Simulation of Natural Airflow in Sustainable Atriums: Case Studies of the Semi-Open Educational Buildings

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Abstract

During the past decade, new trendy semi-open educational architectures in the Bangkok suburb have provided larger multi-purpose atriums in the concept of environmental dependency. Saving energy, facilitating semi-outdoor activities, and having a green atmosphere are the benefits of sustainable atriums. Natural ventilation is a key factor to promote the well-being environment in the semi-open atriums. The research aims to study how architectural spaces and forms influence airflow patterns of case studies by computer simulation. Computational fluid dynamics (CFD) simulation helps to reveal the airflow behaviors inside the atriums. The methods start with analyzing the case studies by calculations, secondly mocking up virtual models of case study buildings, thirdly testing by wind tunnels in CFD simulation, and finally analyzing the results. The results are relationships of natural wind, building openings, and airflow patterns analyzed by observing, theories, and concluding the information. The outcomes show that 1) Orientations, positions, and sizes of openings are the major factors affecting airflow patterns. 2) Airflow and air change rates tell the levels of airflow efficiency. 3) The simulation results show real-time perspective views of airflow patterns in the semi-open atrium of the buildings. The researcher would like to recommend that creative developments of the sustainable building type should be promoted continuously in the future. The building design of natural ventilation in semi-open atriums should have real-time CFD simulation in the process. This research should benefit those people who are concerned with educational buildings or interested in studying the semi-open spaces in a hot and humid environment.

Keywords: *Natural Ventilation, Airflow, Semi-Open Atrium, Educational Building, Air Velocity, CFD Simulation*

1. Introduction

During the past decade, the new educational buildings have provided the trendy semi-open atriums in the heart of the buildings. These provocative academic buildings with huge semi-open atriums are mostly located in university campuses in the Bangkok suburb. The new sustainable atriums of buildings have followed the trend of environmental dependency in the tropical architecture theory. The green concepts of dependency are purposed for the atriums to save energy, be friendly to the environment, facilitate the academic activities, and create a green atmosphere. The use of natural ventilation in public buildings helps lower initial, running and maintenance costs and lower energy consumption and carbon emission. The natural sunlight and open-air ventilation in public spaces promote a healthier well-being of the environment (WHO, 2009). Natural ventilation is an important factor to promote human comfort in semi-outdoor spaces in a hot and humid region (ASHRAE, 2017). Therefore, the atriums of educational buildings should provide adequate airflow patterns. The research aims to investigate the relationships between the atrium characteristics and the effects of airflow inside the atriums. The following literature reviews tell the scope of the study, the importance of natural ventilation and the technical knowledge of airflow and atrium openings;

1.1 Scope of the study

The semi-open atriums in academic buildings provide public spaces that are opened for natural light and ventilation. The atrium is the open-air grand reception hall with multi-purpose spaces under a wide-span transparent roof and is surrounded by public facilities and upper-level classrooms. The multi-purpose spaces promote activities outside the classroom, such as self-learning, group learning, reading, relaxing, socializing, seminars, exhibition, and presentation. The semi-open architecture is friendly to the environment because of their openness which admits a large amount of natural light and fresh air into space.

One of the early semi-open atriums in academic buildings is the Mahidol learning center (MLC) built in 2011. The MCL building provides a grand atrium surrounded by multi-function spaces. One of the latest semi-open atriums is the student center of Rangsit University (SC) built in 2017. The SC building provides a giant multi-purpose space surrounded by shops, dining areas, and classrooms which serve most of the student activities outside the classroom. Examples of the early and latest atriums are shown in Figure 1.

Figure 1 Left: Atrium of the MLC building (Source: pantip.com) and Right: Atrium of the SC building

The research aims to study the effects of airflow inside the case studies of semi-open atriums and discuss how the building shapes and their openings relate to the outcoming airflow patterns. The study is focused only on the wind-driven ventilation effects on the buildings. The airflow patterns inside the case studies will be studied by using computational fluid dynamics (CFD) simulation. The relationships between the atrium characteristics and the effects of airflow inside the atriums will be investigated.

1.2 Benefits of natural ventilation

Natural ventilation is a key factor to promote well-being for the semi-open atriums in Bangkok suburban area. The natural force of wind contributes to the stage of well-being through the movement of air. Natural ventilation can provide significant health benefits such as intake of clean fresh air and also enhance the cooling of buildings, yielding up to 25-50% in energy savings (WHO, 2009). Fresh air is required to achieve a healthy and comfortable building environment. Natural ventilation can ensure and support the supply of adequate breathing air, adequate ventilation of contaminants, adequate thermal conditioning, and moisture dissipation. The effect of airflow in a building depends on natural wind direction, building orientation, site environment, plan organization and vent openings (Loftness and Haase, 2013).

