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Study of Control Strategy Using Outdoor Air to Reduce Winter Indoor Humidity in Taiwanese Apartments—Demonstrated by Ventilation Design for a Bathroom

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ABSTRACT

Dampness in residential buildings is detrimental to the health of the occupants and causes the growth of mold and decay in the fabric of the building materials. In Taiwan the average winter relative humidity is 80% and the average temperature is 15°C (59°F). It has been found that the average winter indoor moisture content in Taiwanese apartments can be higher than the outdoor content by as much as 15%. Although the main cause for the increased indoor humidity levels has not been identified, removing the moisture generated from shower baths can help reduce the humidity. This study focuses on a typical Taiwanese bathroom without windows and exhaust vents. Through an overall airflow design pattern and the utilization of the thermal buoyancy effect, the moisture generated during showers was effectively removed with less outdoor air for maintaining indoor thermal comfort. As guidelines for the design, the appropriate window and transom locations with the corresponding outdoor air supply volume, as well as the lowest possible outdoor air temperature, were identified by several computational fluid dynamics simulations.

INTRODUCTION

Background

Ventilation is needed to provide fresh air for good indoor air quality, and thermal comfort. Natural ventilation is defined as flow through intentional and unintentional openings driven by wind and thermally (stack) generated pressures. Natural ventilation, an energy conservation design strategy, has long been used for indoor thermal comfort. The main drawback of natural ventilation is lack of control, for unreliable driving forces can result in periods of inadequate ventilation followed by periods of overventilation and excessive energy waste. Despite the difficulty of control, natural ventilation is still relied upon to meet the need for fresh air in many types of buildings throughout the world (Liddament 1996).

Much of the design interest in natural ventilation arises from a desire to supplement or replace mechanical cooling rather than to provide indoor pollution control (Grimsrud 1992). Basically, the cooling effect from natural ventilation is employed to offset internal and external heat gain, to cool down the structure of a building, and to provide cooling to occupants (Ernest et al. 1991).

Limited work has been undertaken on natural ventilation as a strategy to improve indoor air quality. The common approach begins with the premise that adequate air quality will be achieved if the appropriate ventilation rates of some standards, e.g., ASHRAE 62-1989, are supplied (Grimsrud 1992). In addition, good indoor air quality can also be achieved by effective contaminant removal.

Field measurements, wind tunnel tests, and mathematical models are three frequently used techniques in natural ventilation research. Although the employment of computational fluid dynamics (CFD) modeling in building research has increased since the late 1980s (Awbi 1989), few applications of CFD modeling have been made to natural ventilation in buildings (Tsutsumi et al. 1988; Shao et al. 1993).

Statement of the Problem

Home dampness has been found to be related to allergic symptoms in asthmatic and rhinitic children (Li and Hsu 1996). In addition, moisture vapor condenses on cold surfaces where it can cause considerable damage through mold growth and fabric decay. Generally speaking, indoor moisture content is higher than the outdoor content. The higher indoor moisture content is mainly due to occupant activities such as cooking, taking showers, and washing and drying clothes.

The indoor environments of 20 apartments selected from the northern, central, and southern regions of Taiwan were examined. The indoor and outdoor relative humidity levels of these

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apartments were monitored for a 24-hour period in winter (Chou 1994; Chiang et al. 1996). The indoor position for monitoring was the living room; the outdoor position, the balcony. There were 16 cases in which either cooking or taking showers occurred while the measurements were taken. Among the 16 cases, 9 of them were monitored during sunny days. With 6 p.m. to 11 p.m. as the time frequently used for cooking and taking showers, the average indoor and outdoor humidity levels of the nine cases were 70.58% and 63.21%, respectively.

Although these field measurements were unable to identify the main contributor to the increased indoor humidity levels, two situations pertaining to Taiwanese apartments in wintertime raise the interior humidity levels. In winter a lower ventilation rate is desired to maintain indoor thermal comfort. Under this condition, less moisture generated from occupant activities can be removed. In most of the Taiwanese apartments considered, the bathroom is located between two bedrooms without direct contact with the outside. In addition, the lack of an exhaust vent in the bathroom eventually causes the moisture generated from showers to disperse throughout the entire apartment unit.

Objective of This Study

This study seeks to reduce the indoor winter humidity levels in Taiwanese apartments by removing the moisture generated by showers in a typical bathroom in which a window and an exhaust vent are absent. To maintain indoor thermal comfort, the effective removal of the moisture with less outdoor air is emphasized. To effectively remove the moisture from showers with outdoor air, the appropriate window and transom locations with the corresponding outdoor air supply volume are provided. The required outdoor air supply volume can be driven indoors by a fan when the natural driving force is insufficient. The lowest possible outdoor temperature for maintaining indoor thermal comfort is suggested.

APPROACH

Control Strategy

A bathroom space was chosen from an apartment unit (Figure 1) located in an apartment complex in Taipei. This apartment unit was one of the 20 cases investigated by Chiang et al. (1996). Since this case was monitored on a rainy day, the average indoor humidity (57.[illegible]%) for this whole day was less than the outdoor humidity (7[illegible]%) by 21%.

A control strategy, an overall airflow pattern design, is proposed to facilitate the effective removal of moisture from the bathroom to the outside during showers. The overall flow pattern (Figure 2), a scheme of the route for removal of the moisture, consists of three approaches. One is to make outdoor air accessible to the bathroom. Then, the thermal buoyancy effect is activated within the bathroom. Finally, the moisture discharged from the bathroom merges into the airstream introduced from the opening of the multipurpose space and leaves the room. The thermal buoyancy phenomenon is generated in the form of a thermal plume when a heat source is present in relatively colder and still ambient air. In such a plume, air and pollutants are moving upward, driven by the buoyancy effect. Instead of mixing with the clean air supply, the polluted air is replaced by the clean air supply by means of the thermal buoyancy effect, which effectively removes the airborne pollutants with a smaller air supply volume (Chen et al. 1988).

