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CONSIDERATION OF THERMAL STRATIFICATION IN MUTLI-ZONE MODELS OF NATURAL VENTILATION

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ABSTRACT

This paper attempts to answer questions like when thermal stratification is important and how to consider it in simple multi-zone models of natural ventilation. Both simple analytical solutions and comparison of CFD and multi-zone analysis suggest that the multi-zone modelling approaches with the assumption of uniform zonal air temperatures can significantly underestimate the neutral levels in buildings with large ventilation openings, indicating that the flow directions through some openings may not be correctly predicted. The predetermined linear vertical air temperature profile method is suggested for modifying existing thermal modelling programs, which may also allow the treatment of surface thermal radiation transfer. An existing multi-zone airflow model, MIX, was modified to include a linear vertical air temperature profile. Future work will include the integration of the airflow and thermal programs considering thermal stratification.

1 INTRODUCTION

It was concluded in a recent Annex 35 state-of-the-art review (Li *et al.* 1999a) that the most promising analysis methods for simulating long-term performance of natural and hybrid ventilation systems is the so-called multi-zone approach based on the Bernoulli's theory of airflows. The multi-zone models may easily be integrated into an existing multi-zone thermal modelling program. The basic ideas in both multi-zone airflow modelling and thermal modelling are the same, i.e. a building is effectively divided into a number of zones. Simplified equations of mass, momentum and energy conservation are established for each zone and solved iteratively.

Many approximations and simplifications are made in multi-zone models. The most essential and commonly made assumption is that.

- Each zone is assumed to be fully mixed, which means that the air temperature and density are uniform in the zone considered.

This significantly simplifies the analysis procedures and data input, and reduces the computational time. In our opinion, these features are the most significant advantages given by a multi-zone approach.

This paper focusses on the extension of the multi-zone methods to include the effects of thermal stratification.

When thermal buoyancy forces dominantly drive natural ventilation, it is unlikely that the room air will be fully mixed. For point, line and wall heat sources, it has been shown experimentally that the flow will be stratified in a room, i.e. lighter air will tend to stay at the ceiling level and heavier air at the floor level.

Ideally, one may like to start from scratch to develop an integrated airflow and thermal program for natural and hybrid ventilation modelling with thermal stratification. But such an approach is too expansive, and may not be necessary as well. The approach we are considering here is to incur minimum changes to the existing airflow and thermal programs and accommodate necessary modifications to the physical models when thermal stratification is considered. In any case, it is not desirable to significantly complicate the zonal modelling approach, as various advantages offered by the multi-zone approach would disappear.

Two most significant aspects with regard to thermal stratification are:

- How to predict thermal stratification in thermal modelling.
- How to predict the effect of thermal stratification in airflow modelling.

2 HOW TO PREDICT THERMAL STRATIFICATION

2.1 What is the air temperature profile?

In a buoyancy-dominated natural ventilation flow, cool ambient air is forced into the room through the ventilation openings at floor level. Depending on the relative strength of the inflow momentum and the buoyancy force, the supply airflow may spread on the floor. At the same time, plumes are generated over various heat sources, such as people, computers and warm wall surfaces. The air at the floor levels is entrained into these plumes and carried upwards to ceiling level, where the air leaves through the top openings. It is this process that establishes thermal stratification. The vertical air temperature profile is determined by many flow and thermal parameters, such as the number, physical size, and location and strengthen of heat sources and ventilation openings.

Without using more detailed analysis methods such as computational fluid dynamics, it is difficult to predict the vertical air temperature profiles in a room. One possible approach is the so-called zonal method, where each zone is again divided into a number of sub-zones, and the air temperatures in each sub-zone and the airflow rates between these sub-zones are predicted. Difficulties remain in determining generally the airflow rates between sub-zones, although the method has been successfully developed and tested for predicting thermal stratified flows in a number of situations.

A somewhat similar approach can be taken in existing airflow and thermal modelling programs, where a room with potential strong thermal stratification is divided into a number of vertical zones, assuming uniform air temperatures in each of these sub-zones. For example, a solar chimney can be divided into a number of zones. It is unclear how accurate this approach is. Further evaluation of the method is still needed. One thing seems certain that it is very difficult to include thermal radiation between the ceiling and floor in this approach.

