Review of recent natural ventilation research study in Japan

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ABSTRACT: With an increased awareness of the cost and environmental impacts of energy use, natural ventilation has become an increasingly attractive method for not only reducing energy use and cost, but also for providing acceptable indoor environmental quality and maintaining a healthy, comfortable, and productive indoor climate rather than the more prevailing approach of using mechanical ventilation. Over the last 2 decades or so, various modeling approaches have been seen for modeling the thermal distribution and airflow movement. However, there is no appropriate simulation tool that can predict indoor thermal environment of natural ventilation. This paper presents a review of the recent natural ventilation studies and the recent achievement of the latest simulation design tools used in building ventilation-related research, as well as demonstrates the state of the art of multi-zone airflow network simulation design tools for natural ventilation in building. Example of simulation results obtained from the new coupled multi-zone airflow network model (COMIS-LDSM and a thermal multi-zone model, TRNSYS) developed by the current authors are given to highlight the significant effects of this coupled model on reduction of building cooling loads.

KEYWORDS: Natural ventilation, CFD, Network model, Building energy simulation.

1 INTRODUCTION

From the continuous scientific research and monitoring of global climate system, it is no doubt that the phenomenon of global warming is mainly caused by human activities. The change in climate system, from macro-scale (continent or country size) to mesoscale (state or county) or even down to micro-scale (city block or garden), resulted from the global warming phenomenon has become a serious issue that the mankind is facing, as it can seriously harm the economies, societies and eco-systems worldwide [1, 2]. In order to avoid reversals in human development and catastrophic risks to future generations, it is necessary to act against global warming with a sense of urgency.

Presently the primary international policy framework against global warming is the UNFCCC, specifically the Kyoto Protocol. Under the Kyoto Protocol, the participating developed countries are committed to reduce their GHG emissions on an average of about 5% by the target years of 2008 to 2012. It is, however, worth noting that no quantitative restrictions were placed on the emissions from developing countries [3]. The current level of CO_2 emissions of some world mega cities is shown in Table 1 [4]. During the G8 Summit held in Heiligendamm on 6-8 June 2007, the participating countries have agreed to seriously consider the target of halving of GHG emissions by 2050 [5]. Japan has launched the national campaign of 'Cool Earth 50', which targeting to cut the CO_2 emissions to half of the present level, cf. Table 2, by the year of 2050. Recently, the new prime minister of Japan, Yukio Hatoyama, announced that Japan would reduce CO_2 emissions by 25% below 1990 levels by 2020.

Table 1. CO_2 emission of some world major cities [4]

City/Region	CO_2 emission (tons)		Population (million)	Year
	Total (million)	CO_2/ capita		
Hong Kong	38.1	5.6	6.8	2005
Tokyo	66.4	5.3	12.6	2005
Greater London	50.8	6.9	7.3	2001

New York State	207.7	10.8	19.0	2000

Table 2. Emission reduction target of worldwide countries [2, 5~7]

Country/city/organization	Emission reduction target
International organization:	
- G8	50% below ‘current level’ by 2050
- European Union	20 % below 1990 level by 2020
Country:	
- Canada	60-70% below 2006 level by 2020
- Japan	50% reduction by 2050
City/Region:	
- State of California (USA)	80% below 1990 level by 2050
- State of New Mexico (USA)	75% below 2000 level by 2050
- Greater London (UK)	60% below 2000 level by 2050

Buildings play an important role in our societies. Having said that, they are also intensive energy consumers while in use, no need to mention their construction already involves consumption of huge amount of resources, and thus a major cause of greenhouse gas emissions. The quality of indoor environment also deserves serious attention, as people spend most of the time within buildings whilst poor indoor air quality (IAQ) can have serious implications directly to the health, well-being and work efficiency of occupants. Nowadays, most newly built houses are airtight. In recent years, the insulation and air-tightness levels of newly constructed residential buildings have been improved for purpose of energy saving, for instance in Japan. However, a reduced design of air permeability (i.e. a high level of air-tightness) will provide insufficient air through infiltration resulting in a significant and negative impact on healthy environment. The emergence of the term ‘sick building syndrome’ highlights the prevalence of IAQ problems in buildings worldwide. Increasing availability of natural ventilation in dwellings helps reduce residents’ reliance on air-conditioners, and hence the associated amount and cost of energy use for thermal comfort control. This will also lead to better indoor air quality and more sustainable building development in modern cities. The potential energy cost savings would be especially valuable to households with low-incomes as the energy expenditure would account for a greater proportion of the household income compared to financially better-off households. Therefore, natural ventilation has become an increasingly attractive strategy for not only reducing energy use and cost in buildings, but also for providing acceptable indoor environmental quality and maintaining a healthy, comfortable, and productive indoor climate rather than the more prevailing approach of using mechanical ventilation. The paper gives a review of recent studies on natural ventilation in building and discusses the state of the art of building simulation design tools such as multi-zone airflow network models.

