#6076

International Symposium on Room Air Convection and Ventilation Effectiveness
University of Tokyo, July 22 – 24, 1992

IMPACT OF INTER-SPACE AIRFLOW ON AIR HUMIDITY BEHAVIOUR WITHIN BUILDINGS

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ABSTRACT

Indoor spaces in a multi-space building are not fully separated since interconnecting elements such as doorways do exist. The presence of inter-space air-flow introduces additional physical characteristics that need to be addressed in order to accurately account for moisture transfer between interconnected spaces by air movement. The objective of this paper is to report the results of a recent study to model and analyze the effect of inter-space air movement within multi-space buildings on air humidity behaviour within each individual space. The influence of inter-space airflow paths characteristics, zonal arrangement, and the building envelope are examined. Moreover, the combined effect of air leakage through the building envelope and the inter-space air movement on the space air humidity behavior is analyzed. Assuming known pressure in each space, the corresponding airflow rates were evaluated for the various building airflow elements. The mass balance concept is then utilized in conjunction with the airflow network modelling technique in order to obtain a set of nodal nonlinear algebraic equations representing the mass balance at different spaces. The spatial pressures are evaluated by simultaneously solving the resulting mass balance equations. The air humidity behaviour in each space as well as the moisture interaction between different spaces are modelled via a system of differential equations which were solved simultaneously to determine air humidity conditions in each space. A case study is presented along with a parametric analysis to demonstrate the influence of each parameter as well as to show the advantage of the proposed model and the computation procedure. Air humidity behaviour showed significant difference when inter-space airflow was considered.

KEYWORDS: Humidity, Moisture, Airflow, Buildings, Building Envelopes.

researchers have attempted to describe the natural convection heat flow through large openings by using a dimensionless correlation using Nusselt's number, Prandtl's number and Grashof's number. Using the orifice equation it has been shown by (Walton 1984) that heat transfer and the corresponding mass flow predicted by a correlation equation for the two-way flow through a doorway can also be expressed by the power law elements. A multi-room airflow model has been developed (Walton 1982) as part of a general model to compute air infiltration and airflow between rooms. A more comprehensive model is later suggested by Walton (1989) by including the HVAC system. In both cases, the resulting mass balance nonlinear algebraic equations are solved by using Newton's iteration method.

The objective of this paper is to model and analyze the effect of inter-space air movement on the behaviour of zonal air humidity in a multi-space building. The influence of inter-space airflow paths characteristics, zonal arrangement and the building envelope are studied. In addition, the combined effect of air leakage through the building envelope and the inter-space air movement on zonal air humidity behaviour is analyzed.

2. THEORETICAL APPROACH

Air humidity level at any time within a particular zone in a multi-zone space is determined by the instantaneous moisture mass balance. Airflow across zonal exterior and inter-space boundaries could be a determining factor in shaping zonal air humidity behaviour since considerable amount of moisture could be added or removed from the space via this moisture transfer process. In order to model air humidity behaviour in a multi-zone space, a moisture mass balance must be performed for each zone, with the interaction between the different zones described by a multi-cell airflow model. Solving the resulting zonal moisture mass balance equations requires the knowledge of airflow rates across the different flow paths. This means that successive evaluation of airflow rates and indoor humidity must be carried out.

2.1 Air Humidity Behaviour in a Multi-Space Building

Using the moisture mass balance concept, air humidity behaviour in a multi-space building can be modelled via a system of linear differential equation, each representing air humidity response within a particular space. The dynamic response of air humidity in a given space can be generally given by:

$$\frac{dW_r}{dt} = \frac{1}{\rho_a V} \left[\sum_{j=1} \frac{dms}{dt} + \sum_{j=1} \frac{dma}{dt} + \sum_{j=1} \frac{dmf}{dt} + \sum_{j=1} \frac{dmc}{dt} + \sum_{j=1} \frac{dme}{dt} + \sum_{j=1} mg' \right] \qquad (1)$$

where

W_r= room air moisture content, *kg/kg*
ρ_a= air density, *kg/m³*
V= room volume, *m³*
dms/dt= rate of moisture absorption or desorption by interior materials, *Kg/s*
dma/dt= rate of moisture added or removed due to air flow across space boundaries, *kg/s*
dmf/dt= rate of moisture transfer by diffusion through large inter-space openings, *kg/s*
dmc/dt= rate of moisture removed by surface condensation, *Kg/s*
dmc/dt= rate of moisture added by evaporation, *Kg/s*
mg= rate of moisture generation from indoor sources, *Kg/s*