An alternative approach is to predetermine the vertical air temperature profile. Following earlier studies of vertical air temperatures in displacement ventilation (e.g. Li *et al.* 1992; Nielsen 1996) and some of our earlier results from CFD modelling of natural ventilation (Li *et al.* 1997), there are at least three possible 'good' profiles (see Figure 1):

- A linear profile – the vertical air temperature profile is assumed to be linear.
- A two-layer profile – each zone is divided into two sub-zones and both sub-zones are considered to have a uniform air temperature. This profile is commonly used in fire modelling using a zonal approach (e.g. Tanaka 1983).
- A mixed profile – each zone is divided into two sub-zones. The bottom zone is assumed to have a linear profile, while the top zone is assumed to have uniform air temperature. This profile is suggested as the mixing effect is expected to be significant in the top zone.

Analytical expressions of the airflow rates through openings may be obtained when the two-layer profile is used (see Tanaka 1983). But similar to the mixed profile, it requires the determination of the clean zone height (i.e. smoker layer interface in fire modelling). With the linear profile, there is no need to determine the clean zone height, but numerical integration is needed for calculating airflow rates through openings.

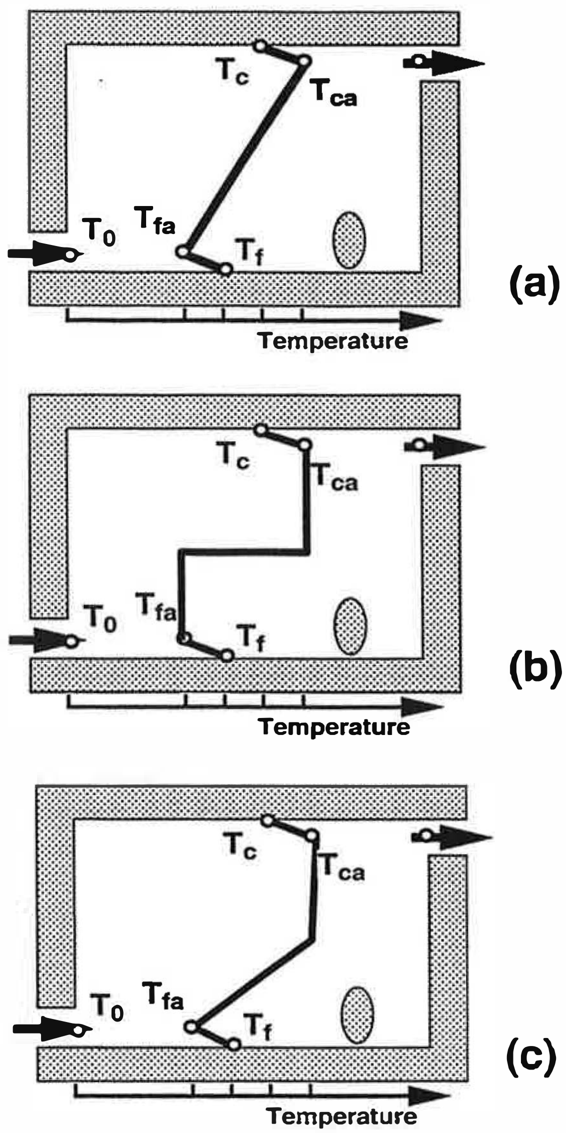

Figure 1. Three models for the vertical air temperature profile in a naturally ventilated room. Ceiling and floor surface temperatures, T_c and T_f, are also indicated. T_0 is the air temperature of outdoors or the neighbouring room, and T_{fa} and T_{ca} are the near-floor and near-ceiling air temperatures respectively: (a) linear mode; (b) two-layer model; and (c) mixed profile model.

The following discussions will be focussed on the linear temperature profile, which was first suggested by Mundt (1990) and later extended by Li *et al.* (1992) for displacement ventilation.

2.2 How to predict thermal stratification

Its should be mentioned that similar to the air temperature profile, the wall surface air temperature is also likely to be a function of the room height. One of the possible approaches to treat wall surface temperature distribution is to divide the vertical wall into a number of separate wall surfaces.