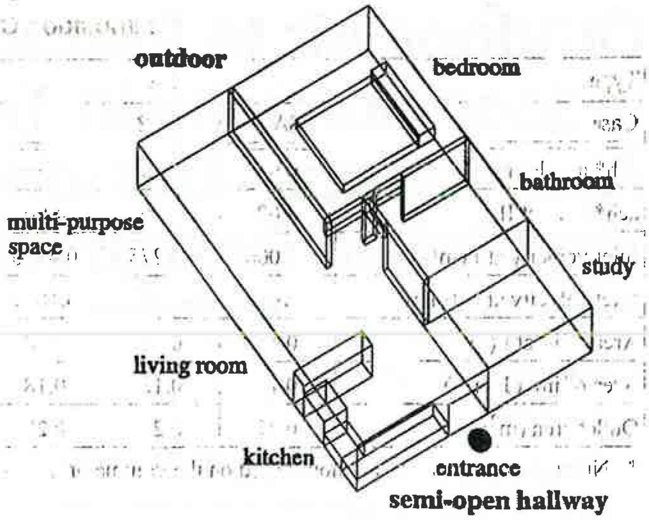

Figure 1 Apartment unit.

Based on the proposed control strategy, proper locations for windows and transoms are suggested to make the removal of moisture possible (Figure 2). To activate the thermal buoyancy effect, the inlet location should be kept lower than the heat/pollutant source and the outlet should be kept high. During showers, the door of the bedroom should be kept closed to ensure the outdoor air supply is accessible to the bathroom.

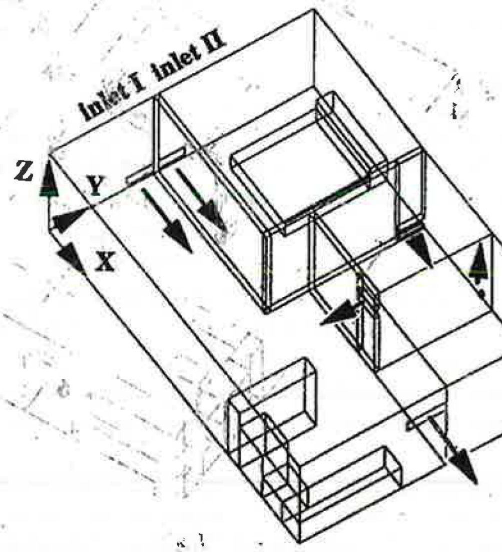

Figure 2 Overall airflow design pattern and the locations of windows and transoms.

TABLE 1
Simulation Cases for Bathroom

Type	SA			SB					
Case	SA-1	SA-2	SA-3	SB-1	SB-2	SB-3	SB-4	SB-5	SB-6
ach* at inlet I	0.00	1.00	16.00	1.00	2.00	8.00	16.00	0.50	0.25
ach* at inlet II	4.00	4.00	4.00	4.00	4.00	4.00	4.00	2.00	1.00
Inlet velocity at I (m/s)	0.0000	0.0275	0.4396	0.0069	0.0137	0.0549	0.1099	0.0034	0.0017
Inlet velocity at II (m/s)	0.1099	0.1099	0.1099	0.1099	0.1099	0.1099	0.1099	0.0549	0.0275
Area of inlet I (m^2)	0.18	0.18	0.18	0.72	0.72	0.72	0.72	0.72	0.72
Area of inlet II (m^2)	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Outlet area (m^2)	0.27	0.27	0.27	0.99	0.99	0.99	0.99	0.99	0.99

* Number of air changes per hour based on the volume of the bathroom.

Design Parameters

There are two focuses involved in this design. The first one is to activate a thermal buoyancy effect in the bathroom to make the removal of moisture from the bathroom successful. The second one is to resolve the influences from the interaction between the two streams from inlets I and II on the evacuation of moisture. Therefore, the parameters examined are the outdoor air supply volume from inlets I and II, the size of inlet I/outlet, and the outdoor temperature. To evaluate various design parameters for effectiveness of moisture removal and indoor thermal comfort, nine cases are examined (Table 1 and Figure 3) by several computational fluid dynamics simulations.

Computational Fluid Dynamics Simulation

The domain and the dimensions for the simulations are shown in Table 2. The heat generated from showers is 185 W (631.405 Btu/h). The moisture emission rate from showers is $1.24¥10^{-3}$ m^3/s (1.24 L/s). No storage of moisture in the interior furnishings and no condensation on walls are considered in the simulations. The moisture content in the air is expressed by the mass of moisture in the air divided by the mass of air. The room temperature, 15°C (59°F), was considered to be 2°C (3.6°F) higher than the outdoor temperature. All simulations are conducted in three dimensions in 38 by 30 by 23 cells in which all walls were treated as adiabatic.