In the present paper the main objective is to study the influence of inter-space air movement on zonal air humidity behaviour hence, the impact of some moisture transport processes, which are not directly relevant, such as surface condensation, can be neglected. For the K-th zone equation 1 can now be written as:

$$\frac{dW_r(k)}{dt} = \frac{1}{\rho_a V(k)} [\sum_{j=1} \frac{dma}{dt} + \sum_{j=1} \frac{dmf}{dt} + \sum_{j=1} mg] \qquad (2)$$

The first term in equation 2 represents moisture transfer due to air leakage through exterior walls, as well as, moisture transfer due to inter-space air movements. The second term represents moisture transfer by diffusion through large openings. Since it is relatively small, Inter-space moisture transfer by diffusion is considered important only in the absence of inter-space airflow. This normally occurs between interior zones which are at the same air temperature. Assuming uniform moisture distribution within each zone, and substituting for the moisture transport processes, equation 2 can be written for the k-th zone to become:

$$\begin{aligned}\frac{dW_r(k)}{dt} = {} & \frac{1}{\rho_a V(k)} [\sum_{j=1}^{noi} Q_{oi} W_{o_i} - W_r(k) \sum_{j=1}^{nio} Q_{io_i}] + \frac{D_{va}}{\Delta L\, V(k)} \sum_{j=1}^{nop} A_{ok_j} [W_r(j) - W_r(k)] \\ & + \frac{1}{\rho_a V(k)} \sum_{j=1}^{ng} mg_j\end{aligned} \qquad (3)$$

Where

Q_{oi}, Q_{io}= airflow into or out of zone i, *kg/s*

W_o= air moisture content outside a given space, *kg/kg*
D_{va}= coefficient of water vapour diffusion in air, m^2/s
ΔL= partition or wall thickness, *m*
A_o= area of opening connecting two zones, m^2
noi= number of airflow processes
ng= number of moisture generation processes
nop= number of inter-space openings

In order to determine zonal air humidity behaviour in a multi-zone space of n zones, n differential equations, similar to equation 3, are required to be solved simultaneously. Solution of such a system of differential equations can be obtained by numerical techniques such as Gill's modified Runge-Kutta method (Terry 1983). Solving this system of differential equations, however, requires the knowledge of inter-space airflow rates as well as air infiltration rates. Because of the nonlinear relationship between the airflow rates, required in Equation 3, and the boundary conditions (i.e., wind pressure), variations in the airflow rate can not be expressed in terms of time via a continuous function. Instead, a discrete time step is used during which airflow rate is assumed constant. At each time interval the system of differential equation is solved and the values of airflow rates are continuously updated

2.2 Airflow Through Building Elements

In buildings, there are a wide range of airflow paths, ranging from a crack in the exterior envelope to a large opening connecting two spaces. For evaluating the airflow rate across each flow path its flow characteristics as well as the pressure differential across it must be known.

2.2.1 Air leakage through exterior walls. the exterior wall is a complicated airflow element containing openings of different sizes. Most airflow models are formulated based on an empirical relationship between the determining parameters which includes flow characteristics of the elements and the pressure difference across it. Airflow rate across the exterior wall is commonly expressed by (ASHRAE 1981):

$$Q = K\rho_a(\Delta P)^n \tag{4}$$

where

Q= airflow rate, *kg/s*
K= flow Coefficient, $m^3/s.Pa^n$
n= flow exponent
P= pressure, *Pa*

The value of the flow exponent can vary from 0.5, corresponding to orifice flow, to as much as 1.0 corresponding to capillary flow. Since in a real wall both type of flows may exist, a value of 0.65 was found to be suitable for describing airflow across many walls and windows (Hutcheon 1983).

The pressure difference across the exterior building envelope arise from wind and thermal forces. The effective pressure difference across the wall at any given point is given by:

$$\Delta P = P_s + P_w - P_m \tag{5}$$

where

P_s = thermal induced pressure
P_w = wind pressure
P_m = room reference pressure

Depending on the location in terms of the neutral axis, thermal induced pressure could be positive or negative, and it varies along the height of the building according to equation 6.

$$P_s = gh(\rho_{ao} - \rho_{ai}) \tag{6}$$

where

g= gravitational constant, m/s^2
h= distance from neutral plane, m

The airflow rate through an incremental area of the exterior wall can be given by:

$$dQ = C_w \, \rho_a \, dA \, \Delta P^n \tag{7}$$

where

C_w= wall air leakage coefficient, $m^3/m^2.Pa^n.s$

Assuming uniform distribution of openings, the neutral axis can be taken at mid-height of the wall. The total airflow can be determined by combining equations 6 and 7 and integrating over half the wall height. In order to account for opposite flows across the exterior wall, the wall is divided into two halves with an upper and lower flow elements each having the same leakage area.