With the assumed linear vertical air temperature profile, it is possible to formulate the energy balance equations for both the near-ceiling air and the near-floor air, which are used to obtain the temperatures of the near-ceiling and near-floor air. From the implementation point of view in a thermal program, this may correspond to dividing the room zone into two sub-zones – near-ceiling air sub-zone and near-floor air sub-zone. One assumption behind the three-node or four-node models of displacement ventilation (Li *et al.* 1992) is that there is no heat and mass transport between the two sub-zones through interface mixing, unless due to thermal plumes. Special treatment is needed to consider the significant radiative heat transfer between wall surfaces, in particular between the floor and ceiling surfaces.

This linear profile model has been implemented in CSIRO's thermal program CHEETAH, but further tests are still needed. To illustrate the application of this approach, the program was used to compare the effect of changing the properties of the wall, ceiling and floor on the temperature gradient as a function of time in a simple room with dimensions of 10 m x 10 m x 3 m. The construction of the lightweight version consists of timber cladding, 50 mm insulation and 10 mm plasterboard, while that of the heavyweight version consists of timber cladding, 50 mm insulation and 100 mm concrete panels. The indoor heat source is 2500 W. A temperature cycle for a hot day was applied to the exterior surfaces. Figure 2 shows the temperature difference between the ceiling air and floor air as a function of time for the two building types. Even though the U-values of the two constructions are identical, the temperature gradients differ.

3 HOW IMPORTANT IS THERMAL STRATIFICATION?

Most of the results presented in this section are taken from Li *et al.* (1998) and Li (1999). The question is: when does the effect of thermal stratification on airflow becomes significant? This is answered here by two approaches:

- Analytical solutions in a simple one-zone building with two openings and a point heat source located at the floor level.
- Comparison of results obtained by both CFD and multi-zone modelling of a smelter building.

Figure 3 shows a comparison of analytical solutions with three different assumptions for a simple building (height of building h = 6 m and outdoor air temperature T_0 = 293.15 K) with two equal ventilation openings (Figures 3a–3c) and unequal opening areas (top opening area is half that of the bottom one) (Figure 3d). The three different assumptions are uniform indoor air temperature (fully mixed model), two-layer profile without thermal radiation (the emptying water–filling box model) and the two-layer profile with thermal radiation (the emptying air–filling box model) (see Li *et al.* 1998). The buoyancy flux is 1.38 x 10^{-2} m^4/s^4 (heat source E = 500 W). The discharge coefficient C_d is 0.6. It seems that as the effective ventilation opening area approaches zero, all models give the same result. As the ventilation opening area increases, the differences between the results of different models also become significant.

At A/h^2 = 0.1, the clean air zone height is the full building height for the fully mixed model due to very high ventilation flow rates (0.72 m^3/s). The water model predicts a result of 77% of the building height. With this model, the bottom zone has the same air temperature as outdoors. The indoor and outdoor air temperature difference in the bottom zone is zero and no ventilation airflow is introduced. This results in a much smaller ventilation flow rate through the ventilation openings (0.42 m^3/s). In displacement ventilation, the value of the non-dimensional number λ is generally around 0.4 (Mundt 1990). Results for three different λ values are shown in Figure 3 for the air model.

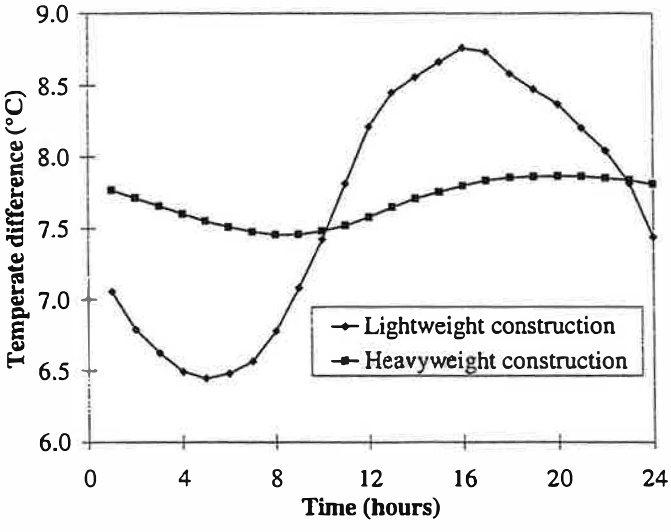

Figure 2. Difference between ceiling air temperature and floor air temperature as a function of time for two types of room construction, using the five-node model.