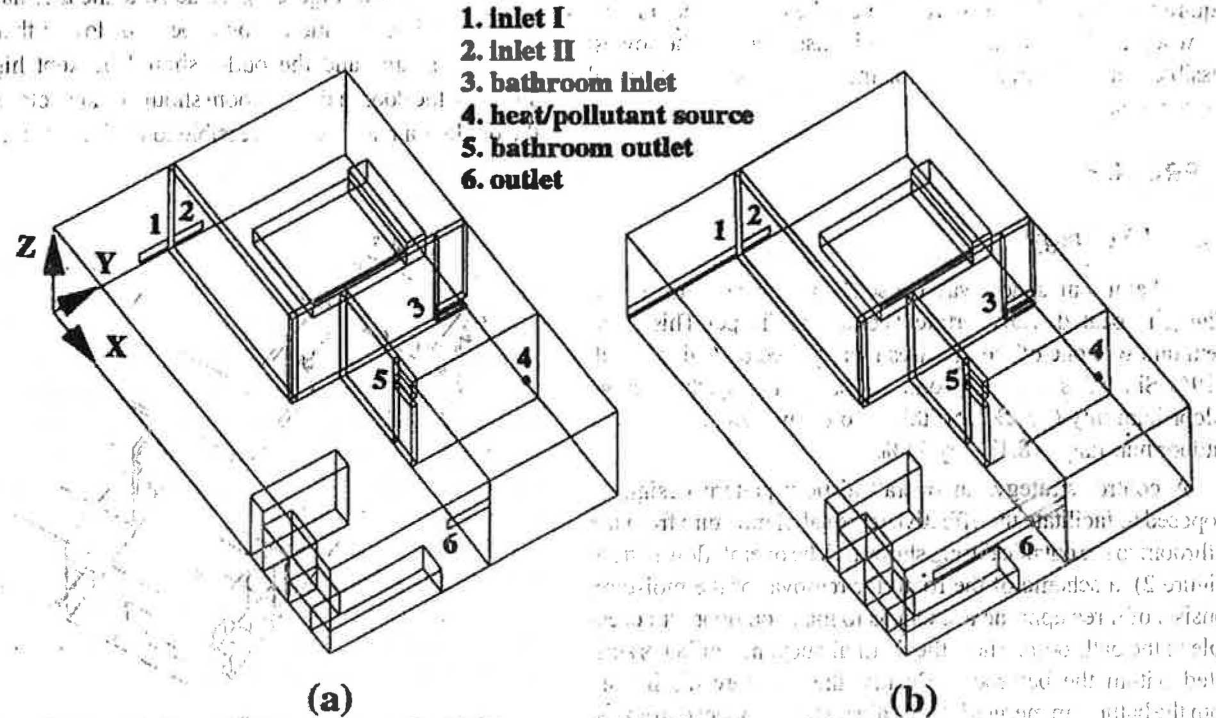

Figure 3 Two cases, (a) SA and (b) SB.

TABLE 2
Dimensions and Locations of Openings and the Heat/Pollutant Source

Dimension (m)	X	Y	Z
Space	8.74	6.12	3.00
Inlet I of SA	0.00	0.60	0.30
Inlet II of SA	0.00	0.60	0.30
Inlet I of SB	0.00	2.40	0.30
Outlet of SA	0.00	0.90	0.30
Outlet of SB	0.00	1.80	0.30
Heat/pollutant source	0.10	0.10	0.10
Location* (m)	**X**	**Y**	**Z**
Inlet I of SA	0.00	1.80	0.10
Inlet II of SA	0.00	2.52	0.10
Inlet I of SB	0.00	0.00	0.10
Outlet of SA	8.74	2.52	2.10
Outlet of SB	8.74	0.60	2.10
Heat/pollutant source	6.02	5.92	0.50

* Measured from the origin to the lower left corner of the object, viewed from the direction of outlet.

Turbulence models are often needed in computational fluid dynamics modeling to make the conservation equations solvable with the present capacity and power of computers. Most turbulence models are developed for specific flows. Therefore, a turbulence model may work excellently for one case but poorly for another. The turbulence model applied in this study is the renormalization group *k*-e model (Yakhot et al. 1992), which is more advanced in predicting the thermal buoyancy effect (Chen and Chao 1996) than the other two eddy-viscosity models, i.e., the standard *k*-e model (Launder and Spalding 1974) and the modified *k*-e model (Malin and Younis 1990). This renormalization group *k*-e model has the same form as the standard *k*-e model, except for the model coefficients. The model coefficients in the renormalization group *k*-e model are:

$$(\delta_k, \delta_\varepsilon, C_{1\varepsilon}, C_{2\varepsilon}, C_\mu) = (0.7194, 0.7194, 1.42, 1.68, 0.0845). \quad (1)$$

In addition, the dissipation-rate transport equation has an additional source term, *R*:

$$R = \frac{C_\mu \eta^3 (1 - \eta/\eta_0)\varepsilon^2}{1 + \beta\eta^3} \frac{}{k} \quad (2)$$

where h_0 = 4.8, b = 0.012, and the dimensionless parameter, h, is defined by

$$\eta = S\frac{k}{\varepsilon},\ S = (2S_{ij}S_{ij})^{1/2},\ S_{ij} = \frac{1}{2}(U_{i,j} + U_{j,i}) \quad (3)$$

The computations are conducted by the airflow program developed by Spalding (1994). This code has several routines accessible to users. Therefore, users are able to modify the codes on the basis of their needs. The governing equations are solved in the finite-volume method with a staggered grid system. A hybrid scheme is used for the numerical solution. The algorithm employed is SIMPLEST (Spalding 1994). As a convergence criterion, the sum of the normalized absolute residuals in each control volume for all calculated variables should be maintained at less than 10^{-3}. To prevent the numerical solution process from oscillating or diverging, three methods are used. They are under-relaxation for the continuity equation, false time-steps for the other dependent variables, and source-term manipulation that treats positive source terms explicitly and negative source terms implicitly. A non-uniform mesh system is used with the finer mesh located in the near-wall region or the place with a large gradient of variables.

Evaluation Models

To assess the performance of each design option, indoor thermal comfort and the level of moisture content are two criteria to be evaluated. Indoor thermal comfort is evaluated using both Fanger's Predicted Mean Vote (Fanger 1982) and his draft risk model (Fanger et al. 1988). The Predicted Mean Vote is determined by three personal parameters and four environmental parameters. The three personal parameters are metabolism, external work, and clothing insulation. The four environmental parameters are air temperature, mean radiant temperature, mean air velocity, and partial water vapor pressure. The draft risk model is a function of mean air velocity, turbulence intensity, and air temperature. To obtain a 90% level of satisfaction in thermal comfort, the value of the PMV should be kept between -0.5 and +0.5. A 15% or lower level of dissatisfaction in draft risk is desirable. The level of moisture content is evaluated at the average indoor moisture content. A low average indoor moisture content indicates an effective removal of moisture.