2.2.2 Inter-Space Airflow. Airflow paths connecting two spaces in a building range from a crack around the edges of a closed door to a large opening. Airflow through a large opening is more complex since it could involve opposite flows due to temperature difference between connected spaces. In the absence of temperature difference, the pressure distribution along the height of the opening can be considered uniform. In this case, airflow through both types of inter-space flow paths can be expressed by the orifice equation. For large openings, the airflow rate can be given by (Hutcheon 1983):

$$Q^{b}_{inz} = C A_f \rho_a \left(\frac{2 \Delta P}{\rho_a} \right)^{1/2} \tag{8}$$

The second term in the right hand side of equation 8 represent the effective flow area, which for large openings is equal to the apparent opening area, and for closed doors, it is equal to the equivalent orifice area. Airflow due to stack effect through closed doors can also be modelled via the orifice equation. However, in order to account for opposite flows, an upper and lower flow elements are assigned each representing airflow through a half of the door. The rate of airflow can be given by:

$$Q^{s}_{inz,d} = C \left(\frac{A_f}{2}\right) \bar{\rho}_a \left(\frac{2 \Delta P_s}{\bar{\rho}_a} \right)^{1/2} \tag{9}$$

In all of the above cases, a discharge coefficient of 0.6 is used, since in these cases either the opening is small relative to pressure variation or the pressure distribution is uniform over the opening height. However, for modelling airflow due to stack effect through large opening the problem becomes more complicated and a discharge coefficient of 0.6 can not be used. In modelling airflow through large openings most researchers have developed a dimensionless correlation which takes the following general form (barakat 1987):

$$\frac{Nu_D}{Pr} = C_D \, Gr_D^{b} \tag{10}$$

Although airflow rate through large openings can be evaluated using equation 10, a more suitable expression can be obtained by applying the orifice equation and the appropriate flow coefficients. The airflow rate through one half of the opening can be given by equation 11 (Brown 1963).

$$Q^{s}_{lnz,o} = \int_{z=0}^{z=H/2} dQ = \frac{C}{3} W \left(\frac{g \, \Delta\rho_a}{\bar{\rho}_a} \right)^{1/2} H^{3/2} \tag{11}$$

where

H= opening height, *m*

W= opening width, *m*

Substituting the expressions of Nusselt's number, Prandtl's number, and Grashof's number, it can be shown that equations 9 and 11 are fundamentally the same with $C = 3C_D$ and $b = 0.5$ (Walton 1984). The value of C_D lies between 0.26 and 0.3 when the average room temperature is used to formulate the correlation. Hence C in equation 11 could have a value of 0.78 or 0.9. According to Walton (1984), a value of 0.78 seems more acceptable when related studies are compared.

2.2.3 Pressure Differential Across Airflow Elements. In order to evaluate the airflow rate across any flow element in a multi-zone space, air pressure in each zone must be known. In the present paper, the airflow network approach is used for evaluating air pressure distribution. In this approach, a set of nodes are used to represent different zones as well as the boundary conditions. These node are connected by airflow resistances each representing the flow characteristics of a particular element such as construction cracks in an exterior wall or a doorway connecting two spaces. For evaluating the air pressure in each zone a mass balance is performed at each zonal node i as given by equation 12.

$$\sum_{j=1}^{na} Q_{ij} = 0 \tag{12}$$

Performing the mass balance at each zonal node will result in a set of nonlinear algebraic equations which have to be solved simultaneously by iterative methods. A widely used technique is the Newton's method. Although this method is not always convergent, it is the most commonly used method for solving a system of nonlinear algebraic equations, because of its better convergence properties relative to other methods. For this study, Newton's method is utilized to solve for the pressure distribution in a multi-zone space.

3. RESULTS AND DISCUSSIONS

In a case study, the above mathematical formulations have been implemented to predict indoor humidity behaviour in a multi-space building with the zonal arrangement shown in Figure 1.

The building consists of five zones each of 180 m^3 in volume and connected either by large openings (i.e. 2 m^2) or closed doors (i.e. .00385 m^2). For the boundary conditions, a wind normal to the west wall is assumed with its average hourly velocities and the corresponding pressures given in Figure 2. Wind pressures are evaluated based on the formulation given by (Swami and Chandra 1988) for low rise buildings. Indoor moisture generation is represented by an assumed daily profile shown in Figure 3. The moisture generation source can be located within any particular zone so as to examine the combined effect of building functional and airflow characteristics on moisture distribution within the building. In this study case, the moisture source was located in zones 1, 2 and 5.