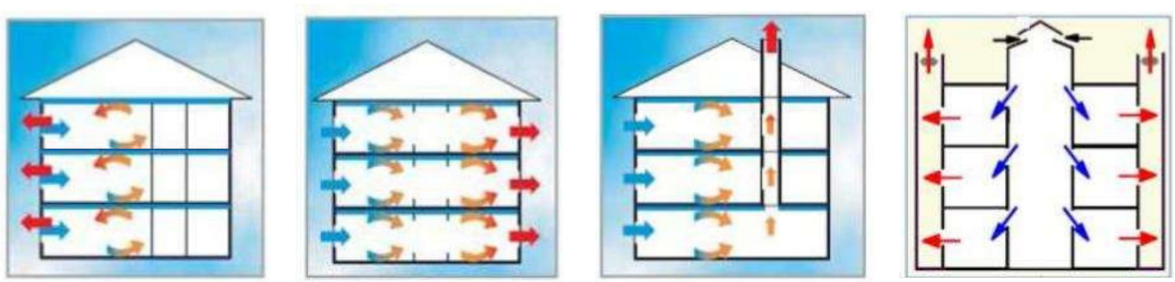
2 CLASSIFICATION OF ARCHITECTURAL VENTILATION

Architectural ventilation (or natural ventilation) is the process of supplying and removing air through an indoor space by natural means. There are two types of natural ventilation occurring in buildings: wind driven ventilation and stack ventilation. The former takes advantage of the natural passage of air without the need for high energy consuming equipment, while the latter is due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences.

2.1 *Type of ventilation*

Generally, there are four common types of ventilation (cf. Figure 1); single-side ventilation (i.e. openable windows), cross flow ventilation (i.e. high and low level louvers), stack ventilation (passive stack turrets) and top-down ventilation (i.e. windcatcher systems).

Single-sided ventilation is supplied and extracted through the same louvres in the room, as shown in Figure 1(a). With single-sided ventilation the openings should equate to 4% of the floor surface. This system is less efficient but is applicable almost everywhere and the internal doors may remain closed. Figure 1(b) illustrates the cross flow ventilation. In this type of ventilation strategy, the ventilation supply and extraction are taken placed on the same level in a building. The air is supplied and extracted through louvres. The internal doors must be opened or equipped with transit ventilation grilles. This system generally achieves good results except in no wind condition. Stack ventilation measure is described in Figure 1(c). Two ventilation openings, a low level grille and high level one, typically placed above the door. Outside air enters through louvres and extracted through a chimney. In this system, there will be ventilation even when there is no wind. The areas that need to be cooled must be in direct contact with the chimney or via efficient transit grilles. Figure 1(d) depicts the top-down ventilation system, which is using roof turrets that encapsulate the wind from any direction. It has been proved to be one of the most reliable and popular forms of natural ventilation, simply because it uses the natural elements of wind movement to encapsulate relatively clean, fresh air from above roof level and the wind pressure pushes that fresh air supply through the wind-catcher device down into the building below.



(a) Single-side ventilation **(b) Cross flow ventilation** **(c) Stack ventilation** **(d) Top-down ventilation**

Figure 1 Type of natural ventilation

The invention of ventilation; natural ventilation to be more precise, cannot be ascribed to a certain date. The first attempt was probably made in the Stone Age period of the prehistoric time, when man brought fire to make heat, prepared food, kept predators away or into the abode, and then discovered the need to have an opening in the roof to let out the smoke and simultaneously to supply air to keep the fire burning. Because the fire warmed the space to a more comfortable temperature, thermal comfort was initially linked to ventilation. A number of historical events, direct and indirect, in the evolution of ventilation, each of which represents a breakthrough, at its time, in understanding, technique or application have been reported by Ohba and Lun [8]. A summary of the evolvement of ventilation study approach is illustrated in Figure 2.