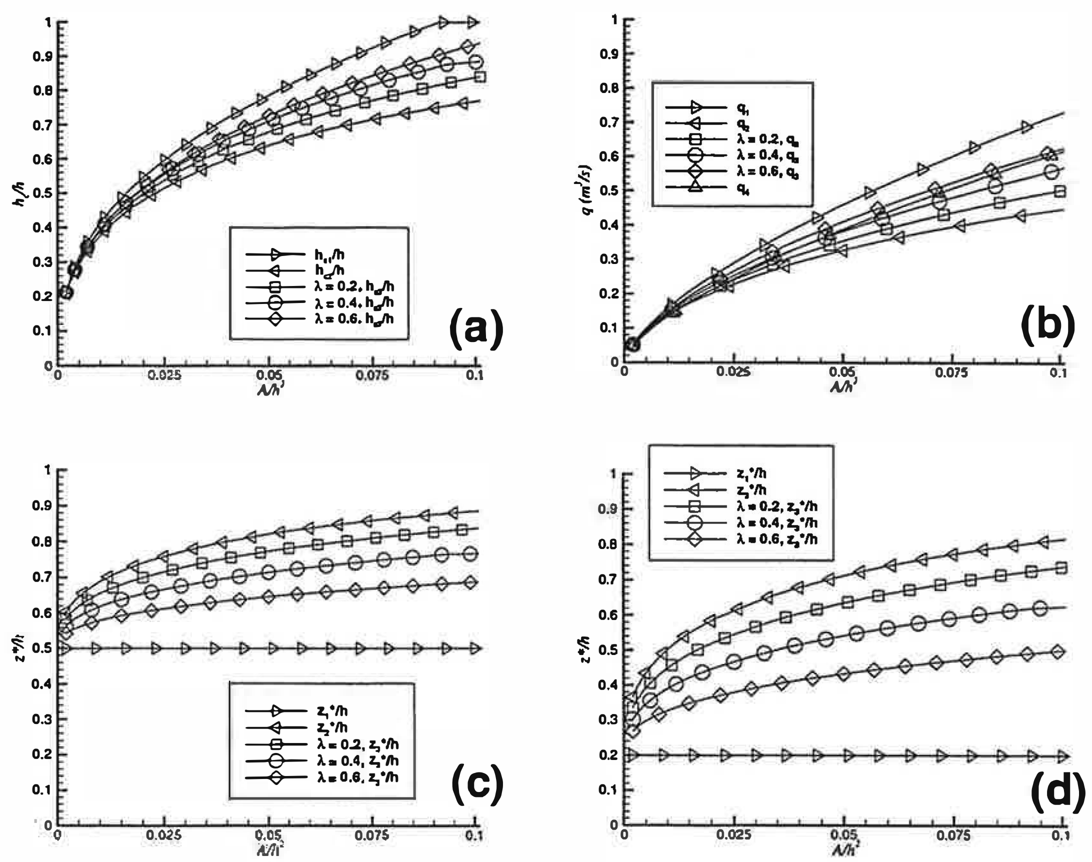

Figure 3. Comparison of predicted clean zone heights, h_c (a), ventilation flow rates q (b), neutral heights z^* (c for γ = 0.5 and d for γ = 0.2) by three different models. The subscript '1' indicates the fully mixed model, '2' the emptying water–filling box model, and '3' the emptying air–filling box model.

But for neutral height predictions, there is a more significant discrepancy between the results of the fully mixed model and the water model. While the fully mixed model predicts a constant neutral height for all ventilation openings, other models predict increasing heights as the ventilation opening areas increase.