In order to investigate the influence of building air leakage and inter-space flow characteristics on air humidity behaviour within the building, nine different cases, given in Table 1, are considered. For all these cases, the initial indoor air humidity ratio is .0078 Kg/Kg, and the outdoor air humidity ratio is taken constant at .0125 Kg/Kg. In case No.1 to case No.3, the effect of exterior wall leakage characteristics is examined. Figures 4 to 6 illustrate the change in zonal air humidity behaviour due to increasing the wall leakage area from 0.01 m^2 to .04 m^2. From Figure 4 it can be seen that for a leakage area of 0.01 m^2, air humidity conditions in zone 1 and zone 5 are subjected to considerable changes while conditions remain almost the same in the other zones. This behaviour can be attributed to the pattern of air leakage and inter-space airflows. For the building under consideration with the given wind pressure distribution, air infiltrates through the east and west walls, however, the bulk of the air infiltration occurs through the west wall because of the positive wind pressure. This explains the quick and considerable changes in air humidity in zone 1 as compared to zone 3. Air exfiltration occurs through the south and north walls, hence, air humidity behaviour in zones 2 and 4 will depend on air conditions in zone 5. Since zone 5 is the only space connected to zone 1 the rate of air infiltration through the west wall should be equal to the airflow rate across the inter-connecting opening. Consequently, air humidity behaviour in zone 5 follows the same pattern of variation as zone 1 as it is apparent from Figure 4. By increasing the effective air leakage area of the exterior walls to .02 m^2, air humidity response in all zones is increased, although the relative pattern of variations remains essentially the same as shown in Figure 5. At relatively large air leakage area (i.e. .04 m^2), zones 1 and 5 came almost instantly to moisture equilibrium with the outdoor air, while air humidity response in the other zones has dramatically increased, although it is still a function of wind pressure fluctuation as shown in

Figure 6.

The presence of larger or more flow paths connecting the different zones will further increase their moisture interdependence. For example, adding four more large openings in the locations were possible paths are indicated in Figure 1, has resulted in dampened air humidity response for zone 5 as shown in Figure 7 compared to its behaviour in the case of four openings shown in Figure 4. This can be explained by the fact that moisture gains into zone 5 from zones 1 and 3, will be shared by the zones 2 and 4 in the presence of four more openings. In this case, air humidity behaviour in zones 1 and 3 remains essentially the same, while the other zones have identical behaviour. When the large openings are replaced by closed doors each with an effective leakage area of 0.00385 m^2, the zonal air humidity will behave completely different as shown in Figure 8. By comparing Fig. 8 and Fig. 4, it can be seen that air humidity response in zones 1 and 5 has been greatly dampened, while air humidity conditions in the other zones have not changed.

Air humidity response when air leakage area of the west wall is reduced to 0.001 m^2 instead of 0.01 m^2 is shown in Figure 9. Comparison with Figure 4, shows that by reducing the air leakage area of the west wall, zonal air humidity response is significantly altered with conditions at zones 1 and 5 remain almost unaffected while zone 3 experiences a major change in humidity behaviour. The change in behaviour is attributed to the decrease in air infiltration rate through the west wall and the increase through the east wall, which is necessary for air mass balance.

The combined influence of inter-space airflow and the building functional (i.e. indoor moisture generation) characteristics is examined by placing a moisture generating source within different zones. The moisture source is capable of generating a daily moisture profile similar to that shown in Figure 3. Placing this moisture source in zone 1 has substantially modified its air humidity behaviour both in magnitude and variational pattern as can be seen from Figure 10. The resulting air humidity behaviour is due to the combined effect of the variation of the moisture generation profile and the fluctuation in wind pressures. Since zone 5 is directly related with zone 1 through inter-space airflow, the change in behaviour of zone 1 is noticeably reflected on zone 5, while it is less noticeable for other zones. In this case, zone 3 is completely unaffected with the moisture generation in zone 1, since no outward airflow occurs from zone 5 to zone 1. Locating the moisture source in zone 5 will have a considerable local impact on air humidity, but a relatively moderate impact on other dependent zones (i.e. zones 2 and 4) as shown in Figure 11. This behaviour can be attributed to the reduced airflow rate across the airflow paths connecting zone 5 with zone 2 or zone 4 since only 50% of the air entering zone 5 will leave through either airflow path. On the other hand, by placing the moisture source in zone 2, it will have no effect on any other zone, while modifying air humidity behaviour in zone 2 to follow the same pattern of variation as the moisture generation profile as shown in Figure 12. This behaviour is obtained because no inter-space airflow occurs from zone 2 to any other zone, hence, it is a dependent zone rather than an influencing one under the present considerations.

