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# Stack Ventilation for an Office Building with a Multi-Story Atrium

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***Abstract*—**This study examines the stack ventilation performance of an office building located in Taipei, Taiwan. Atriums in this building act as stacks that facilitate buoyancy-driven ventilation. Computational Fluid Dynamic (CFD) simulations are used to identify interior airflow patterns, and then used these patterns to assess the building's heat expulsion efficiency. Ambient temperatures of 20°C were adopted as the typical seasonal spring temperature range in Taipei. Further, "zero-wind" conditions are established to ensure simulation results reflected only the buoyancy effect. After checking results against neutral pressure level (NPL) level, airflow, air velocity, and indoor temperature stratification, the lower stack is modified to reduce the NPL in order to remove heat accumulated on the top floor.

***Keywords*—**Natural ventilation, side outlet, stack effect, thermal comfort.

## I. INTRODUCTION

PROVIDING good air quality indoor condition is a must in every building, despite its function. Good air quality means good airflow that can evacuate the heat from inside to outside the building. The indoor heat is caused not only by the climate condition, but also can be caused by the equipment, lighting and people inside. Good airflow will maintain interior temperature ambient in the comfort zone for the occupants [1], [2].

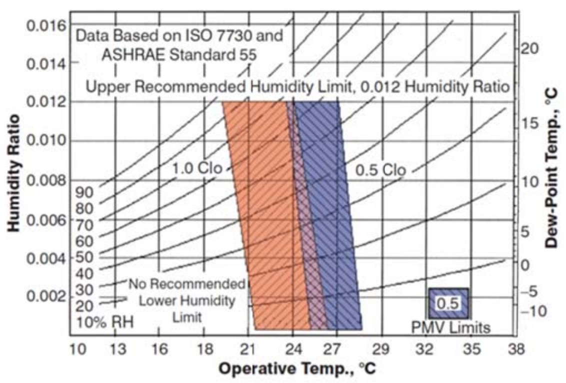


Fig. 1 Temperature in comfort zone [3]

'Occupant Comfort Zone' or 'comfort zone' represents standard of a suitable condition between environmental factors that leads occupants inside the building experience comfort feeling. Thus, indoor temperature is one major indicator whether comfort zone achieved or not. In spring condition, insulation value of clothing (clo) is around 0.5, with humidity ratio around 75% [4]. Based on Fig. 1, the limit of temperature in comfort zone is 21.5°C - 26°C. If the temperature inside in still under the comfortable limit, then it means the heat inside the building effectively removed [3].

Natural ventilation mostly are being translates as cross-ventilation natural ventilation. The wind-driven system is the most common natural ventilation system that most people can think of. Stack ventilation is a wind-free ventilation system. Which means to activate stack ventilation, wind is not necessarily needed [2].

In the absence of the wind or "zero-wind" condition, colder and heavier airflows go through the lower part of the opening, whereas warmer and lighter airflows through the upper part of the opening. These will result in temperature and density stratification within the stack [5]. Stratification in uniform ambient temperature consists of two layers. Upper layer is at uniform ambient temperature and lower layer is at uniform ambient temperature but in higher degree (depends on the heat source flux) [6].

Thus, a level can be defined at which no pressure difference occurs (the point where the pressure reaches the same value as outdoor pressure). This is called the 'Neutral Pressure Level (NPL)'. The direction of flow under the NPL is inflow and above the NPL is outflow [7], [8]. This neutral level located in h from the floor zone. The height determined by the ratio between upper and lower opening area size and independent from the heat source flux [6], [9].

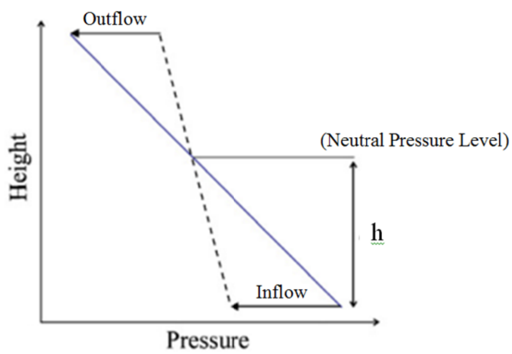


Fig. 2 Neutral Pressure Level scheme [8]

Nowadays, Computational Fluid Dynamics (CFD) is a very common tool to examine a building's performance in term of ventilation. With CFD, user can calculate and simulate the

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condition of indoor air quality. CFD provide relatively fast calculation for a wide spectrum of input data [5]. User can also gain prediction of the airflows inside and outside the building.

## II. Research Methods

### *A. Building Model*

The subject in this paper is an office building located in Taipei area. The building has multiple floors that are connected to the atrium which acted as stacks. The stacks are main natural ventilation for the building. Two stacks (upper part and lower part) are used, which assumed to provide proper air quality to each floor.