Providing suitable natural airflow in the semi-open atriums could promote human comfort. In a hot and humid climate, the non-air-conditioned building should protect heat from the sun and provide good natural ventilation (Passe & Battaglia, 2015). Natural ventilation helps extend the limit of the thermal comfort zone and develop physiological cooling. Air movement makes people feel cooler by the effects of heat convection and sweat evaporation from the human body. People feel differently in air movement as in Table 1. Different airspeed makes people feel differently in temperature by the following formula (Szokolay, 2004);

$$dT = 6 * v_e - 1.6 * v_e^2 \qquad \text{(Equation 1)}$$

where dT = different temperature of physiological cooling (°C), v = effective air velocity at body surface (m/s), $v_e = v - 0.2$, valid from 0.2 to 2 m/s and the situation of clothing at 0.4 clo and activity at 1.5 met

Table 1 Personal reactions and perception of different temperature to airspeed

Airspeed (V; m/s)	Personal Reaction (Feeling)	Perception of Different Temperature (dT; °C)
< 0.1	Stuffy	-
to 0.2	Unnoticed	0
to 0.5	Pleasant	to 1.66
to 1.0	Awareness	to 3.78
to 1.5	Draughty	to 5.10
to 2.0	Annoying	to 5.62

The highest temperature of the comfort zone for humans normally does not exceed about 27.75 °C when humidity is lower than 75 %RH. With natural ventilation, the limit of comfort zone could extend to about 29.75 °C when humidity does not exceed 87 %RH. (Grondzik, et al, 2010).

Airspeed could help extend the limit of the comfort zone. By increasing of average airspeed of 0.10-0.80 m/s, the acceptable ranges of operative temperature could extend from 0-3 °C, for the 1.0-0.5 clo and 1.1 met. Average airspeed (V_a) is also used to calculate operative temperature as the following formula (ASHRAE 55, 2017);

$$t_o = At_a + (1 - A)\, t_r \qquad \text{(Equation 2)}$$

where t_o = operative temperature, t_a = average air temperature, t_r = mean radiant temperature (MRT), A can be selected from the following values as a function of the average airspeed (V_a) in Table 2.

Table 2 A values according to the average airspeed

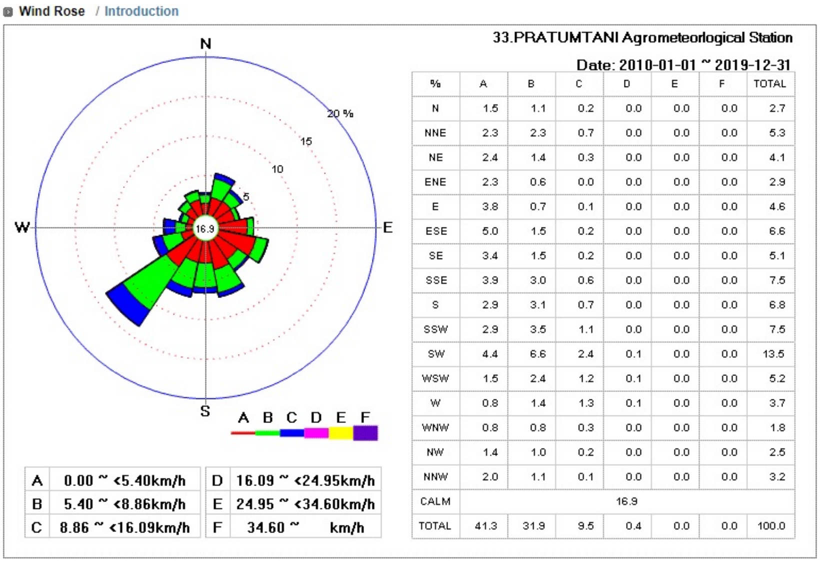
V_a	<0.2 m/s	0.2 to 0.6 m/s	0.6 to 1.0 m/s
A	0.5	0.6	0.7

1.3 Data and Calculations of airflow

In this natural ventilation research, the airflow is due only to cross-ventilation where wind induces through openings on different sides of walls. The factors that influence the airflow through openings are wind direction, wind speed (V), wind pressure (P_w), airflow rate (Q), air change rate (ACH), and effective area of multiple openings (A_{eff}) (CIBSE, 2010). Research of wind and calculations of airflow are listed as follows;

1) Wind Direction

The average wind condition in a ten-year period (2010-2019) measured at Pathum Thani agrometeorological station in the Northern suburb of Bangkok can be seen in the wind rose, shown in Figure 2. The major wind direction is from South West (SW) and the average wind speed measured at 10-meter height is between 5.40-8.86 km/h (1.5-2.5 m/s) (TMD, 2020). The mean wind speed is 2 m/s.



