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ASSESSMENT OF THERMAL ENVIRONMENT IN AN ATRIUM WITH AIR-CONDITIONING

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ABSTRACT

This article is a report on assessing the thermal environment in an atrium with air-conditioning by studying the air temperature at the occupied zone. By surveying the general shapes of the atrium buildings in Hong Kong, it is found that most of the atria have a glazed roof and a lower occupant zone cooled by installing air-conditioning systems. A three-zone model is proposed to study the air temperature in the atrium. The upper zone is hot due to solar radiation heating up the glazed roof, interior side walls and building contents; a middle zone is an intermittent region; and the lower zone is cooled by an air-conditioning system. Heat transfer between the zones through convection is proposed. Air temperature is predicted by solving the system of heat balance equations numerically. Further, a closed form expression on the air temperature at the lower zone is derived by assuming a constant upper layer temperature. The result is useful at the initial stage in designing thermal environmental control systems for atria.

INTRODUCTION

Many atria were built in Hong Kong since 1980; perhaps it is the city with the greatest number of atrium buildings [1]. Such design began while developing the eastern part of the Tsim Sha Tsui (known as the TST East). Atria now can be found in large scale development projects such as multi-level shopping centers, luxury hotels, and prestigious office buildings [2]. The design is popular because comfortable, appealing environments are provided. Most of the atrium floors are well decorated (some even have a musical pond) and can be used for exhibition, entertainment, performance and catering. They are often crowded with people, a

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state of affairs that is highly desirable for developers who can use the building as a shopping mall, which helps offset the high construction costs of atria.

However, there are many technical problems associated with the building services design as reported in different parts of the world [3-7]. In addition to fire safety aspects [8], design of environmental control systems, especially the air conditioning system, is particularly critical. Providing a comfortable thermal environment to the atrium is very important. Shops located in a hot atrium will never attract customers. The air temperature at the occupied zone is the first factor to be considered. Very few research studies have been carried out in the past decade that predict the air temperature in the atrium or the effects of varying parameters of the cool air discharged. Using field models [9] to simulate the induced air flow is helpful but would require a powerful computer (and the computing time is very long). A simple equation for predicting the air temperature in the atrium will be helpful to the engineers.

A survey was made of the types and configurations of atrium buildings in Hong Kong [2]. The atria were found typically to be constructed with a glazed ceiling. The lower part is cooled by an air-conditioning system. A three-zone model is proposed for calculating the air temperature at the occupant zone. Further, by assuming the upper layer is of constant temperature, a closed form expression for the air temperature at the lower cool zone is derived. This equation is useful for preliminary assessments of the thermal environment in the atrium and in determining the operating conditions of the environmental control systems.

ATRIUM BUILDINGS IN HONG KONG

Atrium design in Hong Kong is quite different in scale from that in other countries in terms of size and configuration. For example, the atrium in the China Bank Building [10] has a height of more than 60 m (197 ft); the Hong Kong Bank Building [11] has a large atrium hall of volume 11000 m^3 (0.39 million ft^3); the atrium hall in Shatin New Town Plaza [12] has a length of 88 m (289 ft). All are designed to have special features for accommodating large numbers of occupants. The atrium floor area varies from a few hundred to thousands of square meters. A survey of the geometrical shapes of the atrium spaces in Hong Kong found that the atria can be classified into three main types [8]. The type 1 atrium is of cubic shape. This design is common in Hong Kong: approximately 60 percent of the atrium spaces are of this type. They are smaller in scale (i.e., less than 20 m (66 ft) long) and most are integrated into a shopping center. Type 2 atria have a large transverse dimension in comparison with the height. This form is usually found in large, multi-level shopping malls, and they comprise 25 percent of the atria. Type 3 atria have a height-to-width (or-length) ratio of more than two. These are usually found in prestigious office buildings such as the Hong Kong Bank Building [11] and luxury hotels. About 15 percent of local atria belong to this category.

It is common to find glazed ceilings at the atrium roof to provide daylighting and better views. Solar radiative heat gain from the glazed ceiling will heat up the interior side walls and building contents at the upper level. Heat is then transferred by convection to the lower atrium. Part of the heat will be lost by conduction to the surrounding wall and by convection to the adjacent levels. However, the atrium space is normally constructed inside the middle part of the building and the surrounding levels are cooled by downward air curtains. Most of the heat would then be transferred to the lower part. As the lower level is the occupancy floor, air-conditioning is installed to provide thermally comfortable environment. The discharged cool air from the diffusers would move downward and so the part above the air diffuser is not cooled at this "far-field" region. The ceiling is heated up continuously, and eventually a thermal stratified layer is formed near the ceiling. The part below this hot layer would become an intermediate region with a lower temperature. Therefore, the atrium can be divided into three zones. The upper zone is a hot region, the lower zone is cooled by air-conditioning system and a middle-zone which is a complicated region as shown in Figure 1.

