Cross-ventilation Utilization in Housing in Congested Urban Areas in Taiwan

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Abstract
This research aims to investigate the current condition regarding ventilation use in congested urban areas of Taiwan. There is a remarkably high level of humidity and dense populations in many housing areas. The study targeted terraced houses, which are the most common style of housing in urban Taiwan. The current study attempted to understand the thermal environments of residential buildings as well as utilization of the cross-ventilation system. This was achieved by combining data of the current weather conditions and a questionnaire survey of those tested. Also included in the testing was a series of wind tunnel experiments conducted to examine the issues related to the ventilation flow rates of these congested areas. Following that testing, ventilation improvement techniques were proposed and studied for ways to decrease the negative environmental impact from over-use of air conditioners. The results calculated by simulation software demonstrated that through the use of our roof top designed component for air circulation, the heat removal decreased by 16% annually, compared to current condition.

Keywords: cross-ventilation; wind tunnel experiments; questionnaire; wind tower; Taiwan

1. Introduction
Taiwan has the second largest population density in the world among countries or regions with 10 million people or more, which tends to be steady due to the decreased birthrate over the past several years. However, the population remains concentrated in the cities rather than rural areas due to convenience and modernization. Because of the overcrowded population, increased energy consumption causes thermal environment problems, including the heat island phenomenon. Coolers are used frequently in Taiwan due to its high temperatures and humidity. This has contributed to increased energy consumption and become a big concern. In fact, the possession rate of coolers in the country has increased from 52% in 1991 to 85% in 2003 and the rate is more than 90% in the urban areas. Moreover, the energy consumption from cooler utilization in general housing is increasing every year. Accordingly, it becomes crucial to develop techniques that can diminish excessive energy consumption. Based on the study conducted by Chou and his colleagues (2000), the period during which residents are able to use cross-ventilation is quite long in Taiwan, therefore it is reasonable to expect the use of cross-ventilation as an alternate and effective way to overcome the disadvantage brought by cooler utilization. Indeed, some studies have investigated utilization of cross-ventilation in Taiwan; however, they tended to focus on middle or high rise buildings (Chen et al., 2001). Moreover, some studies did attempt to investigate the utilization of cross-ventilation in low-rise buildings, which are more common in the country, by using only single house models (e.g., Chou, 1995). To date, there is no study investigating issues associated with the utilization of cross-ventilation in low-rise buildings that factors in the surrounding congested buildings in the area. Thus, the current study aims to investigate issues related to the utilization of cross-ventilation in terraced houses, which are the most common style of low-rise housing in Taiwan's urban areas.

2. Weather conditions in Taiwan
The ventilation capable hours according to weather conditions were based on SET*, which was calculated from the standard weather data during the years 1992 to 2001. Besides temperature and humidity obtained from the standard weather data, air velocity with stagnant flow was maintained at 0.13m/s. Clothing level altered between 0.4 and 0.9 during summertime
and wintertime respectively. Reports indicate that it is capable to use natural ventilation for cross-ventilation while SET* is in from 22.2 – 25.6 °C (Gagge, 1971).

The authors' data shows that the velocity of the wind during the non-ventilation capable hours was slower than the ventilation capable hours. The average wind velocity during the ventilation capable hours of the whole country was 2.1m/s. The authors then divided the 14 main cities in Taiwan into four groups based on their average cumulative distribution frequency (i.e., CDF) of the wind velocity of all the cities, (Fig.1. and Table 1.).

![Fig.1. Cumulative Distribution Frequency of the Wind Velocity during Ventilation Capable Hours](image)

Table 1. Characteristics of Cities Based on CDF of the Wind Velocity

<table>
<thead>
<tr>
<th>CDF of the Wind Velocity</th>
<th>City name</th>
<th>Wind velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I &gt;90%</td>
<td>Taichung (TC)</td>
<td>Very low</td>
</tr>
<tr>
<td>II 70% ~ 90%</td>
<td>Taitung (TT)</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Chiayi (CY)</td>
<td></td>
</tr>
<tr>
<td>III 50% ~ 70%</td>
<td>Kaohsiung (KS), Tamsui (TS), Tainan (TN), Keelung (KL), Hualien (HL), Taipei (TP), Hsinchu (SC)</td>
<td>Medium</td>
</tr>
<tr>
<td>IV &lt;50%</td>
<td>Hengchun (HC), Wuchi (WC), Penghu (PH)</td>
<td>High</td>
</tr>
</tbody>
</table>