Two zones (Figure 4) are chosen for the evaluation, namely, the living/kitchen zone (I) and the bathroom zone (II). Average thermal comfort indices and moisture content are calculated in these two zones. The dimensions for zones I-1, I-2, and I-3 are 6.22 m by 2.4 m by 3.0 m (20.41 ft by 7.87 ft by 9.84 ft), 4.82 m by 0.9 m by 3.0 m (15.81 ft by 2.95 ft by 9.84 ft), and 1.52 m by 1.8 m by 3.0 m (4.99 ft by 5.91 ft by 9.84 ft), respectively. The dimensions for zone II are 2.3 m by 2.58 m by 3.0 m (7.55 ft by 8.46 ft by 9.84 ft). The metabolic rate considered in zone I is 50 kcal/h·m^2, simulating a sitting person. Typical business dress, a cotton shirt and trousers, is considered in zone I. The metabolic rate considered in zone II is 90 kcal/h·m^2, simulating a person taking a shower in the nude.

RESULTS AND DISCUSSION

Various Outdoor Air Supply Volumes Applied to the Smaller Inlet I/Outlet

This section investigates the influences of the outdoor air supply volume from the smaller inlet I on the ease of removing moisture from the bathroom to the outside. The outdoor air

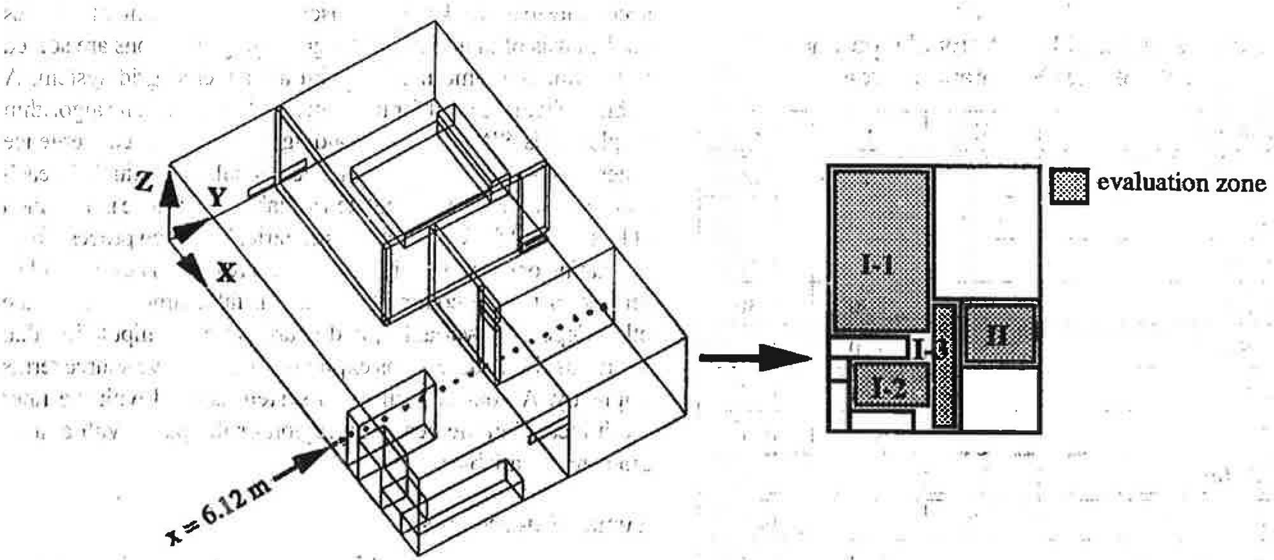

Figure 4 *Zones for evaluation.*

TABLE 3
Impacts of Various ACHs from Smaller Inlet I

Type	SA		
Case	SA-1	SA-2	SA-3
Thermal comfort in zone I (PMV)	-0.539	-0.552	-0.692
Thermal comfort in zone II (PMV)	2.213	2.213	2.213
Draft risk in zone I (%)	0.177	0.238	4.626
Draft risk in zone II (%)	3.891	3,891	3.890
Moisture content* in zone I	5.991×10^{-2}	2.793×10^{-2}	7.075×10^{-3}
Moisture content* in zone II	2.833×10^{-2}	2.833×10^{-2}	2.887×10^{-2}

* kg-moisture/kg-air.

supply volume is expressed by the number of air changes per hour (ACH). With a fixed ACH from inlet II, three cases with varying ACHs from 0 to 16 are examined (Table 3).

From Table 3 one can observe that the moisture content levels achieved in zone II for all three cases are similar. The moisture content level in zone I decreases with an increasing ACH from inlet I. From Figure 5 one can see that a larger air supply volume from inlet I forces the discharged moisture from the bathroom into the ceiling area of zone I, the living/kitchen space. In addition, the strong inflow from inlet I hinders the discharge of moisture from zone II, the bathroom. This situation can be observed in Figure 5c, where contour line 4 does not extend from zone II to zone I as depicted in Figure 5b. Since the hindrance from the inflow from inlet I imposed on the discharge of moisture from the bathroom is not prominent, one can observe only slight differences in the moisture content in zone II from Table 3. With zero inflow from inlet I (case SA-1), the discharged moisture from the bathroom is difficult to remove from the living/kitchen space to the outside. This situation can be observed in Figure 5a, where a high level of moisture content is achieved in zone I. From the above results and discussion, one can see that both no-inflow and high-inflow rates from inlet I cause an accumulation of moisture in either the living/kitchen space or the bathroom.