A	0.00 ~ <5.40km/h	D	16.09 ~ <24.95km/h
B	5.40 ~ <8.86km/h	E	24.95 ~ <34.60km/h
C	8.86 ~ <16.09km/h	F	34.60 ~ km/h

%	A	B	C	D	E	F	TOTAL
N	1.5	1.1	0.2	0.0	0.0	0.0	2.7
NNE	2.3	2.3	0.7	0.0	0.0	0.0	5.3
NE	2.4	1.4	0.3	0.0	0.0	0.0	4.1
ENE	2.3	0.6	0.0	0.0	0.0	0.0	2.9
E	3.8	0.7	0.1	0.0	0.0	0.0	4.6
ESE	5.0	1.5	0.2	0.0	0.0	0.0	6.6
SE	3.4	1.5	0.2	0.0	0.0	0.0	5.1
SSE	3.9	3.0	0.6	0.0	0.0	0.0	7.5
S	2.9	3.1	0.7	0.0	0.0	0.0	6.8
SSW	2.9	3.5	1.1	0.0	0.0	0.0	7.5
SW	4.4	6.6	2.4	0.1	0.0	0.0	13.5
WSW	1.5	2.4	1.2	0.1	0.0	0.0	5.2
W	0.8	1.4	1.3	0.1	0.0	0.0	3.7
WNW	0.8	0.8	0.3	0.0	0.0	0.0	1.8
NW	1.4	1.0	0.2	0.0	0.0	0.0	2.5
NNW	2.0	1.1	0.1	0.0	0.0	0.0	3.2
CALM	16.9						
TOTAL	41.3	31.9	9.5	0.4	0.0	0.0	100.0

Figure 2 Wind rose in the Northern suburb of Bangkok (TMD, 2020)

2) Wind speed

The incoming wind speed is usually calculated at the height of the opening or a reference point on the building by using the following formula (CIBSE, 2010);

$$V / V_{10} = c\ H^{a} \qquad \text{(Equation 3)}$$

where V = the required win speed at height H (m), V_{10} is reference wind speed (at 10 m in open country), c and a are the terrain factors depending on sheltering location (in the countryside with scattered windbreaks, $c = 0.52$, $a = 0.20$)

3) Wind pressure

Wind pressure is deployed on the "windward" and "leeward" sides of the building. The windward pressure varies along with the height of the building, while the leeward pressure is assumed to be constant. Static pressure at a reference point on the building can be calculated as follow (CIBSE, 2010);

$$P_w = ½\ \rho \cdot V^2 \cdot C_p \qquad \text{(Equation 4)}$$

Where P_w = static pressure at some point on the building (Pa), ρ = density of free stream (kg/m^3), V = free stream velocity normally calculated at building height or other reference height (m/s), and C_p = static pressure coefficient (Pa); $C_p = (P_w - P_o) / (1/2\ \rho \cdot V^2)$ where P_o = static pressure of the free stream (Pa)

4) Airflow rate

The natural ventilation rate or the rate of wind-driven airflow through an opening can be calculated using the following formula (WHO, 2009);

$$Q = 0.65\ V \text{ x } A \text{ x } 1000 \qquad \text{(Equation 5)}$$

where Q = airflow rate, or volumetric flow rate through the opening (l/s), 0.65 = discharge coefficient, V = Wind speed (m/s), A = Sum of smaller opening areas of either inlet or outlet (m^2)

5) Air change rate

As a rule of thumb, wind-driven natural ventilation rate through a room with opposite inlet and outlet openings can be calculated as the following formula (WHO, 2009);

$$ACH = \frac{0.65 \times V \times A \times 3600}{Vol} \quad \text{(Equation 6)}$$

Where ACH = air changes per hour (ACH), V = Wind speed (m/s), A = Sum of smaller opening areas of either inlet or outlet (m^2), Vol = volume of the room (m^3)

According to the ASHRAE standard, the minimum ventilation rate in breathing zone for a multi-use assembly area and a lecture classroom in educational facilities is recommended at 0.3 $L/s{\cdot}m^2$ of floor area (ASHRAE, 2010). Whereas in Thai building regulations, the minimum ventilation rate in the hallway and classroom must not be less than 2 $m^3/h{\cdot}m^2$ and 4 $m^3/h{\cdot}m^2$ correspondingly. And the minimum opening area for a non-air-conditioning usable room must not be less than 10 % of the floor area of the room. The minimum air changes per hour (ACH) for an equivalent public hall is 3 times of room volume per hour (ASA, 2017).

1.4 Characteristics of openings

Characteristics of openings are the factors that influence the airflow pattern from natural wind-driven ventilation. Opening characteristics and effective area of openings can be categorized as follows;

1) Orientation of openings

Building orientation should be shaped to expose maximum openings to wind directions. If an opening of a façade faces 90 degrees to the wind direction, it will have maximum wind pressure and get maximum air velocity. However, horizontal inlet openings in several directions are desirable when the wind speed and direction are not constant. (ASHRAE, 2017).