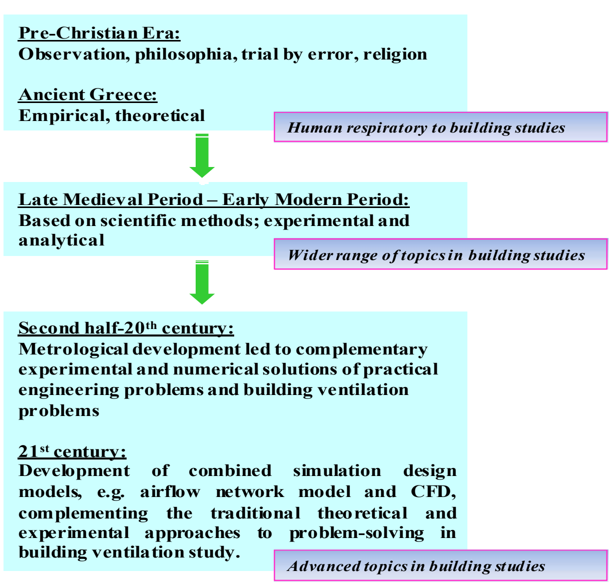


Figure 2 Summary of the evolvement of ventilation study approach

3 CONTEMPORARY TREND OF NATURAL VENTILATION STUDIES

The concept of natural ventilation is well accepted and welcomed by people and designers in the world. Interest in the application of natural ventilation in buildings is growing due to the energy, indoor air quality and environmental problems associated with mechanically ventilated buildings. Over the years, a wide range of efforts, nationwide and worldwide, on natural ventilation studies have been observed in literature and are continuously presented all over the world. A number of natural ventilation related researches, including wind-driven ventilation and stack or buoyancy-driven ventilation, done experimentally by both full- and model-scale as well as analytically, have been reported in literature. These studies have been reviewed and described in detail by Ohba and Lun [8]. The previous reported natural ventilation studies in literature indicated that the general trend of the study approach has been swapped from the conventional methods to computational methods and this also implied that computational modeling seems the way of study problem or solutions for buildings nowadays.

Building simulation is a popular method for studying naturally ventilated building design. Thermal simulation and airflow network are two fundamental modules in building simulation method. Building simulation programs can be classified into two categories; design tools and detailed simulation programs. Some common simulation programs are; DOE-2, COMIS, ESP, TRNSYS. Over the past 50 years, literally hundreds of building energy programs have been developed, enhanced and are in use. A recent up-to-date comparison of the features and capabilities of twenty major building energy simulation programs can be found in the study by Crawley and co-workers [9]. On the other hand, for the study of natural ventilation and wind microclimate, Computational Fluid Dynamics (CFD) is most widely used and perceived as an appropriate tool with reasonable accuracy [10, 11, 12, 13, 14, 15]. This approach is becoming popular not only due to its versatility and informative results, but also its low labour and equipment costs, as a result of the development in turbulence modeling and in computer speed and capacity. It has been shown that CFD is able to model a domain containing stationary objects (e.g. building), non-stationary obstacles (e.g. moving cars, trees etc) [16], its surroundings and its interior spaces.

Energy simulation and CFD both can play an important role in building design by providing complementary information of the building performance. However, separate applications of them usually cannot yield an accurate prediction of building thermal and flow behavior due to the assumptions used in the applications. For instance, most energy simulation programs assume that the air in an indoor space is well mixed, the air temperature and contaminant are uniformly distributed in a zone, the momentum effects are neglected etc.

On the other hand, thermal comfort prediction of naturally ventilated buildings solely used with CFD simulation is not an easy task as comprising; the computation embodies two scales of environment; macro-scale (building clusters) and micro-scale (room), the impacts of climate conditions (ambient temperature, solar radiation, wind, humidity) provide in boundary conditions, the calculations of heat transfer and fluid dynamics involved in indoor thermal environment. Besides, the accuracy of CFD studies for external flows is still quite limited and needs to be carefully considered. However, a CFD study of the airflow around the building will provide an expert with more information on the specific conditions for the particular building. This additional information helps to improve the quality of an estimate of the wind pressure coefficients. Thus, the development and use of CFD based Urban Climate Assessment Tools is necessary [17].

Both study approaches of CFD method and building simulation method have their own disadvantages. However, recent advances in computer performance and CFD software integrate with building simulation have made it possible to improve the accuracy to assess the performance of natural ventilation and also give more realistic predictions of airflow in buildings. The coupling of building simulation with CFD, as the new trend in natural ventilation study, is necessary (for providing an accurate solution) and has become increasingly important in the study of building natural ventilation as well as has been turning into an active research area in recent years [18, 19, 20, 21, 22, 23]. Figure 3 depicts the main approaches adopted in the previous works and the new trend of building simulation design tools in natural ventilation study.