4. CONCLUSIONS

Air humidity behaviour in multi-space buildings has been mathematically modelled by incorporating a multi-cell airflow model with a moisture mass balance model. A set of linear differential equations, each describing moisture balance at a particular space, were solved simultaneously. For solving these differential equations, airflow rate across each airflow paths must be known. A set of nonlinear algebraic equations were required to be solved simultaneously for evaluating the spacial pressure distribution and hence, evaluating the corresponding airflow rate across each flow path. A case study of air humidity behaviour in a multi-space building has revealed the importance of building air leakage and inter-space airflow characteristics in determining air humidity behaviour in a multi-space building. The response of air humidity in a particular zone for changes in ambient conditions depends on the degree and type of interaction with the outdoor environment, as well as the leakage characteristics of the inter-space airflow paths. Together, these factors determine the pressure distribution within the building and hence the rate of air infiltration and inter-space airflow. For the building under consideration, increasing the effective leakage area of the exterior walls from .01 to .04 m^2 has significantly altered the zonal air humidity response with some zones attaining almost instant moisture equilibrium with the outdoor air.

Comparison between zonal air humidity behaviours when large openings and closed doors are connecting the different zones shows that a significant reduction in zonal air humidity response will result when large inter-space openings are replaced by closed doors. In addition, moisture dependency between different zones is greatly reduced resulting in independent zonal air humidity behaviour. On the other hand, increasing the number of inter-space flow paths has resulted in greater moisture interdependence between different zones.

The interaction between the building functional and airflow characteristics will result in a unique zonal air humidity behaviour. For example, when moisture is generated within a zone which is not connected with others or the airflow pattern is such that there is no airflow from that zone to others, in this case, indoor moisture generating effect on air humidity behaviour will be local. From the above discussion, it can be clearly seen that indoor humidity behaviour in a multi-space building is greatly influenced by the airflow characteristics of the exterior building envelope, as well as, the inter-space flow paths. Furthermore, the inter-space airflow pattern combined with the building functional characteristics (i.e., indoor moisture generation) will determine the degree of moisture interaction between different zones and hence, zonal air humidity behaviour.

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TABLE 1 Building Airflow Characteristics and Indoor Moisture Generation for Different Study Cases

Case No.	Air Leakage Area, m^2				Area of Inter-Space Opening, m^2	Number of Inter-Space Openings	Indoor Moisture Generation	
	W. Wall	N. Wall	E. Wall	S. Wall			Location	Rate, kg/s
1	.01	.01	.01	.01	2	4	-	0
2	.02	.02	.02	.02	2	4	-	0
3	.04	.04	.04	.04	2	4	-	0
4	.01	.01	.01	.01	2	8	-	0
5	.01	.01	.01	.01	.00385	4	-	0
6	.001	.01	.01	.01	2	4	-	0
7	.01	.01	.01	.01	2	4	Zone 1	P
8	.01	.01	.01	.01	2	4	Zone 5	P
9	.01	.01	.01	.01	2	4	Zone 2	P

P - Indicates Moisture Generation Profile.