For equal ventilation openings, the water model predicts a neutral height of almost 90% of the full height, while the neutral height for the fully mixed model is only 50%. For the unequal area case, for the fully mixed model it is 20%, while the water model gives 80%. The air model results lie between those predicted by the fully mixed model and the water model.

Figure 4 shows a comparison of predicted neutral levels in a smelter building, where very strong heat sources exist. Not shown here, is that there is fairly good agreement between the predicted overall flow rates by the multi-zone model (29 ACH) and CFD (26.5 ACH), although the CFD-predicted flow rate is lower than that predicted by the multi-zone model. The trend agrees well with the analytical results in Figure 3.

It is interesting that CFD predicted inflows through almost all wall openings for this building, while the multi-zone approach predicted outgoing flows through most upper wall openings. CFD predicts a higher neutral plane than the multi-zone model. This can be attributed to the fact that the multi-zone model does not fully consider the thermal stratification in the building. It may be argued that multiple vertical zones partially account for the thermal stratification in part of the building. The results show that thermal stratification needs to be considered in a multi-zone approach for natural ventilation with large openings.

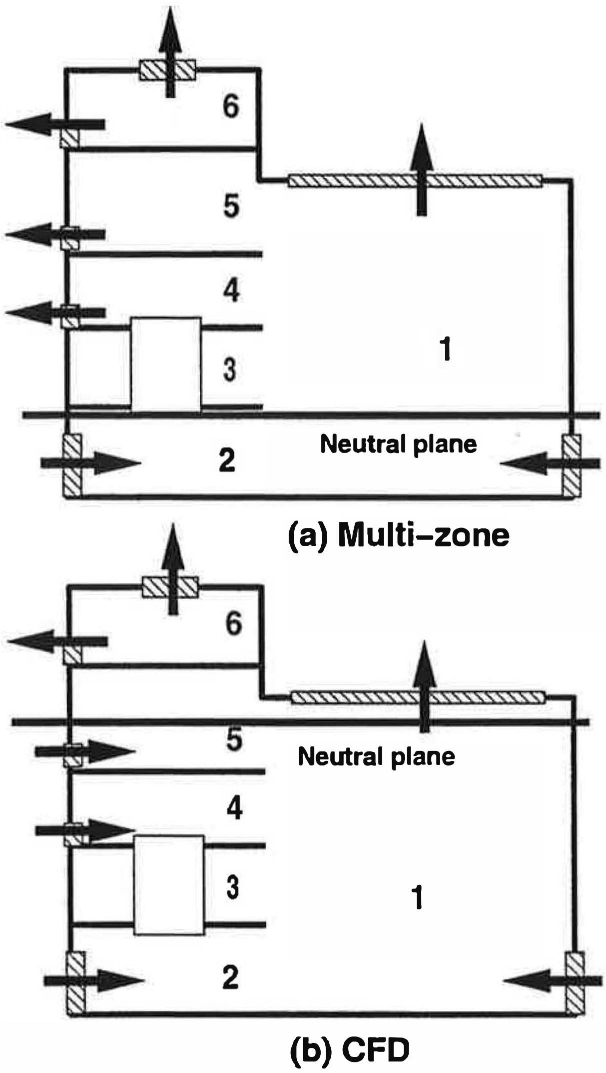

Figure 4. Illustration of predicted neutral levels in a smelter building by: (a) multi-zone model simulation; and (b) CFD simulations (Li *et al.* 1998).

4 MIX3.0 – A SIMPLE MODEL FOR PREDICTING THE EFFECT OF THERMAL STRATIFICATION

Recently, a new program MIX3.0 was developed at CSIRO, which is a revised version of MIX1.0 (Li 1993) and MIX2.0 (Li *et al.* 1999b). This program can be used to predict airflow rates through openings in a multi-zone building where each zone can be thermally stratified with a linear profile or fully mixed. The key ideas in MIX3.0 are as follows:

1. The pressure difference across an opening can be derived to be:

$$\Delta P = \Delta P_f (1 - \frac{Z_{1_1}^* + Z_2^*}{Z_1^* Z_1^*} z - \frac{1}{Z_1^* Z_1^*} z^2) \qquad (1)$$

where ΔP_f is the pressure difference at the floor level, and z is the local vertical coordinate with the floor level as its origin. Z_1* and Z_2* are the two neutral planes. If Z_2* approaches infinity, equation (1) is reduced to the fully mixed version.

