Uncertainty Distribution of Air Infiltration Rates of Thai Detached Homes for Energy Model
ค่าการกระจายของอัตราการรั่วซึมของอากาศของบ้านเดี่ยวในหมู่บ้านจัดสรรของประเทศไทยสำหรับแบบจำลองพลังงาน

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Abstract

Air infiltration through building envelope is considered as a path of outdoor air ventilation in modern Thai detached homes where there is no outdoor air intake in an air condition unit. At present, there are limited studies of air infiltration rate through building envelope for Thai homes and such few studies are insufficient for establishing a database of air infiltration rate for evaluating home energy performance. This present study used a multi-zone airflow model to calculate air infiltration rates in 134 homes from 137 housing development projects located in suburban areas near Bangkok. The calculated air exchange rate (air infiltration) ranged from 0.33-0.58 h^{-1} with an average value of 0.43 h^{-1} (s.d. = 0.04). Compared to the ventilation standards, the calculated air exchange rates were approximately 1.7 times greater than the required ventilation rates defined by the ASHRAE Standard 62.2 (2007) and 93% of those achieved the required ventilation rate prescribed in the Thai Building Control Act B.E. 2522 (2015). Consequently, it has a potential to reduce air infiltration rate for modern Thai detached home to save home energy consumption. The default air infiltration rate typically used in energy models provided a maximum input error ranged from 7-65% when compared to the calculated air infiltration rates.

บทคัดย่อ

การระบายอากาศภายในบ้านพักอาศัยในประเทศไทยมาจากการรั่วซึมของอากาศผ่านกรอบอาคารเมื่อระบบปรับอากาศแบบแยกส่วนที่ใช้ในบ้านจัดสรรไม่มีช่องเติมอากาศจากภายนอก การศึกษาการรั่วซึมของอากาศผ่านกรอบอาคารบ้านพักอาศัยในปัจจุบันมีจำนวนน้อยและขาดฐานข้อมูลเพื่อใช้ในการคำนวณการใช้พลังงานของบ้าน การศึกษานี้ใช้แบบจำลองการเคลื่อนที่ของอากาศระหว่างโซนเพื่อคำนวณอัตราการรั่วซึมของบ้านทั้งหมด 134 หลังของ 137 โครงการหมู่บ้านจัดสรรในเขตปริมณฑล จากการคำนวณ พบว่า อัตราการระบายอากาศ (การรั่วซึมของอากาศ) ของบ้านจัดสรรอยู่ในช่วง 0.33 – 0.58 เท่าของปริมาตรห้องใน 1 ชั่วโมง โดยค่าเฉลี่ยอยู่ที่ 0.43 (s.d. = 0.04) เมื่อเปรียบเทียบผลการคำนวณกับ

มาตรฐานการระบายอากาศ พบว่า ผลคำนวณอัตราการระบายอากาศมีค่า 1.7 เท่าของอัตราการระบายอากาศที่ได้ระบุไว้ในมาตรฐาน ASHRAE 62.2 (2007) และ 93% ของจำนวนบ้านที่ถูกทดสอบมีอัตราการระบายอากาศมากกว่าค่าที่ระบุไว้ในพระราชบัญญัติควบคุมอาคาร ปี พ.ศ. 2522 (2015) ดังนั้น การลดอัตราการรั่วซึมของอากาศในบ้านจัดสรรมีความเป็นไปได้เพื่อการประหยัดพลังงาน ค่าการรั่วซึมของอากาศที่ตั้งไว้ในแบบจำลองพลังงานมีค่าความคลาดเคลื่อนจากผลการคำนวณอยู่ในช่วง 7–65 เปอร์เซ็นต์

Keywords (คำสำคัญ)

Air Infiltration (การรั่วซึมของอากาศ)
Detached Home (บ้านเดี่ยว)
Ventilation Rate (การระบายอากาศ)
Multi-zone Airflow Modeling (แบบจำลองการเคลื่อนที่ของอากาศระหว่างโซน)
Energy Model (แบบจำลองพลังงาน)

1. Introduction

Building ventilation provides good indoor air quality and thermal comfort to building occupants. ASHRAE Standard 62.2 specifies a minimum ventilation rate including air infiltration and outdoor air intake from mechanical ventilation to provide acceptable indoor air quality for residential buildings (ASHRAE, 2007). The air infiltration defined for a home assumed in the Standard 62.2-2007 was 0.1 L/s. m^2 (2 cfm/100 ft^2) and the outdoor air intake from mechanical ventilation provided additional ventilation to qualify the whole-building ventilation rate described in the standard. The calculated ventilation rate required for home uses Equation (1) (ASHRAE, 2007). The Chartered Institution of Building Services Engineers (CIBSE guide A, 2006) specifies the maximum average air infiltration rate for two story residential building. The defined building infiltration rate is 1 h^{-1} for leaky building and 0.35 h^{-1} for tight building.

$$Q = \frac{A}{100} + (N+1)x7.5 \qquad (1)$$

where Q is a whole-building continuous ventilation rate, cfm. A is floor area, ft^2. N is a number of bedrooms.