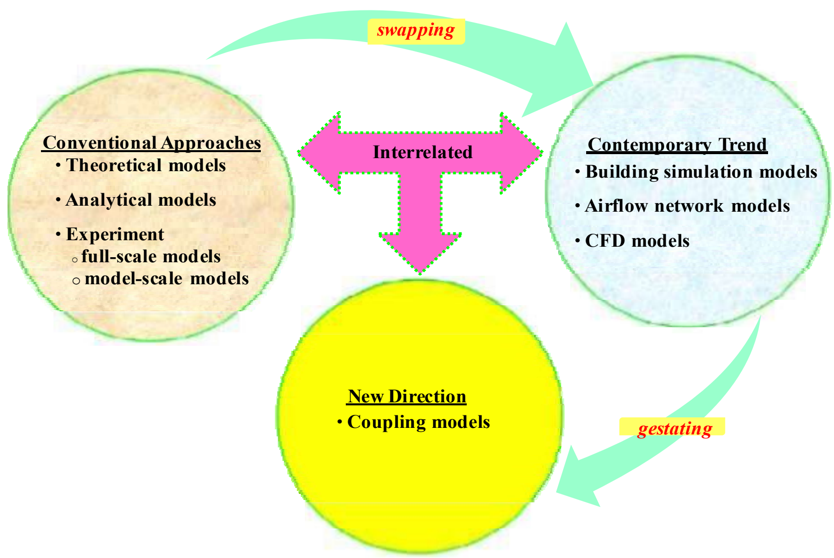


Figure 3 Tools for natural ventilation studies

4 NEW DIRECTION OF BUILDING ENERGY SIMULATION: COUPLING MODELS

In recent years, airflow network simulation programs have been popularly used, as a design tool, in building ventilation studies. In airflow network programs, the most common equation describing the airflow through an opening is the orifice equation. However, validation studies, in the design of cross ventilation, for instance, have shown that modeling of openings remains a significant source of uncertainty as there has been doubt about the accuracy of the orifice flow equation when applied to the calculation of wind induced ventilation through larger openings [24, 25]. One of the main problems is that the discharge coefficients which relate wind pressures to ventilation flow rates, vary with wind direction and opening position although they are treated as constant in the conventional models [26, 27, 28, 29].

Recently, the present authors developed an evaluation method named 'Local Dynamic Similarity Model' (LDSM) that calculates the ventilation flow rates, dynamically, even when the approaching flow is not normal to the upwind openings [30, 31]. This empirical model, derived base on the results of research on CFD analysis and wind tunnel experiments, expresses the variation of discharge coefficient with wind direction, and thus predicts ventilation flow rates more accurately than the conventional method.

4.1 *Outline of coupling model: COMIS-LDSM and TRNSYS multi-zone model*

The details and descriptions of LDSM and a developed ventilation model, based on the local dynamic similarity model theory, coupled with COMIS and TRNSYS can be found in [8, 30, 31]. Simulation results, as an example using this developed ventilation model, on cooling load of a typical Japanese detached house (cf. Figure 4) are given as follows.

Figure 5 shows the block diagram of COMIS-LDSM and TRNSYS model. P_W (wind pressure) and P_t (dynamic pressure tangential to the opening) for the building envelope are provided as input data. The ventilation performance of inflow and outflow openings is also provided as input data. Based on the LDSM model, the COMIS code was revised to calculate the discharge coefficients and airflow rates at inflow/outflow openings. Arbitrary room pressure (P_R) is given as an initial condition and a discharge coefficient corresponding to the dimensionless room pressure (P_R^*) is selected from the ventilation performance curve. P_R^* is defined as the ratio of P_r (ventilation driving pressure) to P_t. The calculation was performed by the Relaxation-Newton method until ventilation flow rates of outflow and inflow in each room were balanced. Since this coupled model can select discharge coefficients suitable for arbitrary wind directions when the wind direction is not normal to the openings, it can estimate ventilation flow rates more accurately than the conventional orifice model. The coupled model can also determine the inflow/outflow angles, $\beta = \tan^{-1}(P_t/P_n)^{1/2}$; where P_n is the dynamic pressure normal to opening, at the openings, which gives important information on the internal flow patterns.