3. Characteristics of Houses in Taiwan and the Questionnaire Survey Regarding Residents' Consciousness Concerning Cross-ventilation

It is crucial to use questionnaire surveys because they serve as an effective way for the researchers to gather information about local residents' concerns, lifestyles, and unit plan preferences. These factors affect residents' utilization of cross-ventilation.

The questionnaire survey has three specific aims. First, the authors aim to understand the opening characteristics in Taiwan. Second, they wish to gather information regarding ventilation utilization during late autumn (i.e., October and November). It is predicted that the rate of ventilation use should be higher during the ventilation capable period, in contrast to the non-ventilation capable period based on the authors' previous analysis of the meteorological data. Finally, the author wish to investigate air-conditioning usage behavior, including when residents begin and stop using it (i.e., ending time) as well as the preset degrees of the air-conditioning systems in residents' living rooms or bedrooms during summer time.

3.1 Outline of investigation

In cooperation with other researchers, data from the questionnaire survey was collected mainly from college students in Taiwan. The outline of the investigation can be found in Table 2.

3.2 Characteristics of opening and closing openings

The results suggest that over 90% of residents have double sliding windows or terrace doors, while over 80% have window screens regardless of regions or house style, as shown in Figs.2. and 3. Thirty five percent of the terraced houses have grilles in their windows and 48% of housing complexes have similar equipment. In addition, when asked "Did you open or close windows during this summer?" 10% answered that they closed windows and 38% that they opened windows all day long. Furthermore, the number who open windows when they are at home becomes 65% or higher. Fig.4. demonstrates the differences between the residents' responses and the data analyzed from the meteorological information in Taipei. It describes which months of a year the residents feel they can use the cross-ventilation (i.e., ventilation capable period). This suggests that residents' subjective feelings concerning temperature and humidity differ from the meteorological data. The relationship between the questionnaire results and the meteorological data are very similar from May to October. The possible explanation for the discrepancy during winter is that people in Taiwan do not typically use heating systems during the winter season.

3.3 Features of air conditioning system use

The results indicate that 64% of participants used coolers and 66% used fans during the summer. The average duration of cooler usage was approximately 110 days in 2003, and became longer when moving from north to south. In Taipei (a northern city), residents mainly began using their coolers in June whereas in Taichung (a city in mid-Taiwan) and Kaohsiung (a southern city), it was in July. Taipei and Taichung residents stopped using them in September and Kaohsiung residents in October. In addition, the results show that the average preset temperature in the living room was 25.0°C, while in the bedroom it was 25.3°C.

3.4 Residents' satisfaction with the indoor air environment

Approximately 70% of residents feel dissatisfied with the air environment in contrast to the environment as a whole. Moreover, people who live on the fifth floor or below complained more because they felt the indoor wind velocity was low. Fig.5. indicates that the problem becomes more remarkable when the building
is low and should be investigated further via wind tunnel experiments.

4. Selection of Type of Houses for Further Investigation

Fig.6. shows the congested urban area in Kaohsiung and an example of the terraced house. In order to avoid