A typical mechanical ventilation for modern Thai homes is split type with no outdoor air intake. The mechanical designers commonly assume that the building ventilation comes from the air infiltration through cracks, penetrations, and other adventitious openings. Air infiltration has a considerable effect on both building energy consumption and indoor air quality. The air infiltration through building envelope accounts for 50-80% of energy consumption in residential buildings (Goswami & Kreith, 2015; Jareemit & Inprom, 2015, pp. 1-14; Srisuwan & Varodompun, 2013, pp. 5-20). The excessive air infiltration rate leads to high energy costs ranging from 10-40% (ASHRAE, 2009; Alpen High Performance Products, n.d.; Sherman, 2009; Jokisalo et al., 2009). In addition, the infiltration of hot and humid air could lead to construction failure and indoor mold growth due to condensation in building envelope (Sherman, 2009; Jareemit & Shu, 2014, pp. 23-32). On the contrary, insufficient air exchange rate leads to high indoor pollution generated from cooking, cleaning activities, and tobacco smoke. Many studies have investigated air infiltration rates in residential buildings, specifically in the U.S. homes (Sherman, 2009; Chan et al., 2013; Chan et al., 2005; Persily et al., 2010; Sherman & Dickerhoff, 1998; Yamamoto et al., 2009; Pandian et al., 1998). The air infiltration rates investigated in U.S. homes varied over a range of 0.22-1.93 h^{-1} as shown in Table 1. However, there are few studies of air infiltration rate in Thai homes (Suthi, 2011; Namtaveesuk, 2003). One study performed the fan pressurized tests to investigate air exchange rates for a traditional Thai home compared to those of a modern home (Suthi, 2011). The study revealed that the traditional Thai home had the air exchange rate ranging from 1.03 -1.89 h^{-1}, which was greater than the rate of 0.55 h^{-1} measured in the modern home. Another study ranked the impact of door-window types and wall constructions on energy consumption in a conventional and traditional Thai homes (Namtaveesuk, 2003). The lowest air infiltration rate was found in the home with sliding door-window, fixed window, and EIFS wall. In the existing studies, the air infiltration rates for Thai homes are investigated in specific case studies. Consequently, it is not representative of the broader housing stock.

Air infiltration is a significant input parameter required for building energy analysis. Measurement of air infiltration rate requires time effort and the measurement accessibility is limited. Consequently, the modelers typically use a default air infiltration value specified in the energy model. The default air infiltration rate provided in eQUEST (2010) model is 0.00192 $m^3/s.m^2$ whereas DesignBuilder (2009) and Ecotect (2006) provide in different unit of 0.5 h^{-1}. The default air infiltration rate prescribed in VisualDOE (2004) is 0.2 h^{-1}. Those default values were established based on the field measurements in the homes in

Table 1. Ranges of air infiltration rates through building envelope for single homes investigated from existing studies.

Study	Type	Volume	Location	ACH
Grot et al. (1979)	Low-income households (frame, masonry, and masonry-veneer wall system)	n/a	14 cities in USA	0.22-0.99[a]
Pandian et al. (1998)	California home	n/a	California, USA	0.22-1.93[a]
Persily et al. (2010)	Detached homes	n/a	19 cities in USA	0.3-0.68[a]
	Attached homes			0.39-0.78[a]
	Manufactured homes			0.3-0.59[a]
Yamamoto et al. (2010)	Site-build and manufactured homes	New Jersey: 88-668 m^3 Texas: 57-1446 m^3 California: 45-357 m^3	New Jersey, Texas, California, USA	0.47-0.87[b]
Suthi (2011)	Modern home	195 m^3	Bangkok, Thailand	0.55-0.56
	Traditional home	79-269 m^3	Bangkok, Thailand	1.03-1.89

Note: [a] is air exchange rate between 25th and 75th percentile. b is the median air exchange rate

other countries. Consequently, such default values might not represent the actual air infiltration rates for typical Thai homes since the design characteristics and building construction system of the Thai homes relatively differs from those of the homes in other countries. With a limited number of air infiltration studies in Thai homes, this study investigated the distribution of air infiltration rates to establish a database of air infiltration rates for Thai detached homes, typically found in housing developments. This database could significantly provide the baseline level of air infiltration rate for Thai housing stock, which can further improve the quality of the predicted home energy performance and indoor air quality.