2) Positions of openings

Openings' positions should be located in opposing high and low-pressure zones. Two openings on opposite sides of a space increase cross-flow ventilation. When two openings are oblique or in angle sides of a room, incoming air velocity is lower but there is more average velocity and better distribution inside the room. To be effective, air movement should flow through the activity zone and distribute through the whole usable space. The different levels of openings should promote the upward air movement to get rid of the inside heat which is the same direction of the stack effect (Atthakorn, 2019).

3) Sizes of openings

The ratio of the inlet and outlet opening areas affects the airflow pattern. In general, inlets should have the same size as outlets in order to allow a uniform flow rate across the building. The largest air velocity happens if the inlet is small and the outlet is large. The total force is acting on a small area and forcing air through the opening at high pressure. If the inlet opening is large, air velocity will be low but the volume of air passing in unit time will be higher (LEARN, 2004).

4) Types of openings

In semi-open atriums, there are two kinds of openings which are clear openings and louvers. There are two types of louvers that are commonly used as screening or heat vent under atrium roofs. One is 100 mm-spacing aluminum with 45 °angle louver and another one is 300 mm-spacing metal or fiber-glass with a 30 °angle louver. The airflow effective area of the 45 °angle louver is about 30 % of full-exposed opening and the 60 °angle louver is just about 20 %. However, louvers are useful for heavy rain protection while full-exposed voids need some architectural elements to protect from heavy rain and strong sunlight.

2. Objectives

The objectives of the research are as follows;

1) To simulate the airflow pattern inside the atriums of case studies by computer simulation.
2) To investigate the relationships between the atrium characteristics and the effects of airflow.

3. Materials and Methods

The materials of the research are the case studies and the tools. And the methods are the process of analyzing the case studies by computer simulation. The research materials and methods are as follows;

3.1 Case studies

The case studies are selected from the same building type and the nearby location. Every educational building has a large semi-open atrium in the center of the building. They are also located in the university campus areas in the Northern suburb of Bangkok. The variety of atrium spaces and opening sizes provides the variable elements for the study. These well-designed sustainable buildings are the new challenging trend of tropical architecture. The 4 case studies are as follows;

1) Flagship building, Silpakorn University, city campus (FB SUCC)
2) Faculty of learning sciences and education, Thammasat University (LSED TU)
3) Digital multimedia complex, Rangsit University (DMC RSU)
4) Operation building, faculty of Economics, Kasetsart University (ECON KU)

The pictures of the case studies are shown in Figure 4. The atrium locations are shown in Figure 5.