Table 2. The Outline of the Investigation

<table>
<thead>
<tr>
<th>Investigation period</th>
<th>Taipei city</th>
<th>Taipei county</th>
<th>Sum</th>
<th>Taichung city</th>
<th>Changhua county</th>
<th>Nanto county</th>
<th>Sum</th>
<th>Kaohsiung city</th>
<th>Kaohsiung county</th>
<th>Sum</th>
<th>Total</th>
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<tr>
<td>Questionnaires sent out</td>
<td>120</td>
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<td>215</td>
<td>31</td>
<td>15</td>
<td>6</td>
<td>93</td>
<td>226</td>
<td>252</td>
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<td>Collections</td>
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<td>40</td>
<td>13</td>
<td>90</td>
<td>191</td>
<td>213</td>
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<tr>
<td>Ratio of collections [%]</td>
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<td></td>
<td>79</td>
<td>78</td>
<td></td>
<td></td>
<td>81</td>
<td>81</td>
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<td>81</td>
<td></td>
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<tr>
<td>Effective collections</td>
<td>42</td>
<td>42</td>
<td>84</td>
<td>31</td>
<td>40</td>
<td>13</td>
<td>90</td>
<td>191</td>
<td>22</td>
<td>213</td>
<td></td>
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<tr>
<td>Ratio of effective collections [%]</td>
<td>82</td>
<td>86</td>
<td>85</td>
<td>100</td>
<td>98</td>
<td>87</td>
<td>100</td>
<td>85</td>
<td>85</td>
<td>88</td>
<td></td>
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<tr>
<td>Housing complex</td>
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<td>41</td>
<td>80</td>
<td>12</td>
<td>18</td>
<td>0</td>
<td>1</td>
<td>115</td>
<td>124</td>
<td>235</td>
<td></td>
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<tr>
<td>Terraced housing</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>15</td>
<td>18</td>
<td>10</td>
<td>3</td>
<td>74</td>
<td>87</td>
<td>136</td>
<td></td>
</tr>
<tr>
<td>Single house</td>
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<td>0</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>13</td>
<td>2</td>
<td>2</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

Fig.2. The Rate of Using Screens in Various Regions and Housing

Fig.3. The Rate of Using Grilles in Various Rooms

Fig.4. Differences between the Result of Questionnaire and the Meteorological Data (Taipei)

Fig.5. Residents' Satisfaction with the Indoor Air Velocity

rainfall, the front side of the first floor of the terraced house is designed to be approximately 3m away from the road, which creates a space called "Chilo", (currently restricted by Building Standard Law), and the height of the first floor is always higher than the other floors. In addition, one house always connects with the other house(s), and the openings are on the back and front sides only. Stairs are usually located in the center of the house. A three-story terraced house
was used as the model in the current study. All the wind tunnel experiments were conducted on the terraced house models in the congested urban areas of Taipei and Kaohsiung. We measured the effects of the amount of wind and wind pressure coefficients on ventilation. Sub-sequentially, based on the results of the wind tunnel experiments, the amount of cross-ventilation is calculated using an airflow network model.

5. Wind Pressure Coefficient of the Target Building Measured in the Wind Tunnel Experiment

5.1 Experiment settings

The scale in the experiments was 1/80, which was the smallest possible. For the purpose of reproducing the wind characteristics to which the group of mid-high-rise buildings was subjected, the power index representing turbulent boundary layer inlet flow was set as 0.27. Wind velocity at the identical height of the top level of the target building (150mm) was set at 7m/s as the reference wind velocity \( U_0 \), (Fig.7.).

The interval of wind direction angle was set at 22.5 degrees with 16 possible patterns. There were a total of 126 measurement points to record the wind pressure coefficients on the surfaces of the target model. The target model has the same shape as the standard terraced house shown in Fig.8. The author manipulated four cases of arrangements (i.e., Single, Raw, Block, and Area) based on the number of buildings surrounding the test building. In the "Block" and "Area" arrangements, the distance between the target model and buildings behind it was 1/6 L (L indicates the width of the target model, 45mm). The "Area" case had the highest resemblance to the current congested urban living area (Fig.9.). The authors then calculated the flow rate based on the room pressures, which were obtained via the Newton-Raphson method.

5.2 Distribution of wind pressure coefficient (Cp)

The pressure values were shown in Fig.10. In the "Single" arrangement condition with a wind direction of 0°, the results showed that the maximal Cp at the windward side was 0.8, while the Cp on the wall side of the Chilo was positive. Moreover, the minimal Cp at the leeward side was -0.3, while the Cps of the flat roof were ranging from 0.4 to -0.6. When the wind direction changed to 45°, the results demonstrated that the maximal Cp at the windward side was 0.3 while the Cp on the wall side of the Chilo was negative. Moreover, the minimal Cp at the leeward side was -0.6, while the Cps of the flat roof ranged from -0.6 to -1.0.