2. Building case studies

The air infiltration calculation in this study focused only a medium-sized home with the area ranging from 103 – 270 m^2, which is the most representative type of the detached housing stock in Thailand. The study observed the layout of 384 detached homes from 137 housing development projects located in suburban areas including Pathumthani, Nontaburi, Bangna, Bangbauthong, Samutprakarn, and Nakornnayok. The housing layouts was categorized into fifteen layouts and the layout

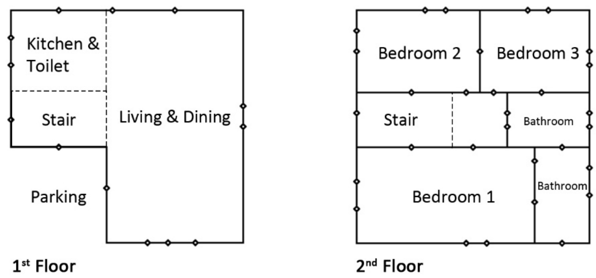

Figure 1. Typical floor plan and functions mostly found in Thai detached homes developed by Thai housing developments.

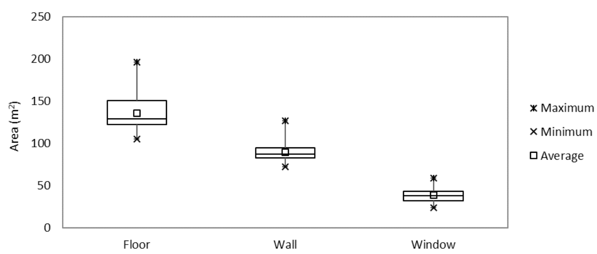

Figure 2. Distributions of total floor, wall, and window areas for the tested homes.

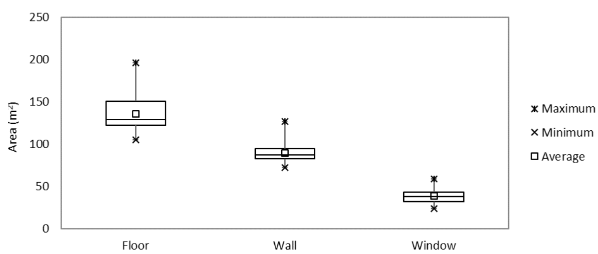

Figure 3. Distribution of space volume of the home functions on the first and second floors.

shown in Figure 1 was the most common layout that represented 36 percent of the studied homes. Typically, the home is a two-story building. The first floor is designed as an open plan living space including dining, kitchen and toilet. The second floor composes of three bedrooms and two bathrooms. Figure 2 presents a distribution range of total floor, wall, and window areas of the tested homes. The floor area observed in the building case studies varies over a range of 105-196 m^2 and the building volume ranges from 219-265 m^3. Wall and window areas ranges from 73-127 m^2 and 24-59 m^2, respectively. Figure 3 presents a distribution of space volume of living area including dining, kitchen, and toilet on the first floor and bedrooms and bathrooms on the second floor. It is found that the floor and wall areas for the tested homes have a relatively wide range when compared to the range of the window area. For the space volume, the volume of living area including dining and kitchen and the bedroom 1 has a wide range from 89-219 m^3 and 47-128 m^3, respectively. The volume of bedroom 2 and 3 ranges from 22-56 m^3.

3. Methodology

The field measurement of air infiltration rate in housing stock is excessive cost and time effort. Numerical model, specifically multi-zone airflow model, has been widely used to investigate zonal ventilation and indoor air quality influenced by driving forces and building operation schedules. The model calculation uses the equation of pressure resistance model as shown in Equation (2) and conservation of mass shown in Equation (3) and (4) to predict airflow and contaminant between zones (Walton & Dols, 2013). To calculate air infiltration in a unit of air exchange rate (ACH) uses Equation (5). In the multi-zone model, the momentum effect is neglected in the model calculation. This assumption results that the space condition has a uniform temperature, humidity, concentration, and pressure (Walton & Dols, 2013).