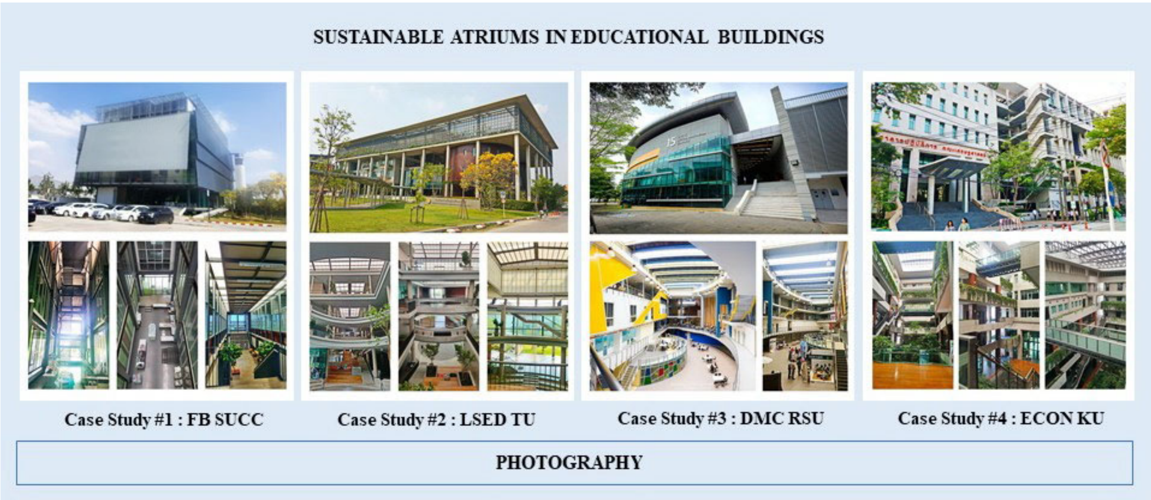


Figure 4 Pictures of semi-open atriums in educational buildings

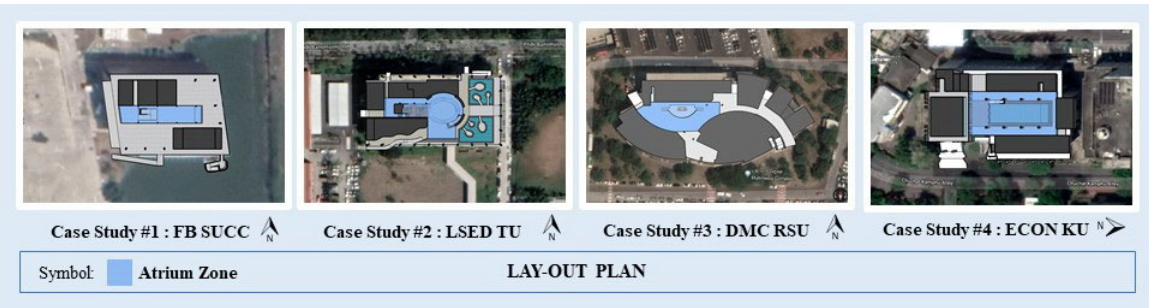


Figure 5 Lay-out plans and the atrium zones of the 4 case studies

3.2 Tools

The research tools used by a computer in the research office consist of the followings;

1) 2D Architectural drawing software

After the case study buildings are surveyed and physical data are collected, the architectural drawings are drawn by the 2D computer software. The software is AUTOCAD which gives the precise 2D drawings. And DWG files are used as data transfer files between 3D modeling and simulation software.

2) 3D modeling software

The 3D modeling software used in the research is SKETCHUP which is a simple and fast application to construct the models. The 3D space of the case studies can be easily created and adjusted to match the requirements of the simulation software. The isometric models of the main floor plans and the section models of the atrium buildings are created to be the input models for the simulation, as shown in Figure 6.

3) Simulation software

To analyzed the airflow inside the atriums, computational fluid dynamics (CFD) software is used as a wind tunnel simulation tool in this research. The software used in this research is FlowDesign. The simulation needs several settings, including model orientation, tunnel boundary, and incoming wind speed. The output data of the airflow pattern are shown as air velocity and air pressure. The graphic images of airflow are shown as flow lines and shaded planes.

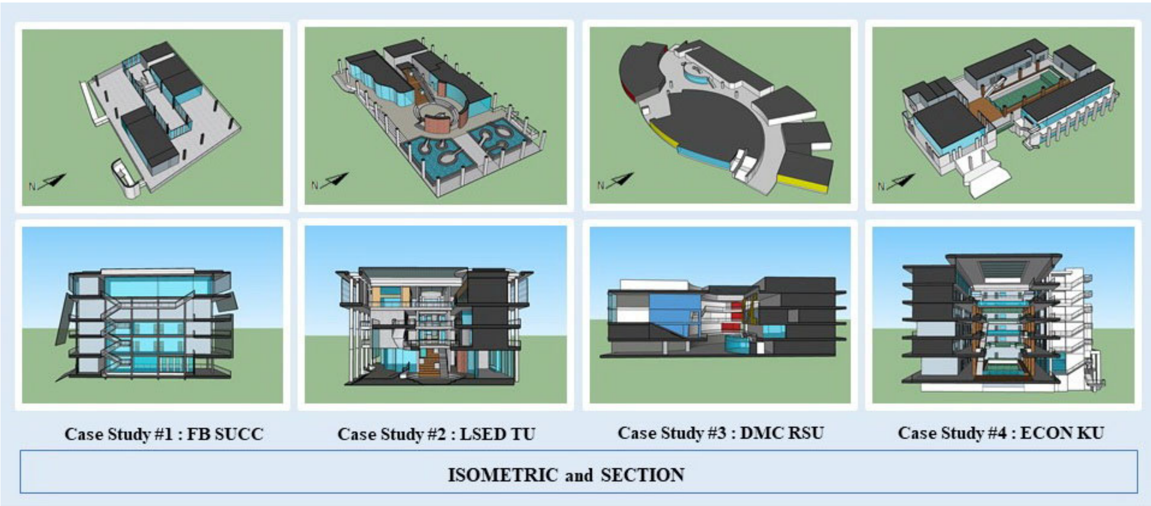


Figure 6 Isometric models of the main floor plans and the sections of the 4 case studies

3.3 Analysis of the case studies

The data analysis in this research aims to provide the building characteristics and the results of airflow patterns by analyzing process as follows;

3.3.1 Analysis of building characteristics

Since the effects of airflow inside an atrium depend mainly on the shape and the openings of the building, the analysis is focused on, as follows,

1) Percentages of the opening area to the atrium floor area, which are analyzed separately by main-floor openings, upper-floor openings, under-roof openings, and total openings.

2) The opening angles toward the incoming wind direction, which are calculated in degrees.

3) Relationships between inlet and outlet positions, which could be direct, oblique, or angle.