HEAT BALANCE EQUATION

It is assumed that there are three zones in the atrium of floor area A, and that the zones have thicknesses and temperatures ℓ_U, ℓ_M, ℓ_L; and T_U, T_M, T_L as shown in Figure 2. Thermal radiative heat flux transfer through the ceiling glazing h_{Rad} (in Wm^{-2}) would heat up the interior side walls at the upper level and then heat up air at the upper zone. Heat is transferred to the middle zone through convection, with part of the heat lost Q_u through the wall and to the adjacent levels, part of which heat up the air:

$$\rho A\, h_{U\rightarrow M}\, Cp \frac{dT_U}{dt} = h_{Rad}\, A - h_{U\rightarrow M}\, A\, (T_U - T_M) - Q_u \tag{1}$$

where $h_{U\rightarrow M}$ is the heat exchange coefficient ($Wm^{-2}K^{-1}$) from the upper to middle zone, ρ is the air density being 1.12 kgm^{-3} and Cp is the heat capacity (1100 Jkg^3K^{-1}).

At the middle zone, part of the convective heat transferred from the upper zone would heat up the air and part of it Q_M will be lost through conduction and convection to the adjacent levels:

$$\rho A\, \ell_M \frac{dT_M}{dt} = h_{U\rightarrow M}\, A\, (T_U - T_M) - h_{M\rightarrow L}\, A\, (T_M - T_L) - Q_M \tag{2}$$

where $h_{M\rightarrow L}$ is the heat exchange coefficient ($Wm^{-2}K^{-1}$) from the middle to lower zone.