$$F_{ji} = f(P_j - P_i) \tag{2}$$

where F_{ji} is the mass airflow rate from zone j (adjacent and ambient zones) to zone i (indoor), kg/s, which is a function of the pressure drop across the flow path. P_j is the absolute pressure in zone j, Pa, and P_i is the pressure in zone i, Pa. For the steady state condition, the calculation of mass of air (m_i), kg, in zone i uses the ideal gas law (Equation 3) while the calculation of transient mass conservation uses Equation (4)

$$m_i = \rho_i V_i = \frac{P_i V_i}{RT_i} \tag{3}$$

where V_i is the volume of zone i, m^3, and ρ_i is the air density of incoming air, kg/m^3. T_i is the zone temperature, K, and R is the gas constant of air 287.055 J/kg.K.

$$\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\rho_i}{\partial t} = \sum_j F_{ji} + F_i \tag{4}$$

where F_i is the non-flow processes that could affect the changes in the amount of air in zone i, kg/s.

$$ACH = \frac{\sum \dot{m}}{\rho_{air}\, x \sum Volume}\, x\ 3600 \tag{5}$$

where $\sum \dot{m}$ is the total mass flow rate from ambient zone to interior zone, kg/s. $\sum Volume$ is the total volume of interior zone, m^3.

In this study, a multi-zone model, CONTAMW (Walton & Dols, 2005), was used to calculate a distribution of air infiltration rates for the representative set of 134 homes. To calculate airflow through leakage paths, the CONTAMW model requires information of leakage characteristics of building envelope. In the simulation model, the exterior wall, interior wall, window, and door leakage areas used the average effective leakage area (AL) conducted from field investigations in the existing studies (Persily 1998; ASHRAE, 1997; Emmerich & Persily, 1996; Persily, 2000) as shown in Table 2. The zonal model and leakage paths locations were presented in Figure 4. The test of those leakage area elements (AL) was performed when the doors and openings closed during the entire test period at a reference pressure difference (ΔPr) of 4 Pa with a discharge flow coefficient of 1 and a flow exponent (n) of 0.65 (Walton & Dols, 2013). The setting of leakage characteristics for building envelope including doors and openings in the CONTAMW model uses the power law model as shown in Equation (5).

$$Q = C\Delta P^{n} \quad (5)$$

where Q is the airflow through the building envelopes including doors and openings, L/s. C is the air leakage coefficient, L/s.Pa^n. ΔP is the pressure difference, Pa^n.

It was assumed that the second floor room ceiling was an exterior envelope, which connected to ambient condition. In addition, floor construction was built airtight and there was no air infiltration through the floor. The air infiltration influenced by window, door, and exhaust fan operations and the contaminant generated from home appliances and cooking activities were not accounted in this present study. Consequently, the calculated air infiltration rate was only from the building envelope leakages, which was driven by weather effect only.

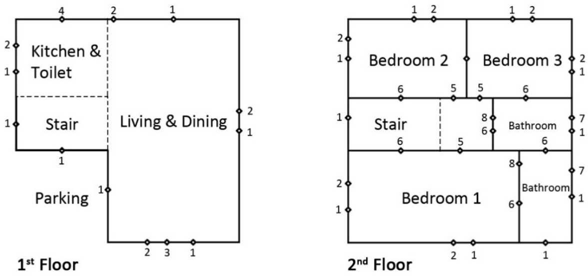

Figure 4. Types and locations of leakage paths on exterior and interior walls specified in the model setting. The numbers lebeled in the picture is a code in Table 2.

The simulation was modeled using TMY3 weather data, including ambient temperature, wind direction, and wind speed, for Bangkok, Thailand (National Renewable Energy Laboratory, 2008). In this study, the air infiltration rate was calculated during the air condition was operated and the operating schedule is shown in Table 3. The mechanical ventilation system in the building model was a split type with no outdoor air intake. It was assumed that the supply and return airflows balance. The room temperature was assumed 25 °C when the air condition was operated and 30 °C when the air condition was turned off. Consequently, the ventilation system did not influence the building air exchange rate. The air-conditioning operating schedules for each zone are shown in Table 3.

Table 2. Effective leakage areas (AL) specified in the model setting.