4) Relationships between inlet and outlet sizes, which could be about the same, larger to smaller, or smaller to larger.

3.3.2 Analysis of airflow patterns

The variables used for the analysis of airflow inside the case study atriums are as follows;

1) Independent variables which are 3D models of 4 case studies shown in main floor isometrics (Horizontal Plane) and building sections (Vertical Plane).

2) Control variables are the settings of the simulation software, including the incoming wind in South West (SW) and the wind speed average at 2 m/s. The horizontal measuring plane is 1.20 m high above the main floor plan and the vertical measuring plane is the section cut through the main space.

3) Dependent variables are the results of airflow patterns in the main floor and the section of the case studies. The graphic results are shown in horizontal and vertical views. The airflow patterns are shown in both flowlines and shaded planes. The results of air velocity are indicated by the color of dark blue, light blue, green, yellow, and red, which are the range of airflow speed level of 0 to over 4 m/s, as shown in the velocity indications.

3.3.3 Analysis of airflow characteristics

The outcome results of the airflow inside the case studies are to be classified as follows;

1) Airflow direction behaviors are described as strait, diagonal, angled, or turbulence.
2) Average speeds of airflow are scored in 3 levels as low, medium, or high.
3) Airflow distribution qualities are scored in 3 levels as low, medium, or high.

4. Results and Discussions

The results from the analysis of the building characteristics, the airflow characteristics, and the relationships of the atrium openings and airflow patterns are shown as follows;

4.1 Results of the analysis of atriums and openings

The analysis of the atriums and openings told that 1) There were 4 different sizes of atriums by volume, in order from smallest of case #1 to the largest of case #4. 2) There were 4 different ratios of total opening areas. Case #3 had the lowest opening ratio whereas Case #2 had a large amount of opening ratio. 3) Case #1 and #2 had a major opening area at the main floor whereas case #3 and #4 had a major opening area at the upper-floor level, 4) case # 1 had a few opening areas at the under-roof level whereas case # 2 had a lot of opening areas at the under-roof level. The table of the analysis is shown in Table 3.

Table 3 Analysis of Atriums Dimensions and ratios of openings to the main floor area

Case Study	Average Proportion Width:Length:Height W : L : H (m)	Floor Area W x L (m^2)	Atrium Volume W x Lx H (m^3)	A) Ratio of Main-Floor Openings Area to Fl. Area (%)	B) Ratio of Upper-Floor Openings Area to Fl. Area (%)	C) Ratio of Under-Roof Louver Area to Fl. Area (%)	Total Opening Ratio A+B+C (%)
1. FB SUCC	5.50 : 26 : 21.40	143	3,060	43.36	23.08	0.30	66.74
2. LSED TU	13.50 : 24.50 : 17	384	5,623	76.17	34.77	55.47	166.41
3. DMC RSU	16 : 50 : 13.50	800	10,800	12.56	24.37	10.75	47.68
4. ECON KU	20 : 40 : 24	800	19,200	14.62	46.12	22.5	83.24

4.2 Results of the airflow and air exchange rates by calculation

The calculations of airflow rate (Q) and air exchange rate per hour (ACH) were based on the formulas and input data from the literature reviews. The results of the calculation showed that 1) Case #2 had the highest air flow and air exchange rate. 2) Every case study achieved high above the standard requirements. 3) The under-roof openings with louvers had a low performance of ventilating, comparing to the clear openings. 4) However, the overall results of the airflow and air exchange rate were outstanding. The results of the calculations can be seen in Table 4.

Table 4 Results of airflow and air exchange rate by calculation

Case Study	Area of Clear Openings (m^2)	Area of Louver 45° (m^2)	Area of Louver 60° (m^2)	Total Area of Openings (m^2)	Sum of Inlet Areas (m^2)	Sum of Outlet Areas (m^2)	Volume of Atrium (m^3)	Airflow Rate (Q) (m^3/s)	Airflow Rate per square m (l/s·m^2)	Air change rate per hour (ACH)
1. FB SUCC	95	4	-	99	58	41	3,060	53.3	17.42	18.86
2. LSED TU	406	102	104	612	362	250	5,623	325.0	57.80	48.80
3. DMC RSU	295	86	-	381	275	156	10,800	202.8	18.78	17.82
4. ECON KU	486	-	180	666	254	412	19,200	303.2	17.20	16.31

4.3 Results of the airflow patterns by simulation

4.2.1 Results of flow-line airflow patterns

The results of flow-line airflow patterns of the 4 case studies told that 1) Case #1 had the most airflow speed moving across the narrowest atrium and case #4 had high airflow speed through the wide building. 2) Case #2 had air movements all over the space while case #1 and #3 had a few air movements with some air turbulence in the upper level. 3) Case #2 and # 3 had diagonal airflow in the atrium. 4) Case #2 and #3 had good airflow distribution in most of the usable areas. 5) Case #2 and #4 had airflow through the under-roof level. The pictures of the flow-line simulation are shown in Figure 7