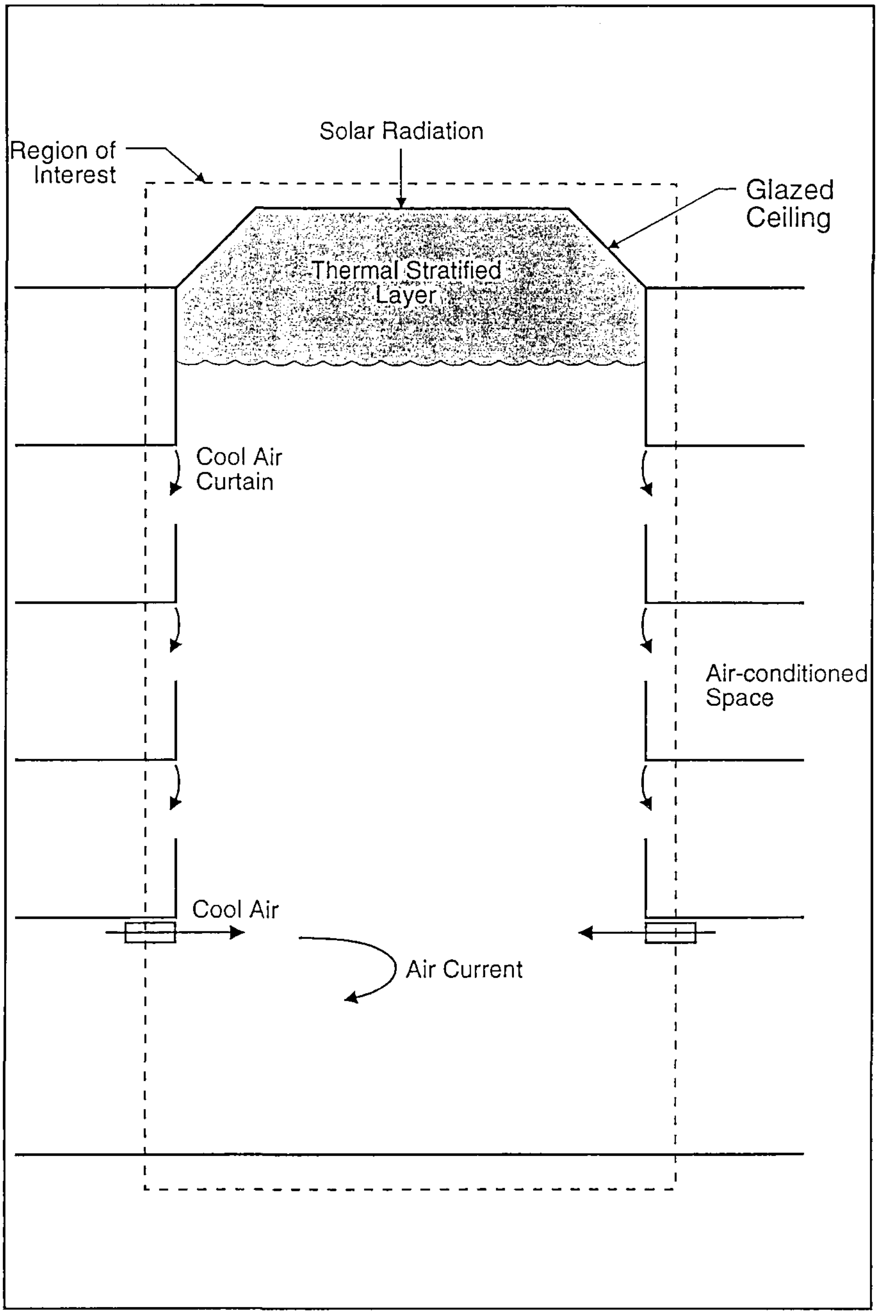

Figure 1. Atrium design.

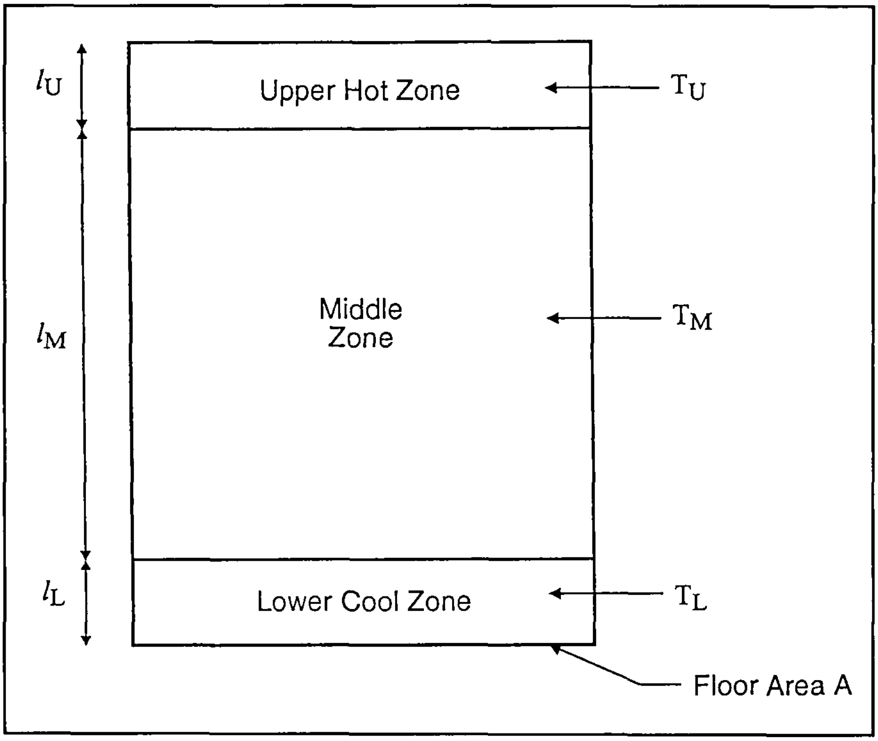

Figure 2. Simplified model.

The lower zone will be cooled down by air-conditioning system. Supposing that cool air at temperature T_{in} flows with a rate $\dot{m}$ (kgs^{-1}) into this zone, the heat balance equation is:

$$\rho A \ell_L \frac{dT_L}{dt} = h_{M \to L} A (T_M - T_L) - \dot{m} Cp (T_L - T_{in}) - Q_L \tag{3}$$

where Q_L is the heat lost to surrounding structures.

As the volume of air is very big in the atrium, the heat lost to the surroundings at the upper and lower zones is very small in comparison to the heat gain from the upper level, convective heat transfer to the lower zones, and the cooling effect due to the air jet; the heat lost terms Q_u, Q_M and Q_L can be neglected. Solving the set of equations would give the transient variation of the air temperature at each zones.