The thermal comfort level in the bathroom (zone II) for all three cases is the same and appears slightly hot. The thermal comfort level in zone I decreases with the increasing inflow rates. Case SA-3, with the largest inflow volume, achieves an 84% level of satisfaction in thermal comfort. In all three cases the percentages of dissatisfaction due to drafts are well below 15%, a desirable criterion.

Various Outdoor Air Supply Volumes Applied to the Larger Inlet I/Outlet

This section investigates the influences of the outdoor air supply volume from the larger inlet I on the ease of removing moisture from the bathroom to the outside. With a fixed ACH from inlet II, four cases with varying ACHs from 1 to 16 are examined (Table 4).

By comparing Tables 3 and 4, one can discover similar trends. In zone I the level of the moisture content decreases with the increasing ACH from inlet I. The lower level of the moisture content in zone I, the living/kitchen space, of case SB-4 is caused by a larger air supply volume from inlet I. This phenomenon can also be seen in Figure 6. In addition, this strong inflow from inlet I imposes a hindrance on the discharge of moisture from the bathroom. This situation can be observed by comparing Figure 6a with Figures 6b, 6c, and 6d. Contour line 4 is pushed back further to the bathroom when the air supply volume from inlet I becomes larger. Since the hindrance is not pronounced, one can observe only slight differences in the moisture content in zone II in Table 4.

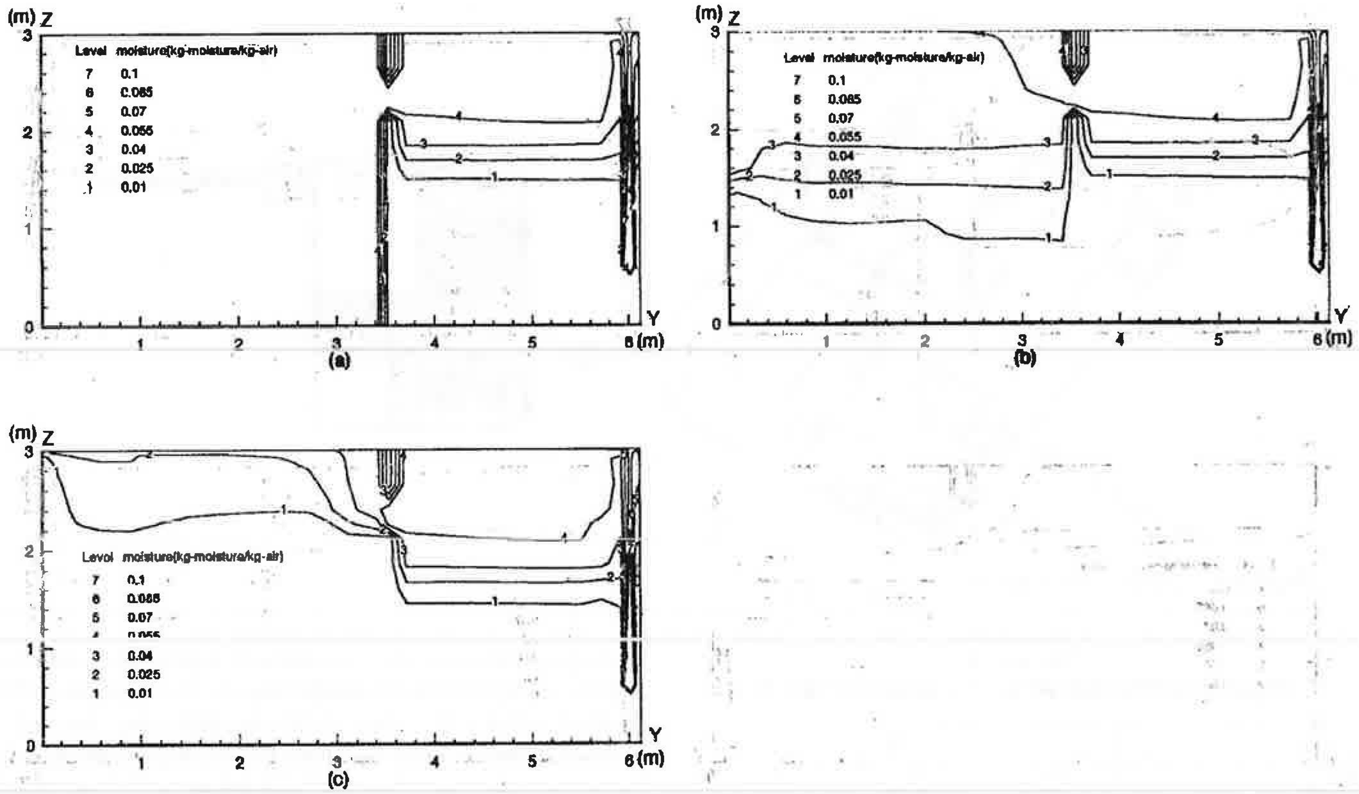

Figure 5 *Distribution of moisture at x = 6.12 m of case (a) SA-1, (b) SA-2, and (c) SA-3.*

TABLE 4
Impacts of Various ACHs from Larger Inlet I

Type	SB			
Case	**SB-1**	**SB-2**	**SB-3**	**SB-4**
Thermal comfort in zone I (PMV)	-0.555	-0.566	-0.635	-0.697
Thermal comfort in zone II (PMV)	2.213	2.213	2.213	2.213
Draft risk in zone I (%)	0.156	0.174	0.804	2.248
Draft risk in zone II (%)	3.891	3.890	3.898	3.887
Moisture content* in zone I	2.723¥10^{-2}	1.967¥10^{-2}	1.117¥10^{-2}	6.786¥10^{-3}
Moisture content* in zone II	2.836¥10^{-2}	2.832¥10^{-2}	2.848¥10^{-2}	2.841¥10^{-2}

* kg-moisture/kg-air.