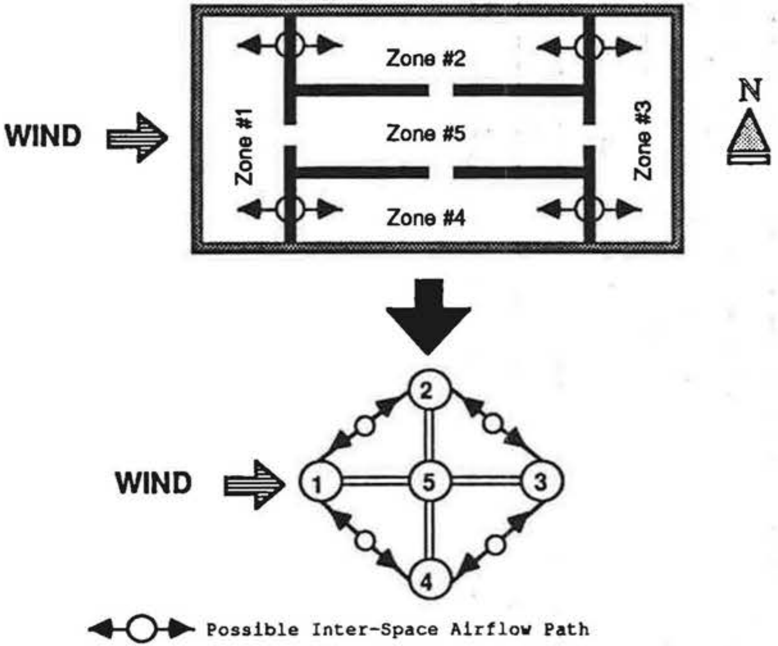

Fig.1 A Schemetic Illustrating Building Zonal Arrangement

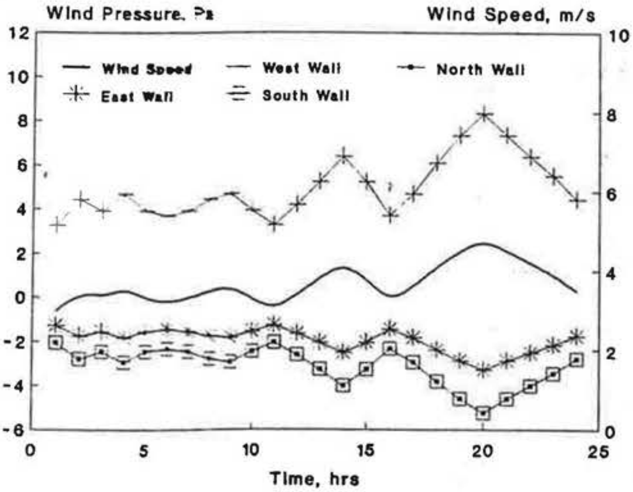

Fig.2 Average Hourly Wind Speed and Corresponding Pressures on Building Exterior Walls.

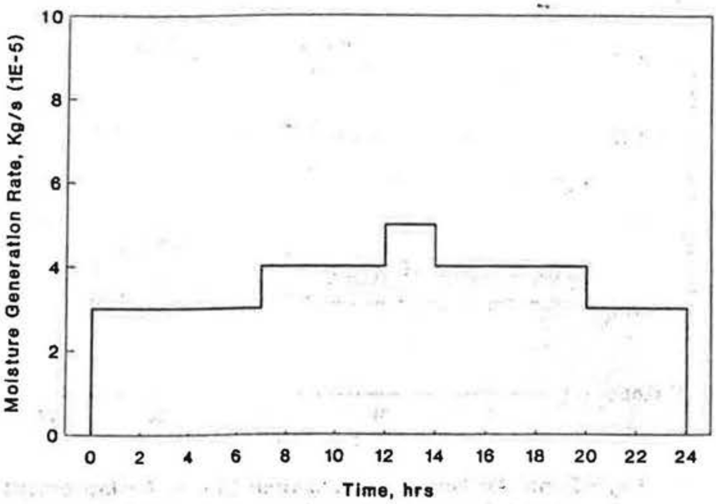

Fig.3 Indoor Daily Moisture Generation Profile

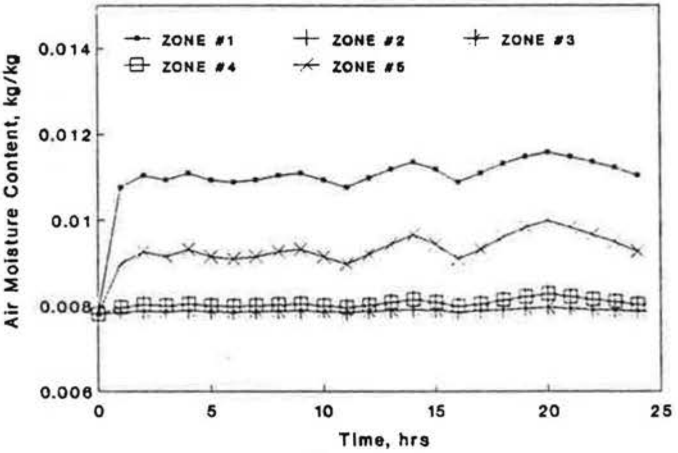

Fig.4 Zonal Air Humidity Behaviour Due to Air Movement Across Enclosure Boundaries at a Wall Leakage Area of .01 Sq. m (Case #1)