2. There is no need to determine the flow direction through different sub-zones separated by two possible neutral planes. This is achieved by a simple analysis.

It is assumed that there are two neutral planes between two zones i and k, although the ic equally applies to multiple neutral planes. All inflows to zone i through an opening is indicated A^+ and outflows as A^-. Inflows are assumed to be positive and all outflows negative (see Figure !

It is easily shown that:

$$q_{i,k} = A^+ + A^- = C\int_{z_1}^{z_2} \Delta P^n dz \tag{2}$$

$$| q_{i,k} | = A^+ - A^- = C\int_{z_1}^{z_2} | \Delta P^n | dz \tag{3}$$

Thus:

$$A^+ = \frac{|q_{i,k}| + q_{i,k}}{2} \tag{4}$$

$$A^- = \frac{|q_{i,k}| - q_{i,k}}{2} \tag{5}$$

where the constant C is a function of the discharge coefficient and the width of the opening. T formula also applies to the fully mixed situation.

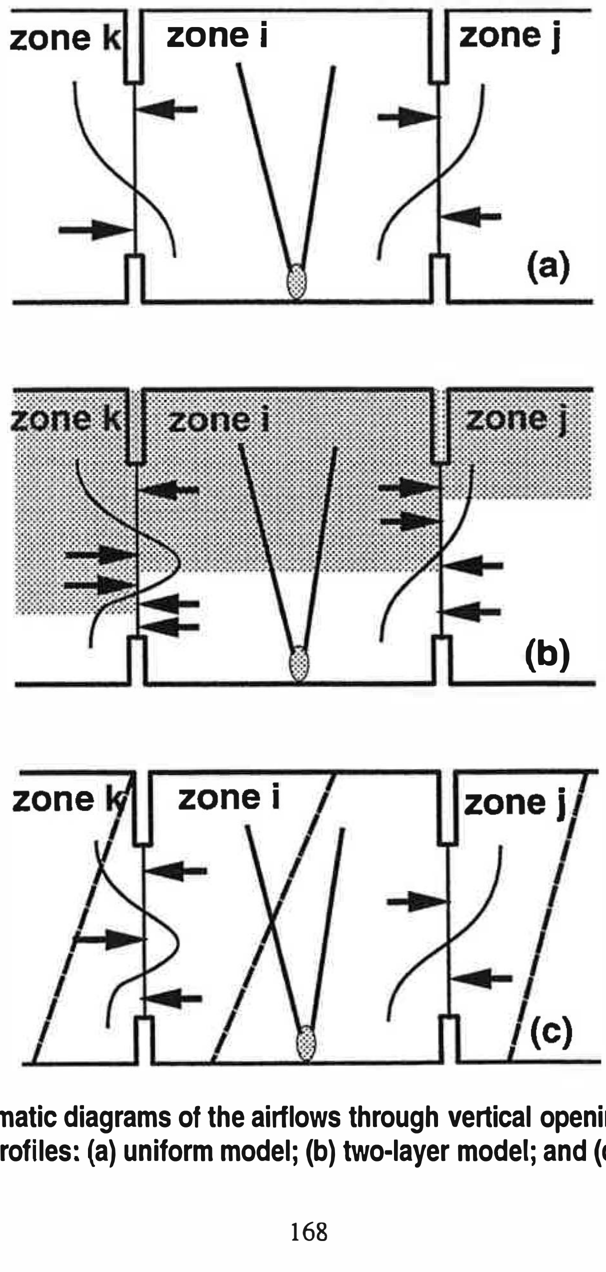

Figure 5. Schematic diagrams of the airflows through vertical openings for three air temperature profiles: (a) uniform model; (b) two-layer model; and (c) linear model.