The thermal comfort level in zone II for all four cases is the same and appears as slightly hot. The thermal comfort level in zone I decreases with an increasing inflow rate. Case SB-4 with the largest inflow volume achieves an 84% level of satisfaction in thermal comfort. For all four cases, the percentage of dissatisfaction due to drafts is well below 15%, a desirable criterion.

Dimensions of Inlet I/Outlet

This section investigates the influences of the size of inlet I/outlet on the ease of removing moisture from the bathroom to the outside. Two kinds of inlet I/outlet sizes are examined. For each size, two kinds of ACHs from inlet I are discussed (Table 5).

Concerning indoor air quality, the performance of cases SA and SB is similar when the inflow volume from inlet I is small. For a higher inflow rate, the case with a larger inlet I/outlet (case SB-4) obtains a slightly lower level of moisture content in both zones I and II compared to the case with a smaller inlet I/outlet (case SA-3). Besides, the draft risk in zone I of case SB-4 is lower than that of case SA-3. The possible explanation is that the larger inlet I has a lower inlet velocity and a more even distribution of air supply in the living/kitchen space than the smaller inlet case, which enables a more effective removal of moisture from the living/kitchen space to the outside and obtains a lower level of draft risk in this space. Also, the larger inlet I and its smaller inlet velocity impose less hindrance, thereby making the removal of moisture from the bathroom slightly easier.

The thermal comfort performance for cases SA and SB is similar. The thermal comfort level in zone I is neutral and slightly hot in zone II. For all four cases, the percentage of dissatisfaction due to draft is well below 15%, a desirable criterion.

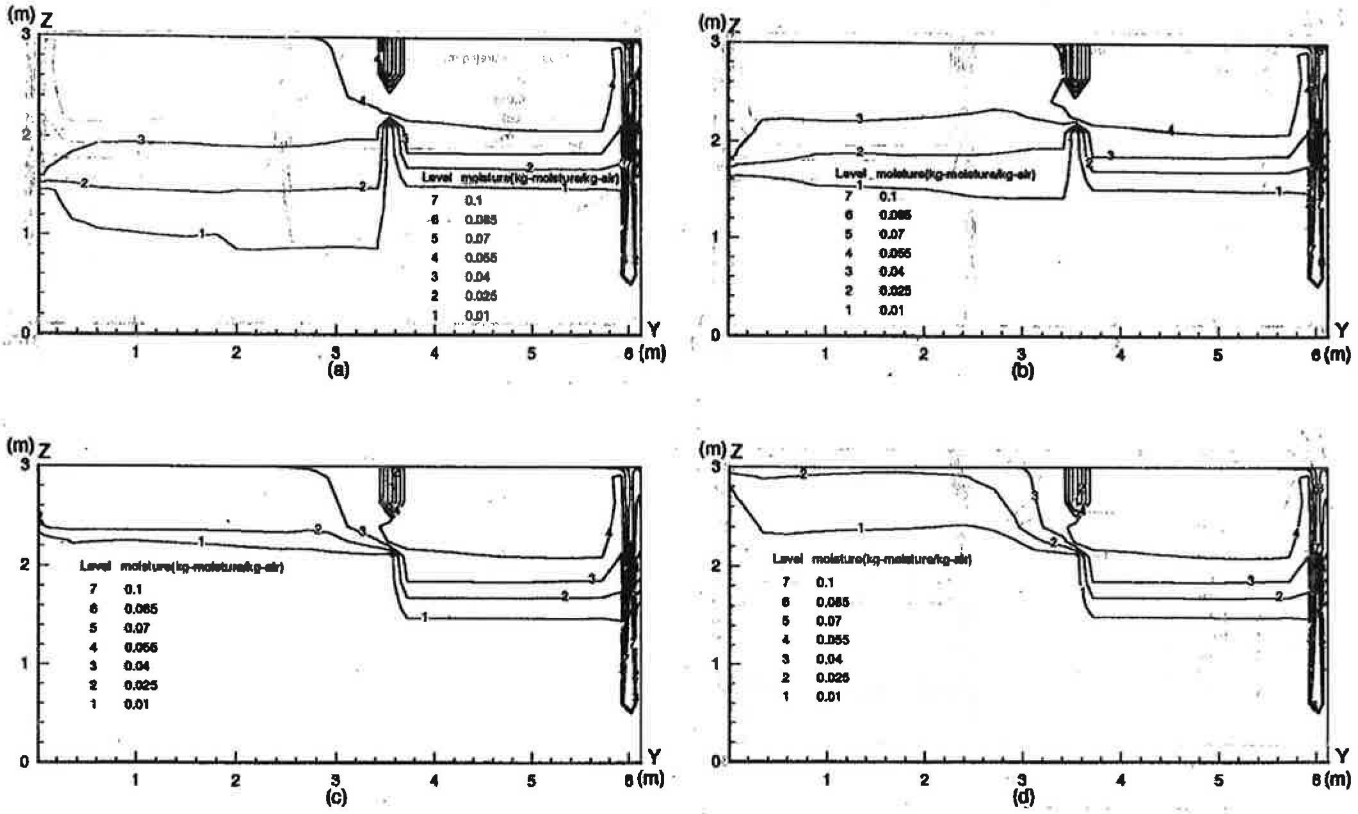

Figure 6 Distribution of moisture at x = 6.12 m of case (a) SB-1, (b) SB-2, (c) SB-3, and (d) SB-4.