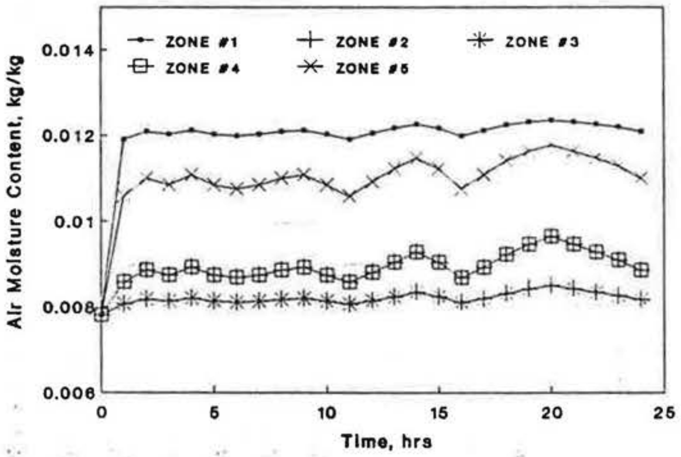

Fig.5 Zonal Air Humidity Behaviour Due to Air Movement Across Enclosure Boundaries at a Wall Leakage Area of .02 Sq. m (Case #2)

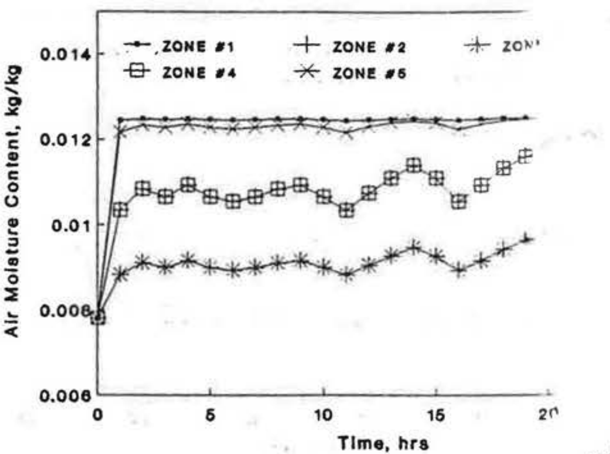

Fig.6 Zonal Air Humidity Behaviour Due to Ai
Across Enclosure Boundaries at a Wall
Area of .04 Sq. m (Case #3)

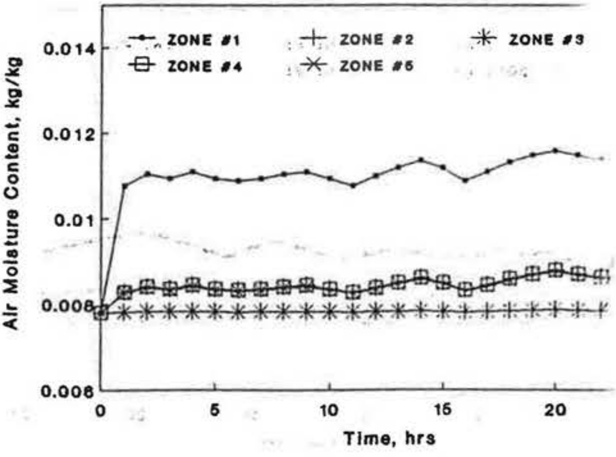

Fig.7 Zonal Air Humidity Behaviour When Spac
Connected by Eight Large Openings (Cas

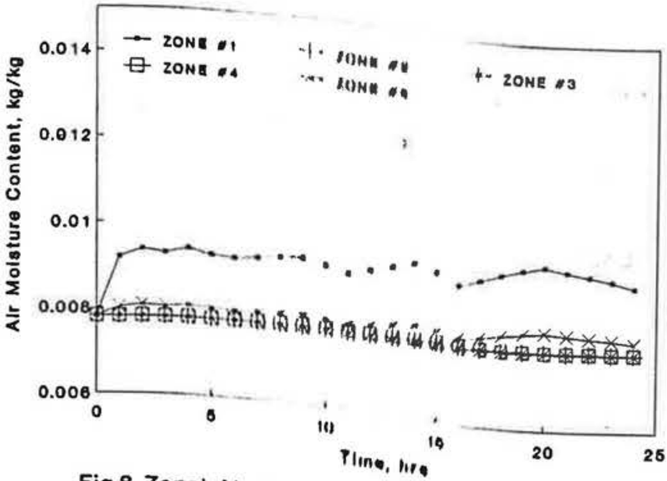

Fig.8 Zonal Air Humidity Behaviour When Space are Connected By Closed Doors With an Effective Leakage Area of .00366 Sq. m (Case #5)