An example is taken in an atrium of height 16 m (52.5 ft), floor area 100 m^2 (1076 ft^2), and radiative heat gain at the ceiling is 90 Wm^{-2} (28.6 Btu/(h·ft^2)). The upper zone is assumed to be of thickness 1 m (3.28 ft). The lower zone thickness is 5 m (16.4 ft), as it is quite common to have air diffusers installed at 5 m above the atrium floor. This region is treated as the 'near-field' regions of the air jet discharging from the diffuser. As a result, the middle zone thickness becomes 10 m (32.8 ft).

Suppose the initial are 35°C at the upper zone, 32°C at the middle zone, and 30°C at the lower zone. Air is discharging at a temperature of 14°C with a rate of two air-changes per hour. The existence of the three zones in fact can be verified by simulating the air flow and temperature inside using the Computational Fluid Dynamics package PHOENICS with the FLAIR [13] menu designed for studying heating, ventilation and air-conditioning systems. Under those conditions, results of the velocity vectors and the temperature contour at the central plane are shown in Figure 3. Now using the present model, and taking the heat exchange coefficients [14], $h_{U\to M}$ and $h_{M\to L}$ to be 10 $Wm^{-2}K^{-1}$ (1.76 Btu/(h·ft^2°F)), the set of equations is solved numerically by the Ordinary Differential Equation package DIFFEQ [15]. The results on the transient variation of the temperature at the lower zone are shown in Figure 4. It can be seen that steady-state temperature would be about 22°C and the cooling time is less than two minutes. The indoor thermal environmental conditions are satisfactory.

If a higher cool air temperature is designed, say 22°C, cooling would not be so efficient. The results for the lower zone air temperature are shown in Figure 5. It can be seen that the air temperature can only be cooled down to 28°C and that the cooling time is increased to longer than ten minutes. This temperature of the supply cool air is not low enough to provide thermally comfortable conditions at the occupant zone.

ANALYTICAL STUDIES

Closed from expressions for the lower layer temperature T_L can be derived with some approximation. Suppose the upper layer temperature T_U is constant. Equation (1) would give:

$$T_U - T_M = \frac{h_{Rad}}{h_{U\to M}} \tag{4}$$

As the middle zone is a very complicated region, equation (2) is not used. An expression for T_M is put into equation (3):

$$\rho A \ell_L Cp \frac{dT_L}{dt} = h_{M\to L} A \left(T_U \frac{h_{rad}}{h_{U\to M}} - T_L\right) - \dot{m}\, Cp\, (T_L - T_{in}) \tag{5}$$

Re-arranging:

$$\frac{dT_L}{dt} = F - G\, T_L \tag{6}$$

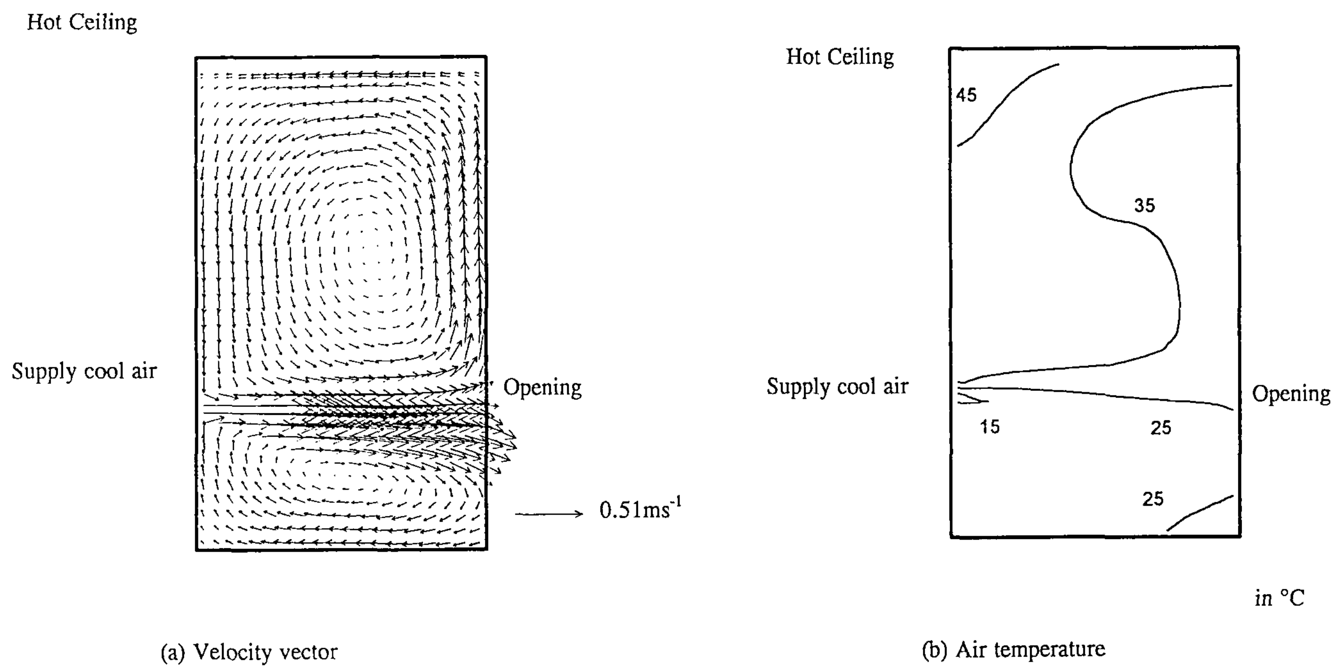

Figure 3. Predicted air temperature at the atrium using Computational Fluid Dynamics with the supply cool air temperature at 14°C.

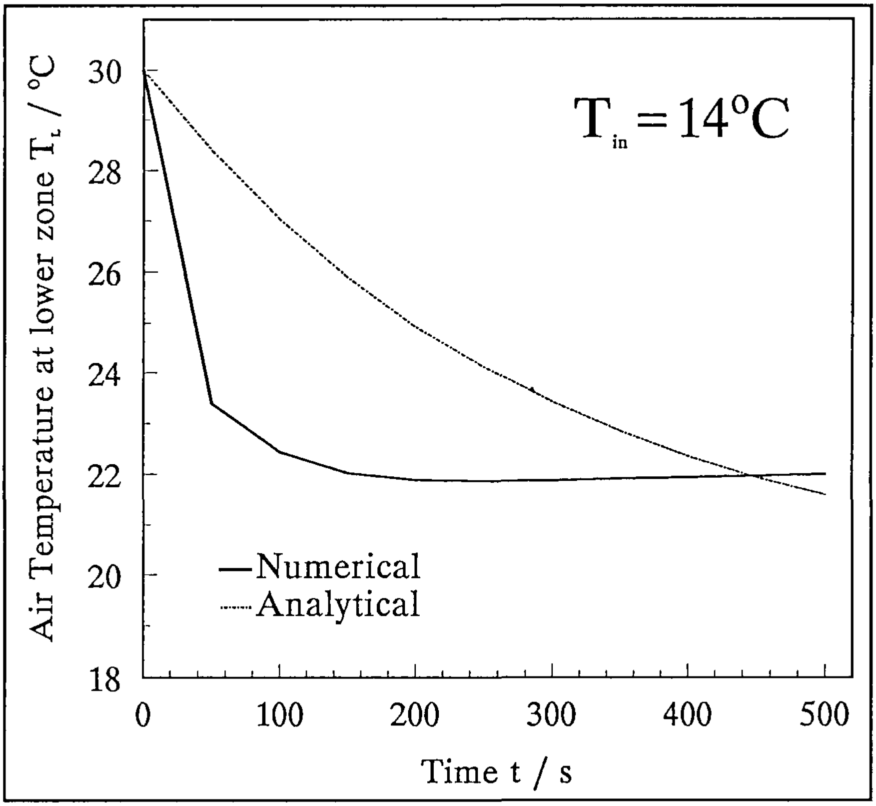

Figure 4. Predicted air temperature at the lower zone with cool air temperature 14°C.

where

$$F = \frac{h_{M \rightarrow L} A}{\rho A \ell_L Cp}\left(T_U - \frac{h_{Rad}}{h_{U \rightarrow M}}\right) + \frac{\dot{m} Cp T_{in}}{\rho A \ell_L Cp} \tag{7}$$

$$G = \frac{\dot{m} Cp + h_{M \rightarrow L} A}{\rho A \ell_L Cp} \tag{8}$$

An expression for T_L can be derived in term of its initial value T_{Li}:

$$T_L = \frac{1}{G}\left\{ F - (F - GT_{Li})\, e^{-Gt} \right\} \tag{9}$$

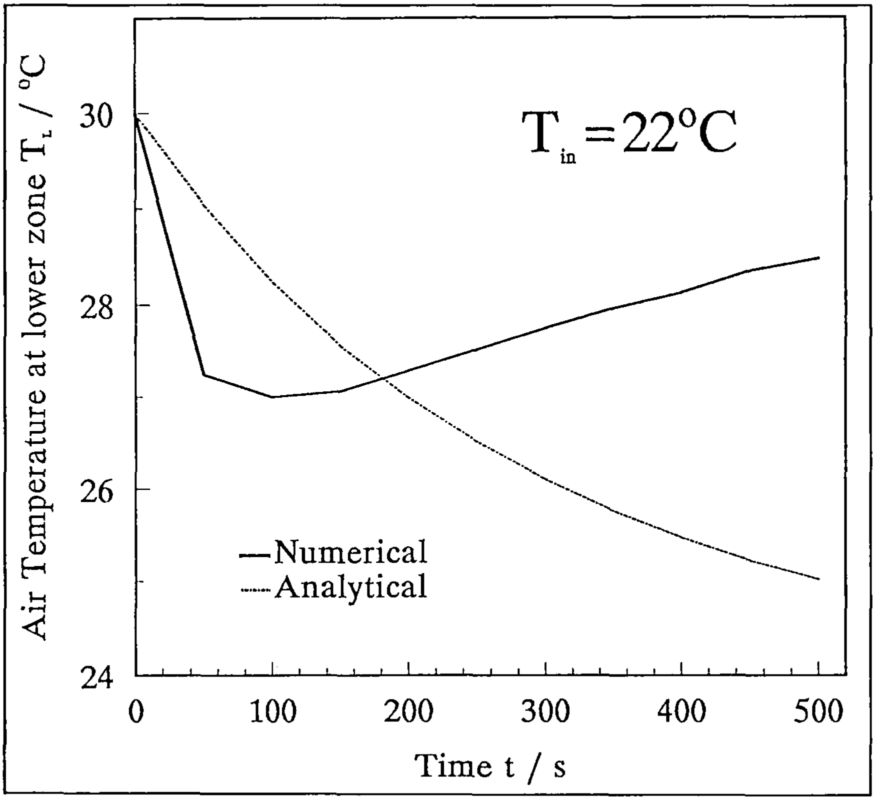

Figure 5. Predicted air temperature at the lower zone with cool air temperature 22°C.

The asympotatic value of T_L is $T_{L\infty}$:

$$T_{L\infty} \rightarrow \frac{F}{G} \tag{10}$$

The same results can be derived by setting $\frac{dT_L}{dt}$ in equation (3) to zero:

$$h_{Rad}\, A = h_{M\rightarrow L}\, A\, (T_U - T_{L\infty}) - \dot{m}\, Cp\, (T_{L\infty} - T_{in}) \tag{11}$$

This would give an expression relating the asympotatic value of the temperature at the lower zone with the air intake rate $\dot{m}$ and temperature T_{in}.

Using the same example of the atrium discussed above with the same initial conditions, and taking the cool air intake temperature to be 14°C, the following results are computed:

$$
\begin{aligned}
&F = 0.9956 \quad Ks^{-1} \\
&G = 3.4012 \times 10^{-3} \quad s^{-1} \\
&T_{\infty} = 292.72 \quad K
\end{aligned}
\tag{12}
$$

The results in the lower zone temperature are plotted in Figure 4. Very good agreement is obtained (except the cooling time is longer).

Now, when higher cool air intake temperature of 22°C is used, the results become:

$$
\begin{aligned}
&F = 1.0098 \quad Ks^{-1} \\
&G = 3.4012 \times 10^{-3} \quad s^{-1} \\
&T_{\infty} = 269.91 \quad K
\end{aligned}
\tag{13}
$$

The results for the lower zone temperature are shown in Figure 5. Large differences are found as the cooling effect of the intake air is not significant. Care must be taken in using the analytical expressions, which are derived using the approximation of T_M given by equation (4), rather than by solving equation (2). Therefore, these results are valid only for large temperature differences between the supply air temperature and the initial space temperature. Nevertheless, this is very useful for quick estimation on the resultant space air temperature due to the supply cool air for the case with large differences between the two.

CONCLUSIONS

By dividing an atrium with a glazed roof into three zones, the air temperature at the occupant zone which is cooled by air-conditioning system can be predicted using the above model. The derived equations are useful in assessing the thermal environment at different supply cool air temperatures. Operating conditions of the thermal environmental control systems can be determined.

Although many empirical parameters such as the heat exchange coefficients appear in the equation, quick estimation of the air temperature at the lower zone is possible with some predetermined parameters obtained either experimentally or numerically. In this way, long computing times are not required for the initial design stage of environmental control systems (as in the case for using computational fluid dynamics) [8].

The model can be improved if thermal storage effect of the walls can be included or perhaps integrated with the building energy simulation programs [16]. In this way, actual cooling load of the system can be estimated.

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