Code	Description	Value	Sources
1	Exterior wall (Masonry)	4.2 cm^2/m^2	Persily (1998)
2	Window with frame	1.3 cm^2/m^2	ASHRAE, Chapter 25 Table 3 (1997)
3	Sliding door (Exterior glass patio)	5.5 cm^2/m^2	ASHRAE, Chapter 25 Table 3 (1997)
4	Single door	21 cm^2/item	ASHRAE, Chapter 25 Table 3 (1997)
5	Interior door (Closed)	140 cm^2/item	Emmerich and Persily (1996)
6	Interior wall (Masonry)	2 cm^2/m^2	Emmerich and Persily (1996)
7	Jalousie window	3.38 cm^2/item	ASHRAE, Chapter 25 Table 3 (1997)
8	Bathroom door (Closed including undercut)	330 cm^2/item	Persily (2000)
9	Ceiling	1.8 cm^2/m^2	Persily (1998)

Table 3. Operating schedules of air condition in living area including dining and kitchen on the first floor and bedrooms on the second floor.

Date	Rooms	Operation time
Monday-Friday	Living and Dining	18:00-20:00
	Bedrooms	22:00-06:00
Saturday-Sunday	Living and Dining	14:00-22:00
	Bedrooms	22:00-10:00

4. Results

In this section, the calculated air infiltration rates are discussed into three following topics:

1) How is envelope airtightness for typical modern Thai homes?
2) Can ventilation rate in Thai homes achieve the ventilation standards?
3) Is the default infiltration rate prescribed in energy models reliable to use?

4.1 Envelope airtightness for modern Thai homes

Figure 5 presents the distribution of calculated air infiltration rate (ACH) for 134 homes from 137 housing developments compared with the air infiltration rate investigated by the existing studies (Grot et al., 1979; Pandian et al., 1998; Persily et al., 2010; Yamamoto et al., 2010; Suthi, 2011). It was found that the calculated air infiltration rates for the tested homes varied over a range of 0.33-0.58 h^{-1}, which was considered air-tight envelope. The CIBSE guide A (2006) specifies the average air infiltration rate defined for tight building of 0.35 h^{-1}, (horizontal dashed line). The previous study (Suthi, 2011) investigated air infiltration in a modern Thai home of 0.55 h^{-1}, which was in the top rank of the calculated range of the tested homes. In comparison with the traditional Thai home, the calculated air infiltration rates for the modern Thai homes with masonry wall system were approximately half of the rates of the traditional Thai home, which has a ventilated prefabricated timber wall system. The range of air infiltration rates calculated in the tested homes was considerably lower than the air infiltration ranging from 0.22 - 0.87 h^{-1} investigated in the U.S. homes (Grot et al., 1979; Pandian et al., 1998; Persily et al., 2010; Yamamoto et al., 2010).

4.2 Ventilation rate requirement for residential building

The ASHRAE ventilation Standard 62.2-2007 specified the ventilation rate, which maintains acceptable indoor air quality for low-rise residential building (ASHRAE, 2007). Figure 6 presents a cumulative probability distribution for the average air infiltration rate (ACH) calculated in the studied homes compared to the calculations following the Standard 62.2-2007 According to the Standard 62.2-2007, the dashed and center lines are the calculated air infiltration rates ranging from 0.18-0.32 h^{-1} with an average value of 0.26 h^{-1} (s.d.= 0.03) and total ventilation rates ranging from 0.15-0.18 h^{-1} with an average of 0.17 h^{-1} (s.d.=0.004) of the tested homes, respectively. The calculated air infiltration rates were approximately two-third of the total ventilation rates prescribed in the Standard 62.2-2007 However, the calculated ventilation rates required in the Standard 62.2-2007 were under the ventilation code for living space of 0.35 h^{-1} (vertical solid line) defined by the Thai Building Control Act B.E. 2522 (2015). The calculated air infiltration rates obtained from the simulation model ranged from 0.33 - 0.58 h^{-1} with an average value of 0.4 h^{-1} (s.d.=0.04). This range was approximately 1.7 times greater than the required whole ventilation rate defined by the Standard 62.2-2007 and 97 percent of the studied homes has the air exchange rates above the ventilation code defined by the Thai Building Control Act B.E. 2522 (2015).