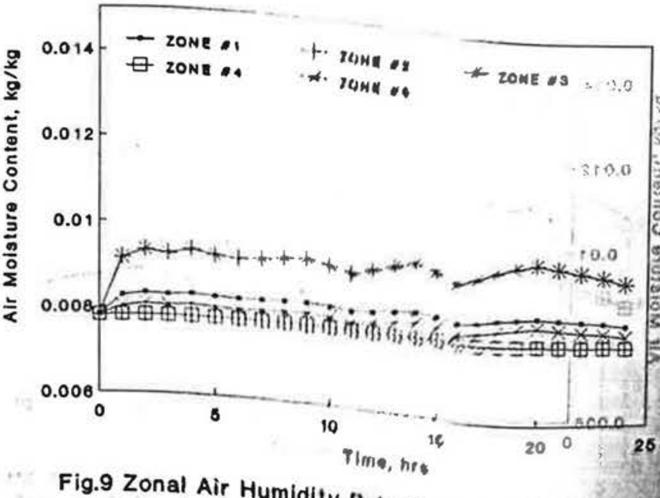

Fig.9 Zonal Air Humidity Behaviour When Exterior Walls are at Different Air Leakage Areas (Case #6)

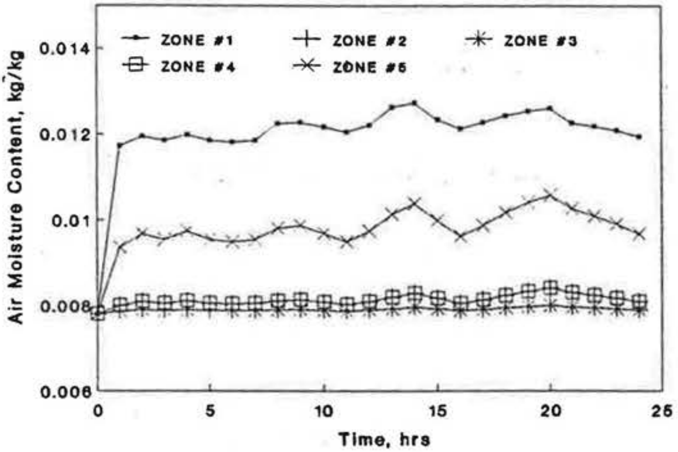

Fig.10 Zonal Air Humidity Behaviour When the Moisture Source is Located in Zone #1 (Case #7)

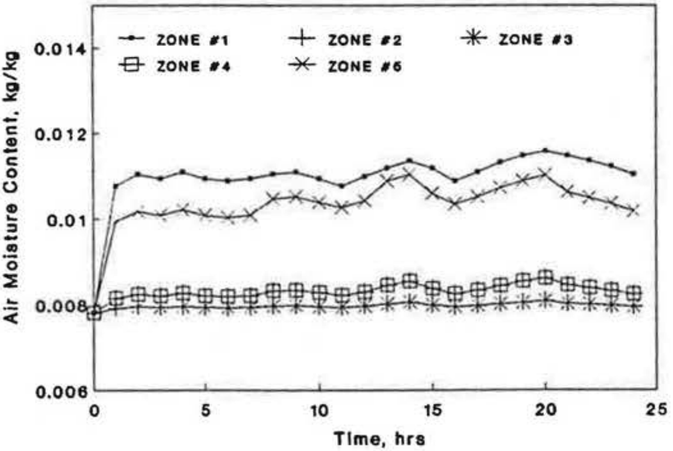

Fig.11 Zonal Air Humidity Behaviour When the Moisture Source is Located Within Zone #5 (Case #8)

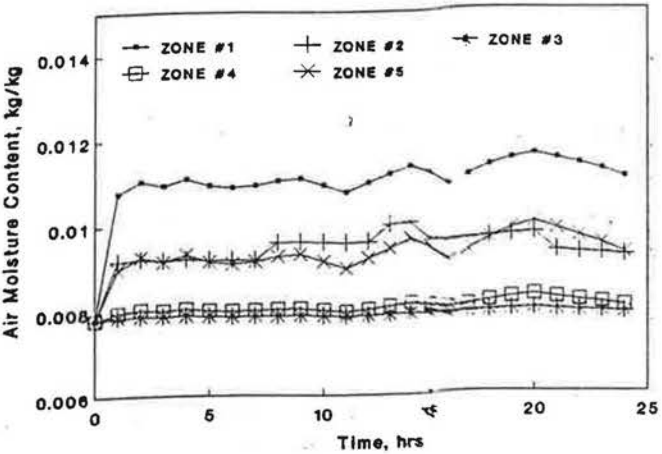

Fig.12 Zonal Air Humidity Behaviour When the Moisture Source is Located Within Zone # 2 (Case #9)