TABLE 5
Impacts of the Dimensions of Inlet I and Outlet

Type	SA		SB	
Case	SA-2	SA-3	SB-1	SB-4
Thermal comfort in zone I (PMV)	-0.552	-0.692	-0.555	-0.697
Thermal comfort in zone II (PMV)	2.213	2.213	2.213	2.213
Draft risk in zone I (%)	0.238	4.626	0.156	2.248
Draft risk in zone II (%)	3.891	3.890	3.891	3.887
Moisture content* in zone I	2.793¥10^{-2}	7.075¥10^{-3}	2.723¥10^{-2}	6.786¥10^{-3}
Moisture content* in zone II	2.833¥10^{-2}	2.887¥10^{-2}	2.836¥10^{-2}	2.841¥10^{-2}

* kg-moisture/kg-air.

Various Outdoor Air Supply Air Volumes Applied to Inlet II

This section investigates the influences of the outdoor air supply air volume from inlet II on the ease of removing moisture from the bathroom to the living/kitchen space. According to the previous results, the case with a larger inlet I/outlet and an inflow ratio of 0.25 between the inflow rates from inlets I and II is adopted in the investigation for its good performance in moisture removal and indoor thermal comfort. Three cases are examined, and the air supply volumes considered from inlet I are 0.25 ACH, 0.5 ACH, and 1 ACH (Table 6).

From Table 6 one can observe that the level of the moisture content in both zones increases with the decreasing ACH from inlet II. This situation can also be observed in Figure 7. From Figure 7a to 7c the stratified contour lines in both zones descend with a decreasing ACH from inlet II, which indicates a gradual accumulation of moisture in both zones. The high accumulation of moisture is caused by an insufficient air supply volume from inlet II, which results in a poorly developed thermal plume, thereby making the removal of moisture difficult (Figures 7b and 7c).

The performance in thermal comfort for all three cases is very similar. The thermal comfort level in zone I is neutral and slightly hot in zone II. For all cases, the percentage of dissatisfaction due to drafts in the two zones is well below 15%, a desirable criterion.

Outdoor Temperature

This section discusses the impact of outdoor temperature on indoor thermal comfort (Table 7). Case SB-1 is selected for this examination for its best performance in removing moisture from both zones while maintaining indoor thermal comfort. The influence of a decreasing outdoor air temperature on the thermal

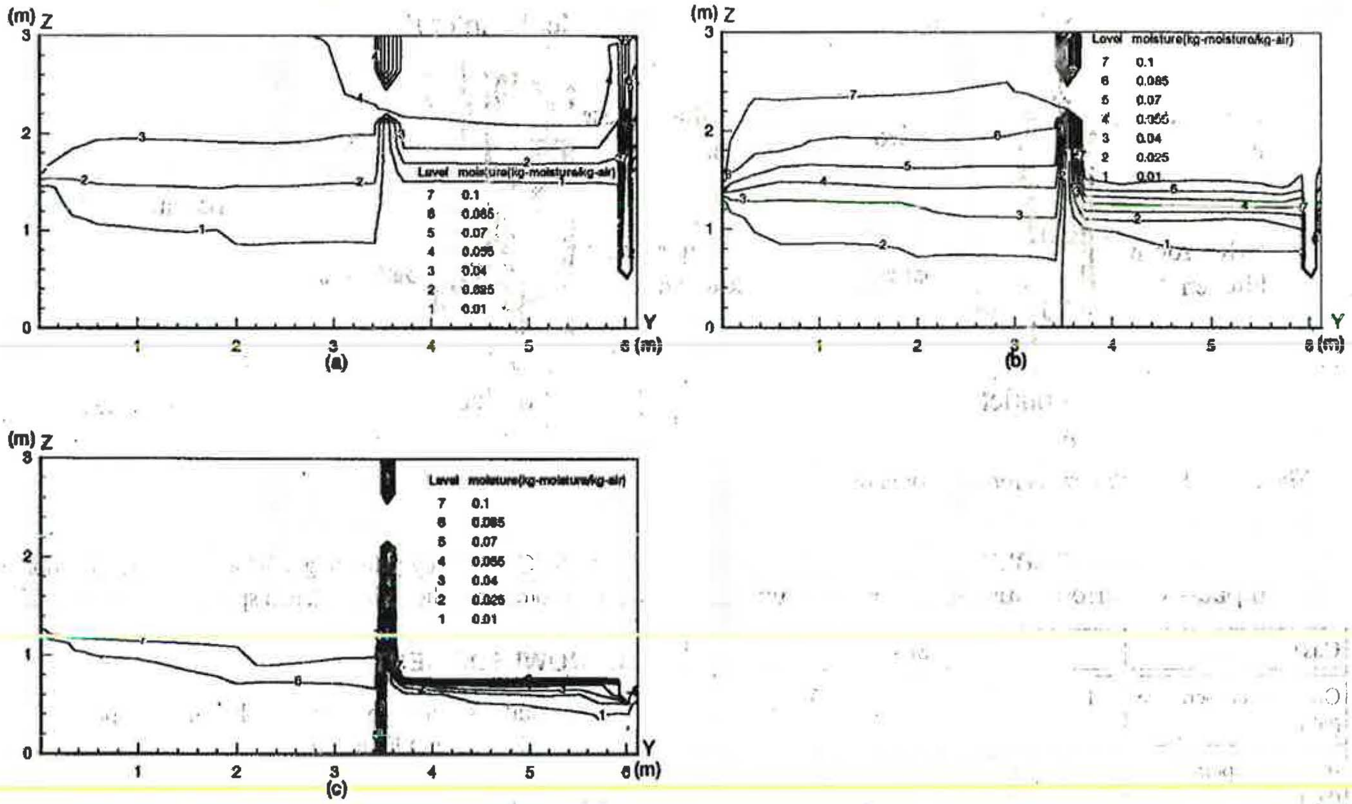

Figure 7 *Distribution of moisture at x = 6.12 m of case (a) SB-1, (b) SB-5, and (c) SB-6.*