Figure 7 presents the room ventilation rate including the air infiltration from ambient zone (grey box) and the air infiltration from adjacent zones (white box) in comparison to the required ventilation rate prescribed in the Standard 62.2-2007 normalized by the room area (circle symbol). Such transient airflow rates between the zones were calculated using Equation

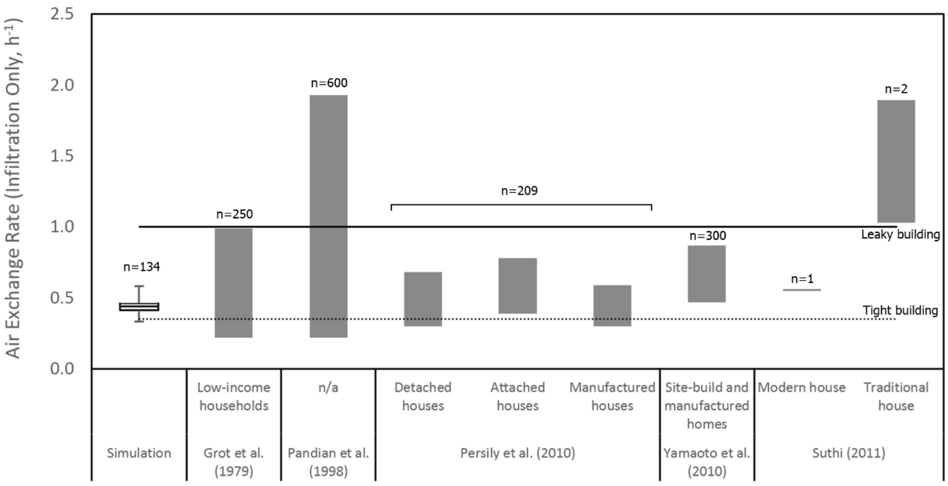

Figure 5. Distributions of the calculated air infiltration rates compared with the rates investigated in previous studies and the airtightness characteristics defined by the CIBSE guide A (2006).

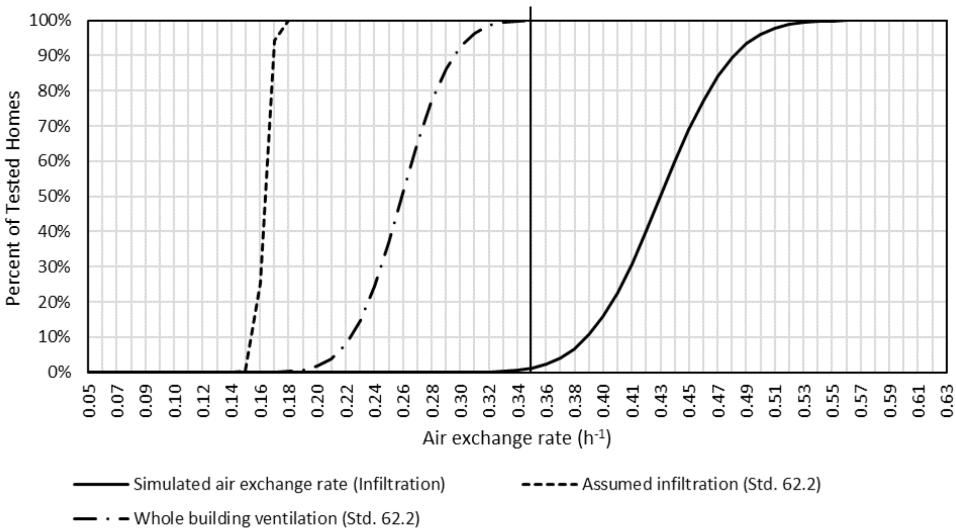

Figure 6. Cumulative distribution curves for the air infiltration rate (ACH) assumed by ASHRAE Standard 62.2-2007 (dashed line), whole building ventilation rate requirement defined in the Standard 62.2-2007 (center line), and the calculated air infiltration rates from the tested homes (solid line). The vertical line represents the air exchange rate defined by the Thai Building Control Act B.E. 2522 (2015)

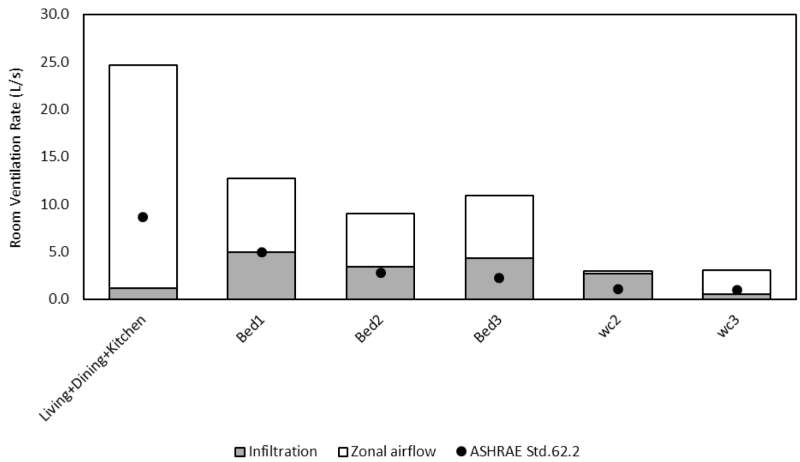

Figure 7. Comparison of the calculated room ventilation rates including the air infiltration from ambient zone (grey box) and the air infiltration from adjacent zones (white box) with the required ventilation rate prescribed by the ASHRAE Standard 62.2-2007 (black circle).

