily solar heat gain on 21st March (i.e. the hottest day of the year) between both atrium forms was 110.62 kW. In top-lit model, the 2.5 m high wall-to-roof void area lowered the predicted air and mean radiant temperatures on the second floor level around 0.7 K and 1.8 K, respectively. For side-lit model, the 1.5 m wide roof overhangs above the clerestory areas generally improves the thermal and energy performance within the central atrium throughout the year. It is evident from this study that full natural ventilation strategy is less possible for Malaysian atria during hottest seasons. Increasing the opening areas and wind speeds has greatly reduced the atria's vertical temperature gradients; however, the indoor air temperatures were still higher than the outside air temperatures and well above the indoor comfort temperature.

Although natural ventilation works well during mild seasons, additional cooling is needed during the hottest season. The pressurising ventilation, an easy and cheap solution, was proven very effective. This is primarily because the pressurisation enhances the buoyancy effect and drives the hot air at the top out of the atrium.

For both side-lit and top-lit forms, the full pressurisation can improve greatly the thermal condition in the occupied levels. The resultant temperature on the top occupied floor throughout the day was generally less than 29 °C, the comfort temperature normally considered acceptable for occupants in hot climate in air-conditioned space.

Interestingly, with ground floor only pressurised ventilation, the thermal performance in the occupied levels of the side-lit was generally in the comfort range during office hours, as the resultant temperatures were generally below 29 °C on the second floor walkways. For top-lit model, however, the second floor resultant temperatures were generally well above the 29 °C but less than 32 °C. In the case of ground floor only pressurised, the upper levels of both representative atrium forms were naturally ventilated. Hence, the comfort temperature on the occupied levels can be relaxed and extended up to 33 °C with the presence of air movement of about 0.15–1.0 m/s. Taking this consideration into account the thermal comfort within the occupied floors of both representative atrium forms can also be reasonably achieved by only introducing cooler air on the ground level. As such, in order to reduce annual energy demand this low-energy ventilation strategy can be possibly incorporated with the low-rise atrium forms without causing great discomfort to the occupants.

Acceptable thermal comfort can be achieved using low cost ventilation solutions when design options are carefully tested using the modelling techniques so that atrium spaces are effectively shaded from direct solar penetration and clerestory windows or top vents are properly sized for effective hot air removal.

Evolved over years to suit local climate, the traditional roof form has demonstrated a much better thermal performance than modern glazed rooftop for large atrium spaces. Although the modelling was based on Malaysian weather data, the conclusions drawn so far are applicable to other South Asian regions, or other places on Northern and Southern hemispheres with similar latitude.

As the overhangs may reduce daylighting in the atrium and its surrounding rooms, modelling studies, on both thermal and daylighting, at early design stage can help to gain the essential balance between thermal and daylighting in atrium environment (see Tables 1 and 2).

When top-lit form is chosen for commercial buildings, blinds are essential and removable ones are recommended with downside surfaces light coloured or polished. Hence during sunny days, they can provide proper shading while low re-emission of radiation heat during overcast days, they can be opened to allow full daylight entry.

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Appendix A.

A.1. Internal conditions

The internal conditions for the atrium zones were specified accordingly as follows:

Ground floor atrium zones	
Infiltration rate = 0.5 ach (24 h)	Occupants sensible gains = 2.0 W/m^2
Lighting gains = 5.0 W/m^2	Occupants latent gains = 1.0 W/m^2
First and Second Floor atrium zones	
Infiltration rate = 0.5 ach (24 h)	Occupants sensible gains = 2.0 W/m^2
Lighting gains = 10.0 W/m^2	Occupants latent gains = 1.0 W/m^2
Wall-to-roof void and below roof area zones	
Infiltration rate = 0.5 ach (24 h)	Occupants sensible gains = 0.0 W/m^2
Lighting gains = 10.0 W/m^2	Occupants latent gains = 0.0 W/m^2

Based on the typical floor plan of the model buildings (Fig. 3), the office zones were divided into three categories according to the floor area namely Office Type A (for office zones of 59.23 m^2 floor area), Office Type B (for office zones of 49.66 m^2 floor area), and Office Type C (for office zones of 42.97 m^2 floor area). The following general assumptions had been made to determine the internal conditions for the office zones:

- Recommended fresh air supply per person = 10.4 l/s (=37.44 m^3/h). Calculated ventilation rate required per office type: Offices: Type A = 2.21 ach; Type B = 2.15 ach; and Type C = 2.21 ach

- Infiltration rate = 0.5 ach
- Occupancy:

  Floor space per person = 4.5 m^2. It was assumed that only 84% of the total floor area was occupied while the remaining 16% was used for internal circulation.

  Thus, occupancy per office zone = (floor area × 0.84)/4.5.

  Sensible and latent heat dissipation per person was 80 W and 60 W, respectively. It was assumed that the percentage presence for occupants for each office zone was constant at 84%.

  Thus, sensible heat gains per office zone (W/m^2) = (no. of person × 80 × 0.84)/floor area.

  Latent heat gains per office zone (W/m^2) = (no. of person × 60 × 0.84)/floor area.