In the "Raw" arrangement condition with a wind direction of 0°, the results showed that the maximal Cp at the windward side was 0.8, while the Cp on the wall side of the Chilo was positive. Moreover, the minimal Cp at the leeward side was -0.4, while the Cps of flat roof were negative. When the wind direction changed to 45°, the results demonstrated that the maximal Cp at the windward side was 0.3 and the Cp on the wall side of the Chilo was also 0.3. Moreover, the minimal Cp at the leeward side was -0.6, while the Cps of the flat roof ranged from 0.1 to -0.7.

The results found in the "Block" arrangement condition were similar to those found in the "Raw" arrangement condition with wind directions of 0° and 45°. However, when the wind direction was 180°, the Cps at the windward side, leeward side, and roof all showed negative values.

In the "Area" arrangement condition, the Cps at the windward side, leeward side, and roof all showed negative values in the 16 wind directions. The absolute values of the Cp on the wall side of the Chilo were smaller than those on the wall of the windward or leeward sides. The difference of Cp between the windward and leeward sides was less than 0.1.

Differences between the windward and leeward wind pressure coefficients of each floor and arrangement in wind directions 0° and 180° are shown in Table 3.

6. Prediction of Cross-ventilation Flow Rate in the Target Buildings

Cross-ventilation flow rates were calculated from the Cps obtained from the experiments by using the Newton-Raphson method. Parameters relevant to the calculation are listed in Table 4. The discharge coefficients of all openings of the model were set as 0.67. Each story was considered as one unit. The cross-ventilation flow rate indicated the sum of flow rates of the three stories and represented the overall flow rate of the whole building. Fig.11. shows the results for each of the arrangements (i.e., Single, Raw, Block, and Area). The results demonstrated that the "Area" arrangement, which was closest to the real urban areas when compared to the other three arrangements, generated the smallest flow rate, particularly when the
Fig. 7. Profile of Inlet Flow in Wind Tunnel Experiments

Fig. 8. Plan, Section and Elevations of the Standard Terraced House

Fig. 9. Arrangements for Wind Tunnel Experiments (L=45mm)

Fig. 10. Distributions of Wind Pressure Coefficients of the Target Building
wind directions were 0° and 180°. Furthermore, the velocity of the openings became 0.1 m/s on average if the partition is included in the calculation. So the velocity is not significant enough to have an impact on the utilization of ventilation. Overall, the findings from the wind tunnel experiments had similar results to those obtained from the survey; both suggesting that the indoor wind velocity was low. Based on the results described above, the improvement of cross-ventilation was limited by changing the openings, and the roof gained greater wind pressure. The results also indicated that changing the roof design could increase the cross-ventilation flow rate.

7. Strategy for Improving Cross-ventilation in the Target Buildings

7.1 Experiment settings

In order to examine the relationship between the roof design and the cross-ventilation flow rate, three roof designs were used: 1) lantern, 2) gable roof with a lantern, and 3) wind tower. Specifically, the lantern in design 1 was set at the flat roof directly above the staircase (Case-PL). In design 2, the additional gable roof was added to the top of the model with a lantern located just above the staircase (Case-RL). In design 3, varying of heights with rectangular pillar shaped wind towers were added directly above the staircase (Cases-V1~7). The heights of the wind towers of Cases-V1~7 were H, 4/3H, 5/3H, 2H, 7/3H, 8/3H, and 3H, respectively (H indicates the height of one floor; 45mm). Furthermore, the current study focused on examining the variables described above in the Area arrangement. Similar to previous experiments, Cps were obtained from the wind tunnel experiments and the average cross-ventilation flow rates of all directions were calculated from Cps by using the Newton-Raphson method.