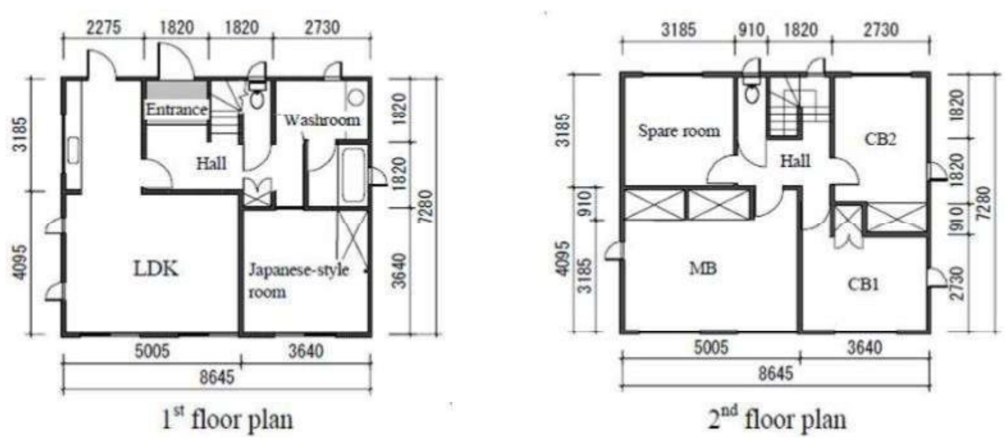


Figure 4 Floor plan of typical Japanese detached house

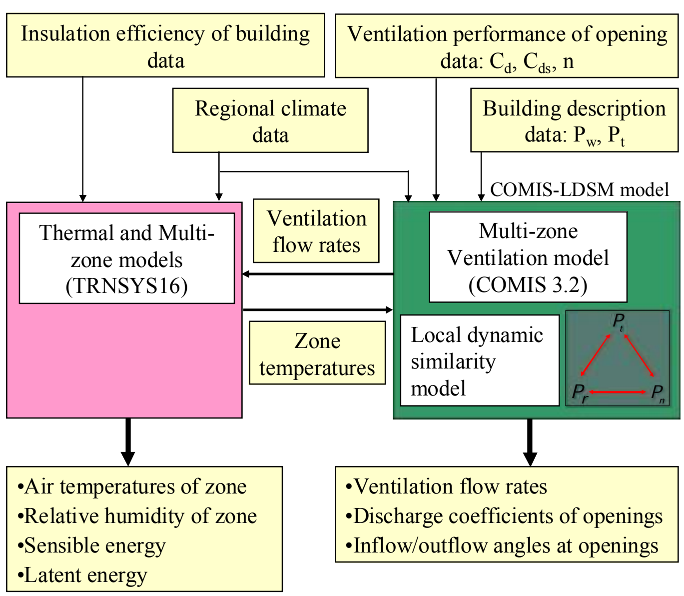


Figure 5 Black diagram of COMIS-LDSM and TRNSYS model

4.2 *Simulation results of cooling loads in Living-Dinning-Kitchen*

Three cases were simulated and examined (cf. Figure 6); Case 1, the logic of switching the air-conditioning on/off with all windows closed was used; Case 2, the basic logic of opening/closing windows was used; Case 3, the active logic of opening/closing doors was used. Figure 7 illustrates the results of room temperatures on a single day of these three cases. Table 3 shows the cumulative cooling loads in June and the effects of reducing energy through cross-ventilation in Cases 1, 2 and 3 for 20% building coverage ratio. It can be seen that utilization of cross-ventilation succeeded in reducing cooling loads by 14 KW (5%) compared to those required when the windows were closed. When the windows also remained open during the unoccupied time zone or while residents were sleeping, the cooling load was 141 KW less than that required when the windows remained closed. When the windows remained open during the unoccupied time zone or while residents were sleeping, the cooling load was reduced by 51%.