The above two principal ideas allow us to develop a multi-zone model, which applies to both fully mixed zones and zones with a linear vertical air temperature profile. The model has been tested against an analytical solution in a two-zone building with effectively two openings in each zone (see Figure 6). Linear stratification is assumed in both zones. The height of each zone is 8 m. The opening area for each opening is 10 m^2. This model building is not meant to represent a realistic building, but rather to examine the accuracy of the algorithms behind MIX3.0. The results are shown in Figure 7. Flow rates increase as temperature gradients increase in the top room. As both the top and bottom openings have a height of 0.1 m, a slight underestimate by MIX3.0 is expected. Otherwise, the analytical solutions should be almost identical to MIX3.0 results, as both solutions are based on the same sets of equations, although MIX3.0 uses numerical solutions. Further evaluation of the programs will be published elsewhere.

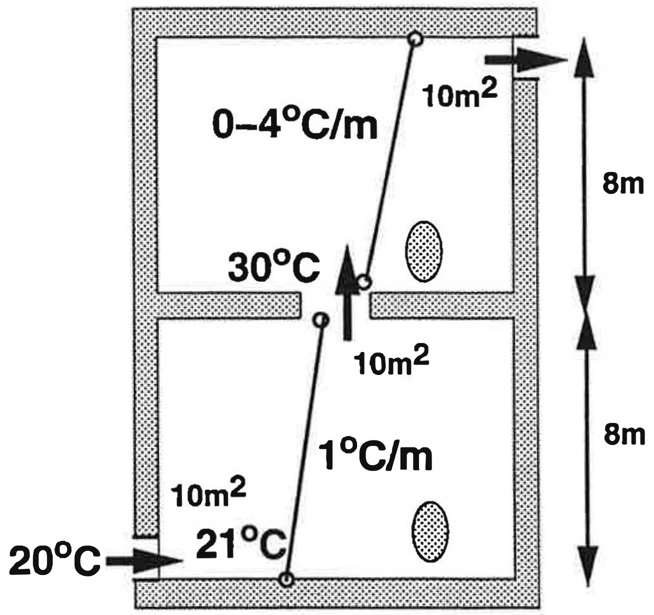

Figure 6. A simple two-zone building where analytical solutions exist.

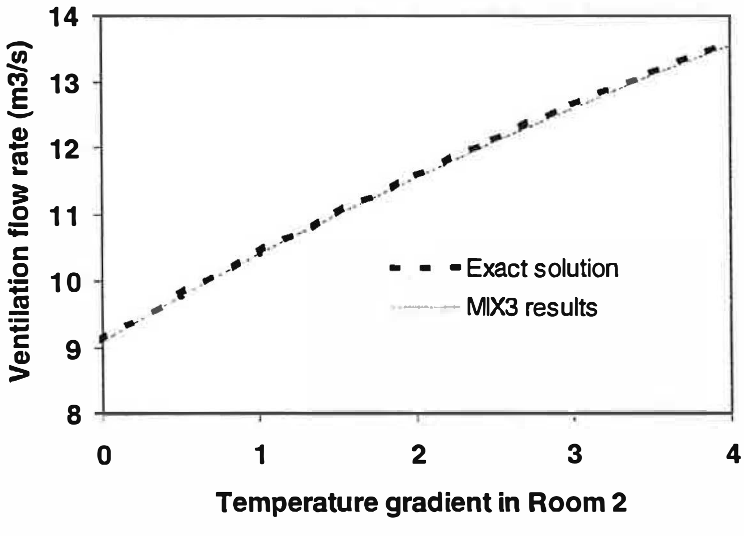

Figure 7. Comparison of predicted ventilation flow rates through the building by MIX3.0 and analytical solutions.

5 CONCLUSIONS

A number of conclusions can be drawn from the above discussion and analysis:

- The effect of thermal stratification on airflow can be very significant, and ignoring it can lead tc significant underestimatation of the neutral levels in a building. When the walls are noi insulated, thermal stratification may also significantly affect the heat transfer between the insidє air and wall surfaces, which modifies the thermal buoyancy force and the ventilation flow rate.
- The linear vertical air temperature profile is suggested for simulating the thermal stratification effect in natural ventilation. Such a linear profile may be easily implemented into a thermal program, which predicts the near-floor and near-ceiling air temperatures.
- A multi-zone airflow model incorporating a linear air temperature profile has been developed anc preliminary tests have been carried out. Further development is still needed.

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