(4) and the total airflow rate to the studied zone is the sum of the air infiltration rates from ambient zone and from adjacent zones. It was found that only outdoor air infiltration (grey box) of 1.2 L/s for living area including dining and kitchen was considerably lower than the standard requirement of 8.7 L/s (black circle). However, if the air infiltration from adjacent zones (white box) was accounted for, the ventilation rate for the living room increased to 25 L/s, which achieved the standard requirement. The outdoor air infiltration for the bedrooms and bathrooms on the second floor were equal and greater than the required ventilation rate. According to the simulation model, the outdoor air infiltration was found in the rooms on the second floor. The ventilated air from the second floor then flew though living space and exited the building at the first floor since the outdoor temperature setting in the model was higher than the assumed room air temperature.

According to the simulation results, the modern Thai homes have sufficient ventilation rate, which maintains acceptable indoor air quality based on the ASHRAE Standard 62.2-2007 and Thai Building Control Act B.E. 2522 (2015). However, when the ASHRAE Standard 62.2-2007 is applied, the range of outdoor air ventilation for the modern Thai homes is considerably high. To reduce energy consumption and energy cost from such exceeding ventilation rate (air infiltration), the amount of air infiltration rate might be possibly reduced by approximately one-third. However, reduced ventilation rate (air infiltration) might lead to poor indoor air quality, especially the contaminants generated from cooking activity or moisture from bathrooms.

4.3 Input of default air infiltration rate in energy models

In energy model, the modeler has to fill information of building ventilation including mechanical ventilation and air infiltration through building envelope to calculated heating and cooling load. Mechanical ventilation rate can obtain from specific value provided in the design document while unexpected air infiltration rate only get from field investigation. Air infiltration measurement in homes requires time effort and has accessibility limitation. Consequently, the modelers typically assume air infiltration rate by using the default value embedded in the energy models. The default air infiltration rate in eQUEST model is 0.00192 $m^3/s.m^2$ (Hirsch, 2010) whereas the default air infiltration rate in DesignBuilder and Ecotect is 0.5 h^{-1} (DesignBuilder, 2009; Marsh, 2006). Those default air infiltration rates in the energy model typically obtained from the field measurements. However, such air infiltration rates might not be a good representative for the air infiltration characteristics for modern Thai detached homes since the home construction system and climate condition are different.

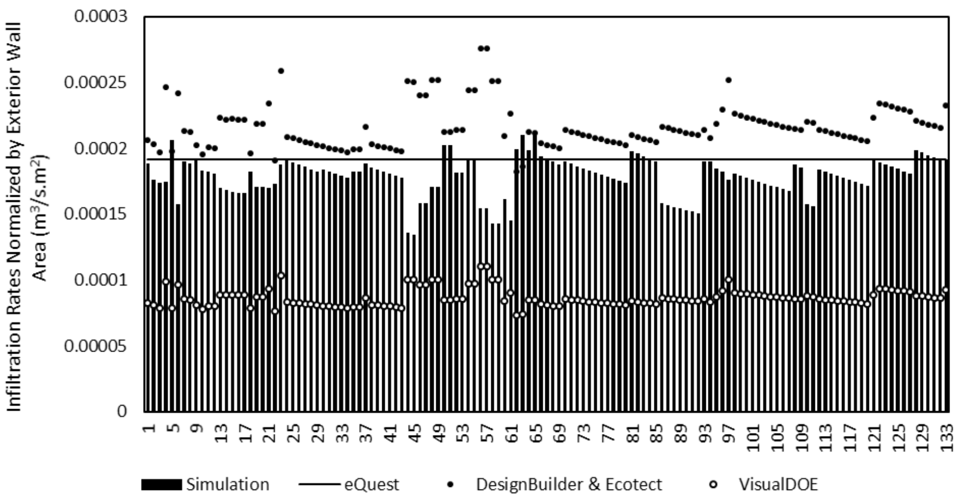

Figure 8. Calculated air infiltration rates normalized by the envelope area when compared with the default air infiltration rates provided by four energy models.