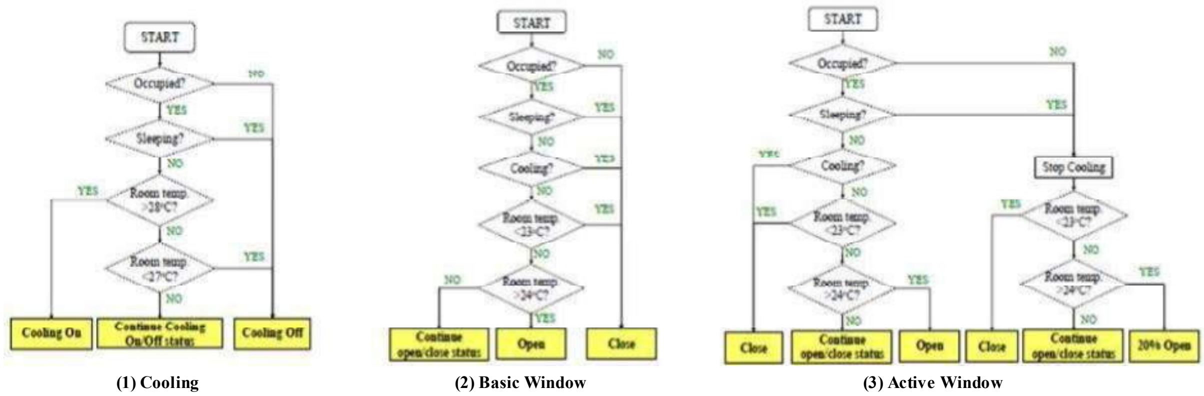


Figure 6 Logic of operation of cooling and windows

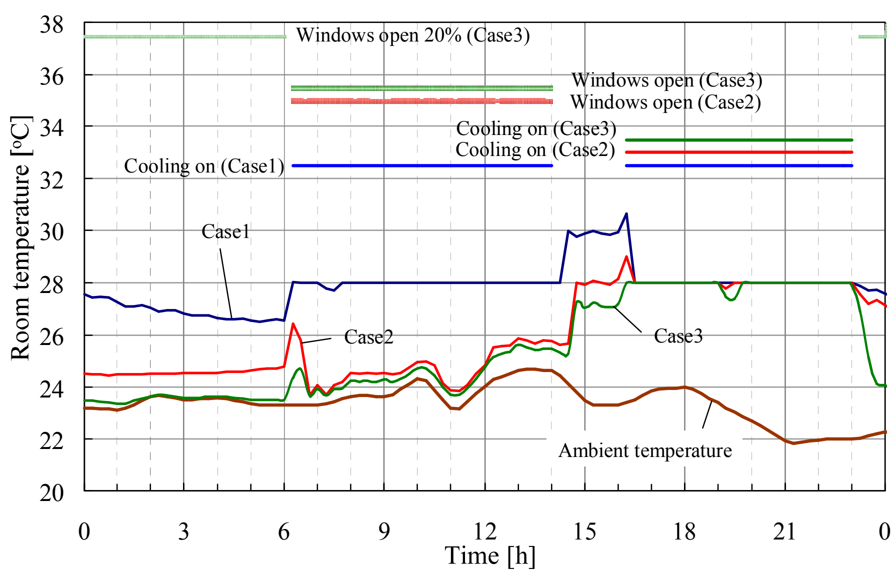


Figure 7 Simulation results of room temperatures on a single day

Table 3 Cumulative cooling load and reduction of cooling load in June for gross coverage ratio of 20%

Case	Window operation	Cumulative cooling load [KW]	Reduction of cooling load [%]
1	Closed	261	-
2	Basic opened/closed	247	5.1
3	Active opened/closed	120	51.4

5 CONCLUDING REMARKS

This paper presents a review of the recent natural ventilation studies and the recent achievement of the latest simulation design tools used in building ventilation-related research, as well as demonstrates the state of the art of multi-zone airflow network simulation design tools for natural ventilation in building. Simulation results obtained from the new coupled multi-zone airflow network model (COMIS-LDSM and a thermal multi-zone model, TRNSYS) developed by the current authors are given, as an example, to highlight the significant effects of this coupled model on reduction of building cooling loads.

In retrospect to the reported natural ventilation studies over the last 2 decades in literature, there is an indication that the general trend of the study approach has been swapped from the conventional methods to computational methods, and it also implies that computational modeling may be the way of study problem or solutions for buildings nowadays. This may be true as the recent advances in computer performance and CFD software move '*ichi nichi sen ri*' (a Chinese idiom; literally: a thousand miles in a single day). The methodology of computation for natural ventilation studies can improve the accuracy and efficiency for indoor thermal environment, as well as provide fruitful information for understanding natural cross-ventilation. In addition, coupling strategies for combined simulation using multi-zone and CFD models can be used as a convenient and essential tool for natural ventilation study in buildings.

The typical approach in natural ventilation modeling is generally carried out based on orifice equation (i.e. static wind condition). This approach may be erroneous when applied to real situations, where dynamic conditions exist. The newly developed coupled multi-zone airflow network model: COMIS-LDSM and TRNSYS model, illustrated as well as emphasised the significance of the effects of dynamic wind characteristics on the prediction accuracy of the network model.

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