7.2 Experiment results

The results demonstrated that with the lantern design, the flow rate was 2.36 times higher than with the original design. Using the gable roof with a lantern condition, the flow rate was 3.94 times higher than in the original condition. Finally, in the wind tower condition, the flow rate was 3.31~7.58 times higher than in the original condition, depending upon the heights of the towers, (Fig.10.). In one case (Case-V4) of the wind tower condition, the Cps changed with the wind directions on the side walls of the wind tower. However, the Cps of the top of the wind tower remained stable regardless the wind direction. Thus, it is necessary to consider the direction of prevailing winds if the opening is built on the side wall of the wind tower. Theoretically, the higher the wind tower, the greater the flow rate. In reality, however, a wind tower less than two-stories high in a three-story building seems to be reasonable.

8. The Effect on Energy Conservation Due to Improvement of Cross-ventilation

Numerical simulation of the thermal and airflow network model, AE-Sim/Heat, was used to calculate the effect of energy conservation through improvement of cross-ventilation. Three cases of terraced house models were used for the simulation. The first case (Case P) was the original condition without cross-ventilation; the second case (Case PV) was the original condition with cross-ventilation, and the third case (Case-V4) was the original condition with a two-story wind tower and cross-ventilation. Standard weather data was based on the information obtained in Taipei city. The wind pressure coefficients were based on the results obtained in the Area arrangement experiment. The cooling loads (heat removal) of the model were calculated via the numerical simulation in order to evaluate the effect on improvement of cross-ventilation.

8.1 Calculation settings

The opening area was 0m² for Case P, 4.32m² for Case PV, and 7.20m² for Case-V4. The daylight...
areas of the three cases were 20.16m$^2$. The radiation area of Case P and Case PV was 97.2m$^2$, and was 160.6m$^2$ for Case-V4. All daylight windows were assumed to receive both direct and diffused solar radiation. Because the assumption was established in the congested urban area, where there was more solar shading. The shading coefficient of the windows was set as 0.2. The schedules of occupant numbers, lighting heat generation, and machine heat generation are presented in Fig.13. Annual outdoor temperature and humidity data of Taipei is also shown in Fig.14. The minimal ventilation airflow rate of all rooms was set as 0.5 times per hour. Kitchen fans and curtain utilization were not taken into account. The shading coefficient of all openings was set as 0.67. It was assumed that there was no infiltration around the daylight model. The width of the slit of the entrance was set as 2 mm and its discharge coefficient was also 0.67. Finally, the air conditioning of all cases was a hybrid ventilation system.

The setting temperature of the cooler was set at 27°C. If the room temperature was above 27°C, the cooler would be operated and the windows would be closed. Cooling loads (heat removal) were simply calculated at a room temperature set at 27°C with a relative humidity of 60%.

8.2 Calculation results
The monthly accumulated values of sensible and latent heat removal in the three cases by the cooler are presented in Fig.15. Because the cross-ventilation was unable to be operated in July and August, the heat removal of the three cases did not differ significantly. There were sensible reductions of heat removal by the wind tower cross-ventilation in May, June, September, and October, as well as significant latent heat removal in May and August. In May and October, the values of sensible heat removal were close to 0. The annually accumulated values of heat removal (sensible and latent) of the three cases are shown in Fig.16. Compared to Case P, the heat removal of Case V4 decreased 16%. The heat removal of Case V4 was 39% smaller than Case P without considering the data of July and August.
9. Conclusions

The results, based on the questionnaire survey indicate that it is very common for residents in Taiwan to have the screen and grille in the open position, which may affect the cross-ventilation. Therefore, it is essential and necessary to consider the effect of the existence of the screen and grille in these openings when conducting a wind tunnel experiment and calculating the results. The data also suggests that the Taiwanese open their windows not only during the ventilation capable period, but also during the non-ventilation capable period, such as summer. The effect of natural ventilation caused by the ventilation driving force is extremely small given the layout of the present type of buildings. The best way to improve the cross-ventilation in such houses is to install ventilation devices on the roof, because such changes can produce greater wind pressure and therefore improve the ventilation. If a two-story wind tower is added on top of the roof, the cross-ventilation flow rate can increase more than five times. Plus, compared to current conditions, it can decrease the heat removal by 16% annually.

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References