TABLE 6
Impacts of Various ACHs from Inlet II

Type	SB		
Case	SB-1	SB-5	SB-6
Thermal comfort in zone I (PMV)	-0.555	-0.551	-0.550
Thermal comfort in zone II (PMV)	2.213	2.215	2.216
Draft risk in zone I (%)	0.156	0.112	0.066
Draft risk in zone II (%)	3.891	3.209	3.312
Moisture content* in zone I	2.723¥10^{-2}	5.867¥10^{-2}	1.360¥10^{-1}
Moisture content* in zone II	2.836¥10^{-2}	6.733¥10^{-2}	1.575¥10^{-1}

* kg-moisture/kg-air

comfort level in zone II is very small. Although it is slightly cold in zone I, by achieving a 50% level of satisfaction at an outdoor temperature of 10°C (50°F), such a low temperature is still applicable if a short period for ventilation is considered. The percentage of dissatisfaction due to drafts in the two zones for all cases is well below 15%, a desirable criterion.

CONCLUSIONS

The objective of this study was to reduce the winter indoor humidity levels in a Taiwanese apartment by removing the moisture generated by showers in the bathroom. The key issue was to maintain the indoor thermal comfort by the effective removal of the moisture with less outdoor air, rather than the conventional approach of dilution. To facilitate the effective removal of moisture, two approaches were proposed: an overall airflow pattern design and the utilization of the thermal buoyancy effect. Two focuses were involved in the approaches. One was to successfully activate a thermal buoyancy effect within the bathroom. The other was to resolve the influences from the interaction between the two streams from inlets I and II on the evacuation of moisture. As guidelines for the design, the appropriate window and transom locations with the corresponding air supply volume, as well as the lowest possible outdoor air temperature, were identified through the examination of computational fluid dynamics simulations.

To conclude the bathroom design, two flow diagrams (Figure 8) were used. Diagram A (cases SA-1 and SB-1) represents a more favorable design in which less hindrance is imposed on the discharge of moisture when a small inflow volume is applied to inlet I. When the inflow volume from inlet I increased, more hindrance was imposed on the discharge of moisture. Diagram B (cases SA-2, SA-3, SB-2, SB-3, and SB-4) presents

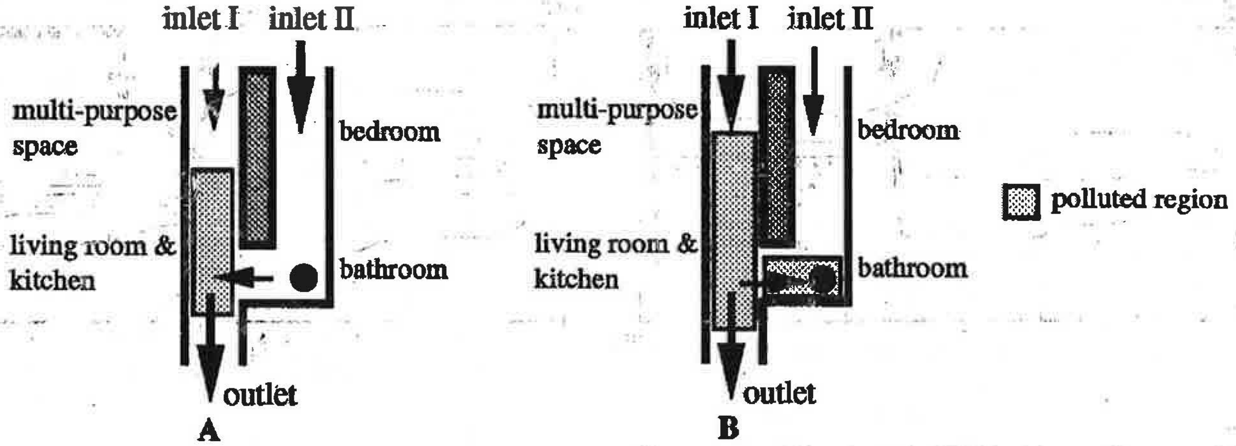

Figure 8 *Flow diagrams for bathroom design.*

TABLE 7
Impacts of Various Outdoor Temperatures

Case	SB-1				
Outdoor temperature (°C)	10.	11.	12.	13.	14.
Indoor temperature (°C)	12.	13.	14.	15.	16.
Thermal comfort in zone I (PMV)	-1.471	-1.288	-1.105	-0.921	-0.738
Thermal comfort in zone II (PMV)	2.189	2.194	2.199	2.204	2.208
Draft risk in zone I (%)	0.199	0.190	0.182	0.173	0.164
Draft risk in zone II (%)	5.038	4.808	4.579	4.349	4.120

the situation of removing moisture with difficulties. In addition, the air supply volume from inlet II should not be lower than 3 ACH. The low inflow rate causes an underdeveloped thermal plume, which makes the removal of moisture difficult. A large inlet I obtains a slightly lower level of moisture content in the living/kitchen zone than a small inlet by yielding a more uniform air distribution there and imposing less hindrance on the discharge of moisture from the bathroom. In this study the adopted ratio between the air supply volumes from inlet I and inlet II was 1 to 4, which is roughly the ratio between the volume of the bathroom and the volume outside the bathroom, including the multipurpose space plus the living/kitchen space.

It was found feasible to reduce the winter indoor humidity levels in a typical Taiwanese apartment with outdoor air. The thermal comfort level in the bathroom during showers appeared slightly hot, even when the air supply temperature was 10°C (50°F). However, the thermal comfort level in the space outside the bathroom appeared slightly cold when the air supply temperature was lower than 13°C (55.4°F). When a short period for ventilation was considered, the outdoor temperature could be as low as 10°C (50°F) by achieving a 50% level of satisfaction in thermal comfort in the living/kitchen space.

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