Figure 8 presents a comparison of calculated air infiltration rates normalized by envelope area with the default air infiltration rates for four energy models. According to the air infiltration rate calculated from 134 modern Thai detached homes via using CONTAM model, the calculated air infiltration rates ranged from 0.00135–0.0021 $m^3/s.m^2$. Ten percent of the calculated air infiltration rates were lower than the default air infiltration rate of 0.00192 $m^3/s.m^2$ in eQUEST model (horizontal line). When normalized the default air infiltration rate of 5 h^{-1} (in DesignBuilder and Ecotect) by envelope area, the air infiltration rates ranged from 0.0018-0.0028 $m^3/s.m^2$ (black circle), which were mostly greater than the air infiltration rates calculated in this present study. The default air infiltration rate of 0.2 h^{-1} (0.0007-0.0011 $m^3/s.m^2$ white circle) used in VisualDOE (Architectural Energy Corporation, 2004) was relatively lower than those in other models as well as the rate calculated in this present study.

Table 3 presents the calculation of maximum and average errors of default air infiltration rates in the energy models when compared to the air infiltration calculated in this present study. The calculation of average errors uses Equation (7). It was found that the use of default air infiltration rate in the energy models provided a maximum error ranging from 7% to 65%. The default air infiltration in eQUEST model provided more reliable input air infiltration rate than those in other models. The average input error was only 7% (s.d.=7) while DesignBuilder and Ecotect models had the average input error of 17% (s.d.=10). The highest average input error of 51% (s.d.=7) was found in VisualDOE. Such errors might lead to unreliable calculated home energy performance.

$$\overline{err} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|Inf_{cal} - Inf_{def}|}{Inf_{cal}} x100\right) \quad (7)$$

where N is number of air infiltration rate calculated from the tested home. Inf_{cal} is the calculated air infiltration rate and Inf_{def} is the default air infiltration rate provided in energy model, L/s.

5. Study limitations

This present study used a numerical multi-zone model, CONTAMW to perform air infiltration rates in a typical layout, observed in Thai detached housing stock. Consequently, the range of calculated air infiltration rates represents only a specific one home layout. In this present study, the air infiltration rates are calculated with the assumptions that 1) there is no cooking activity; 2) the exhaust fan is not operated; 3) the air condition is operated at balance airflow rate; and 4) the exterior and interior doors are closed. As a consequent, the estimated air infiltration rate might be lower than the rates when those assumptions are considered in the simulation model. Concerning the home energy consumption, it is recommended that the ventilation rate (air infiltration) can be reduced by one-third. However, the present study did not perform energy analysis, which cannot present how energy saving due to reduced ventilation rate. As indoor air quality concern, the reduced ventilation rate might increase indoor contaminant concentrations, especially pollutions from cooking activity and moisture from bathroom. Future study should investigate the impact of reduced ventilation rate on both energy saving and indoor contaminant control. To increase more accuracy of the air infiltration database, future

Table 3. Default air infiltration rates and the errors between its default value and the calculated air infiltration rate for four energy models.

Parameters	eQuest (2011)	Design Builder (2009)	Ecotect (2006)	VisualDOE (2004)
Default value	0.00192 $m^3/s.m^2$	0.5 ACH	0.5 ACH	0.2 ACH
Maximum input error	30%	46%	46%	65%
Average input error	7%	17%	17%	51%
Standard deviation (s.d.)	7	11	11	7

studies should validate the simulation results with field experiment data. In addition, the air infiltration calculation should be investigated more home layouts and construction types, especially pre-cast concrete wall, since a range of air infiltration rates might differ from the range calculated in this present study.

6. Conclusions

This paper developed the database of air infiltration rates for the modern Thai detached homes based on the calculation using a multi-zone model. The typical Thai homes are considerably airtight with a range of air exchange rate (air infiltration) of 0.33-0.58 h^{-1}. This range of air exchange rate can provide acceptable ventilation rate prescribed by the Ventilation Rate Procedure (VRP), which was approximately 1.7 times greater than the required ventilation rate defined in the ASHRAE Standard 62.2. Consequently, the air infiltration rates for modern Thai homes could be reduced by approximately one-third. It is noted that the default air infiltration rates used as an input in energy models had maximum error ranging from 7-65% when compared to the air infiltration rates calculated in this present study.

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