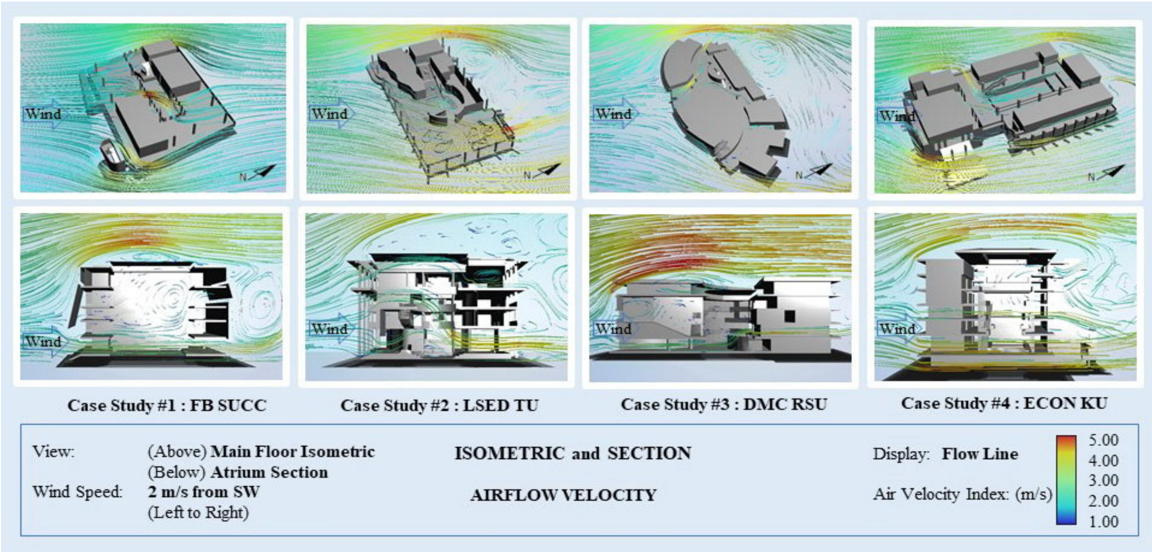


Figure 7 Results of flow-line airflow patterns of the 4 case studies

4.2.2 Results of shaded-plane airflow patterns

The results of shaded-plane airflow patterns showed that 1) Case #1 and #2 had an average airflow speed in most of the atriums in the plan. 2) Case #4 had the most airflow speed in the section whereas case #3 had the lowest airflow speed. 3) Case #3 had a more uniform airflow speed than the others. 4) Case #2 and #4 had high airflow speed in multi-level. 5) Case #2 had the fewest difference between inside and outside airflow speed whereas case #3 had the most difference. The pictures of shaded-plane airflow patterns are in Figure 8.