  The produced heat was transferred to the room partly by convection (50%) and partly by thermal radiation (50%); the thermal radiation was (homogeneously) distributed over all surfaces facing the room.
- Lighting:

  The power, including the power of the ballast/starter was 13 W/m^2. It was assumed that the lights switched-on percentage was constant at 84%.

  Thus, lighting heat gains per office zone = 13 × 0.84 = 10.92 W/m^2.

  The produced heat was 100% sensible heat and 0% latent heat. The heat was transferred to the room partly by convection (72%) and partly by thermal radiation (28%); the thermal radiation was (homogeneously) distributed over all surfaces facing the room.
- Equipment:

  Heat production from one PC was 160 W. It was assumed that there would be 1PC/person per office zone and switched-on percentage was constant at 67%.

  Thus, equipment heat gains per office zone (W/m) = (no. of PC × 160 × 0.67)/floor area.

  The produced heat was 100% sensible heat and 0% latent heat. The heat was transferred to the room purely by convection (100%) and not by thermal radiation.
- Hence, the internal conditions for all office categories were specified as follows:

Office zones for Office Type A (floor area = 59.23 m^2; no. of occupants = 11)

Infiltration rate = 0.5 ach (24 h)	Occupants sensible gains = 12.480 W/m
Lighting gains = 10.92 W/m^2	Occupants latent gains = 9.360 W/m^2
Equipment sensible gains = 19.909 W/m^2	

Office zones for Office Type B (floor area = 49.66 m; no. of occupants = 9)

Infiltration rate = 0.5 ach (24 h)	Occupants sensible gains = 12.179 W/m
Lighting gains = 10.92 W/m^2	Occupants latent gains = 9.134 W/m^2
Equipment sensible gains = 19.428 W/m^2	

Office zones for Office Type B (floor area = 42.97 m; no. of occupants = 8)

Infiltration rate = 0.5 ach (24 h)	Occupants sensible gains = 12.511 W/m
Lighting gains = 10.92 W/m^2	Occupants latent gains = 9.383 W/m^2
Equipment sensible gains = 19.958 W/m^2	

A.2. Pressurised ventilation simulation

For this simulation, it was assumed that the 23 °C recycle return serviced air from the adjacent offices was pressurised and introduced into the atrium space. The two representative models were simulated with two types of pressurised ventilation: all floors pressurised and the ground floor only pressurised. These pressurised ventilation systems were considered as the proposed low-energy ventilation scheme to ventilate the atrium space, particularly in Malaysia where the outdoor weather is generally warm and humid with low wind velocity for most parts of the year.Additional settings and general assumptions for these pressurised ventilation simulations for the two representative 3-D TAS atrium models were as follows:

- Main entrances on either sides of the building were assumed to be completely closed during office hours (0800–1800 h).
- The high-level opening area for side-lit model (clerestory window vent) and top-lit model (glass roof vent) was 10.0 m^2, respectively. Thus, the openable proportion specified in the Aperture Types Table for side-lit and top-lit models was 0.118 and 0.088, respectively. These outlets were set to be always open.
- The vents for all windows, internal doors and main entrance doors were set to be 100% open starting from 1800 to 0700 h the next morning for night cooling purposes.
- The pressurised air at 23 °C was introduced from the office zones into the atrium zones only during office hours (0800–1800 h).
- The air conditioning system for the office zones which was scheduled to operate daily from 0700 to 1800 h was set as follows:

- Supply air temperature (T_s) = 18 °C;
- Return air temperature (T_r) = 23 °C.

The supply mass flow rate (in kg/s) was found by multiplying the volume flow rate, V_s (m^3/s), by the density of air at the air-conditioned spaces. In this case, the density of air, p_{air} at 23 °C dry-bulb temperature is 1.193 kg/m^3. The fact that the volume flow does change with temperature, the mass flow rate (in kg/s) is used in TAS program, as it does not change with temperature.

Using the principle of mass balance where the mass flow into the zone is equal to the mass flow out of the zone, the return mass flow rate from the air-conditioned office zone which is equal to the supply mass flow rate to the office zone was introduced into the atrium zone to ventilate the atrium space. In order to simulate the pressurised air atrium ventilation, the inter-zone air movement from the office zones to atrium zones as well as the inter-zone air movement among the atrium zones were specified accordingly based on the principle of mass balance. Tables 3 and 4 show the inter-zone mass airflow rate for simulating all occupied floors pressurised ventilation for the side-lit and top-lit models respectively.

In the case of ground floor only pressurised simulation, the inter-zone airflow was allocated for all the ground floor zones (zone 1–zone 11) and zone 17, the centre atrium core on the first floor, to which the air from zone 6 would be forced to flow (Tables 5 and 6). Then, TAS would automatically calculate the inter-zone airflow for other atrium zones on upper levels.For these pressurised ventilation simulations, the existing hourly wind speed in the 1978 TAS weather file for Kuala Lumpur for simulation day 80 was used. Since the existing weather file has no wind direction (0°), the hourly wind direction was purposely set to 90° to represent the easterly wind in March.

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