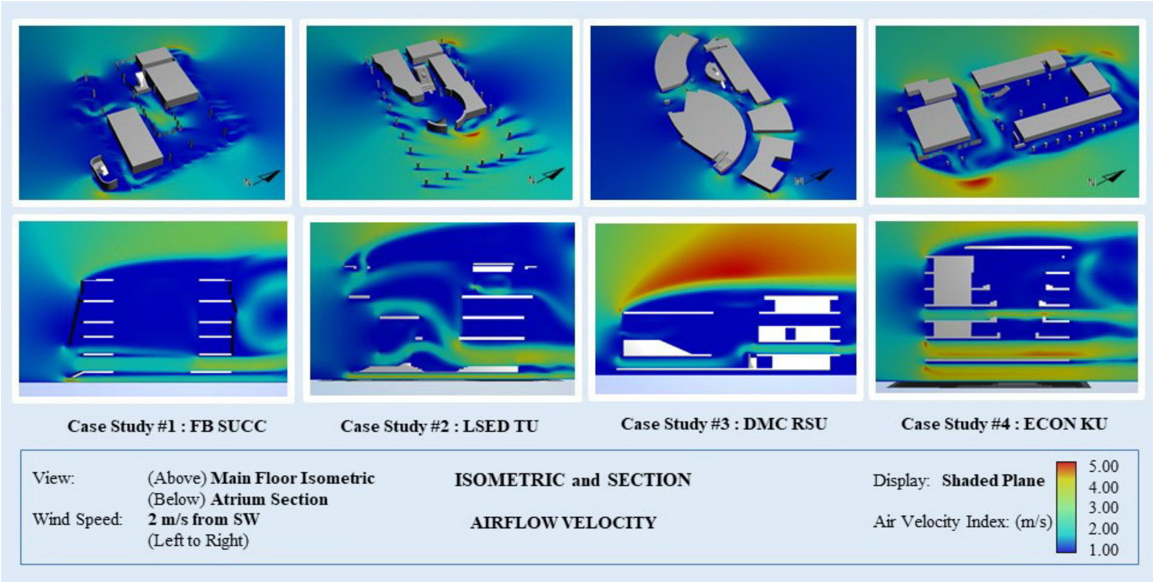


Figure 8 Results of shaded-plane airflow patterns of the 4 case studies

4.4 Relationships of the atrium openings and airflow patterns

The relationships analysis of openings and airflow patterns told that 1) Every case study caught the wind at a 45° angle to the wind direction. 2) When inlet and outlet positions were direct or oblique, the results of the average speed of the airflow were high as in case #1 and #4. Whereas angle positions and different levels of openings caused lower airflow speed but greater airflow distribution. 3) The same sides of the inlet to outlet in case #1 caused a high amount of airflow, and also the smaller inlet to larger outlet in case #4, caused a high speed of airflow whereas the larger to smaller openings caused lower airflow speed but high airflow distribution. 4) All airflow behaviors followed the direction between inlet and outlet positions. The analysis is shown in Table 5.

Table 5 Analysis of atrium openings characteristics and results of airflow patterns characteristics

Case Study	Input: Atrium Opening Characteristics			Output: Airflow Patterns Characteristics		
	Inlet Direction to the Wind	Inlet & Outlet Position	Inlet to Outlet Sizes	Airflow Direction Behaviors	Average Speed of Airflow	Airflow Distribution
1. FB SUCC	45°	Direct & Oblique	About the Same	Strait & Turbulence	High	Medium
2. LSED TU	45°	Angle & diff. lv.	Larger to Smaller	Angle & Downward	Medium	High
3. DMC RSU	45°	Angle & diff.lv.	Larger to Smaller	Angle & Upward	Medium	High
4. ECON KU	45°	Direct & Oblique	Smaller to Larger	Strait & Angle	High	Medium

5. Conclusion

From the analysis and simulation of the case studies, the major findings of this research were the effects of the atrium forms, spaces, and openings to the results of airflow patterns as follows;

1) Opening orientation

The more inlet openings opened to the wind direction, the more amounts of airflow there are. Although inlet openings of all case studies were oriented 45° to the wind from South West (SW), both of case #1 and #4 could have high average airflow speed. The inlet openings facing South and West could also have good results. This could be understood by the ASHRAE's recommendation that building orientation should be shaped to expose maximum openings to wind directions. (ASHRAE, 2017)

2) Opening position

Table 5 showed that when the positions of inlets and outlets were more direct. They provided higher airflow speed but having lower airflow distribution. On the other hand, when the position between inlets and outlets had more angle, they provided lower airflow speed, but they had higher airflow distribution. This could be explained by ASHRAE's recommendation that openings' positions should be located against high and low pressure zones. Two openings on opposite sides of a space increase cross-flow ventilation. When two openings are oblique or in angle sides of a room, incoming air velocity is lower but there is more average velocity and better distribution (Atthakorn, 2019).

3) Opening size

From Table 5, if the inlet to outlet sizes were about the same or the inlet is smaller than the outlet, the average speed of the airflow would be high. And if the inlet was larger than the outlet, the speed would be lower with better air distribution. This can be understood by the theory that in general, inlets should have the same size as outlets to allow a uniform flow rate across the building. The largest air velocity happens if the inlet is small and the outlet is large. If the inlet opening is large, air velocity will be low but the volume of air passing in unit time will be higher (LEARN, 2004).

4) Airflow rate and air change rate

From Table 4, Airflow rates gave a proportional sense of the number of opening areas while air change rates gave a proportional sense of opening areas to the volume of atriums. Results of the airflow rate per square meter told that the proportion of opening to the floor is a comparable indicator. The airflow rate and air change rate could tell the amount of airflow and the performance of the atriums. The calculations could be done by the formulas in Equation 5 and 6 (WHO, 2009).

5) Airflow pattern

The results of the airflow pattern from the CFD simulation could confirm the above conclusion. The graphic images of flow-line and shaded-plane airflow patterns gave perspective view in real-time of the result. The simulation results showed how the atriums forms and openings affected the airflow pattern.

This research has confirmed the assumption relating to natural ventilation theories. The case studies of the semi-open atrium in educational buildings have shown the high performance in generating good airflow qualities which are much higher than the regulations and standards. The researcher would like to recommend that creative developments of the sustainable building type should be promoted continuously in the future. And the building design process of natural ventilation in semi-open atriums should use real-time CFD simulation as a design tool. Hopefully, this research could benefit those people who deal with the semi-open space in a hot and humid environment. Further studies such as stack effect, natural daylighting, or thermal comfort in the educational buildings would be recommended.

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