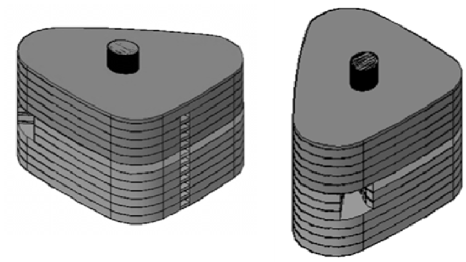


Fig. 3 Axonometric of the subject's overall shape

Each stack consists of two segments, chimney and atrium. Chimney is part of stack that doesn't have direct encounter with occupant's area and have solid wall boundary. In the other hand, atrium is part of stack that have direct encounter with occupant's areas. Occupant's areas are the area that ventilated by stacks, hence are called the public space.

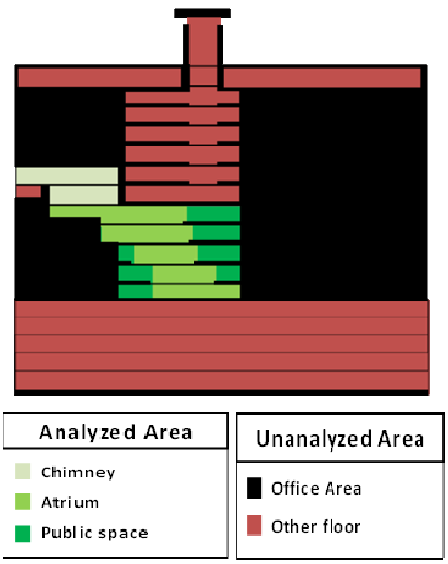



Fig. 4 Schematic section of the analyzed area

The lower part of the stack has 2 floors of chimney height and covering 5 floors. Furthermore, the shape of the stack is diagonal shape. These conditions are the focal points in this subject, which makes lower stack as main analyzed area.

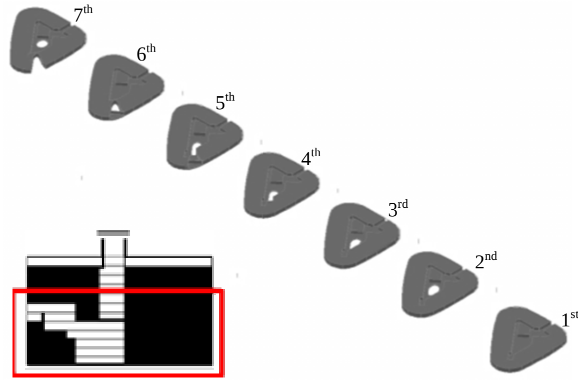



Fig. 5 Stack location on each floor

TABLE I
OPENING AREA SIZE ($M^2$)

| Floor | Inlet | Atrium | Chimney | Outlet |
|---|---|---|---|---|
| $1^{st}$ | 7.4 | 56.9 | - | - |
| $2^{nd}$ | 7.4 | 57 | - | - |
| $3^{rd}$ | 7.4 | 49.4 | - | - |
| $4^{th}$ | 7.4 | 50.2 | - | - |
| $5^{th}$ | 7.4 | - | 52.6 | - |
| $6^{th}$ | - | - | 52.6 | - |
| $7^{th}$ | - | - | - | 22.2 |

This paper is focusing on the stack performances. Thus, only the airflows in public area and stack location are analyzed.

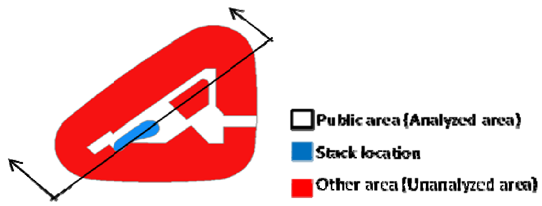



Fig. 6 Schematic plan of the analyzed area

This paper is focusing on the stack performances. Thus, only the airflows in public area and stack location are analyzed.

### *B. Temperature and Heat Source Setting*

Spring season in Taiwan start from February-May, which have temperatures vary from 16.5°C to 25.5°C [10]. From this range, we can deduct that the average temperature happen in spring season is 20.8°C (due to simplification, in the setting the temperature is set in 20°C).

The occupants, equipment and lighting loads at the floor level act as the source of heat and provide buoyancy driving the ventilation with a nearly uniform distribution of heat [4], [11].

According to table in Mechanical and Electrical Equipment for Building [4], the heat source consists of latent and sensible heat. Initially the sensible heat source set according the table (10.7 W/$m^2$), but this table imply in US condition. Since the subject is designed for 8 $m^2$/person, the sensible heat source value increases two times from 10.7 W/$m^2$ became 21.4 W/$m^2$. Since the analyzed areas are inside the building where have little natural daylight, lighting loads heat in office depends heavily on artificial lighting. Thus, Daylight Factor (DF) inside is less than 1, which means sensible heat gain from lighting loads is 16.1 W/m$^2$. When it added up with previous heat, total heat source become 37.5 W/m$^2$.

Latent heat in office work is 55 W for each person, means 6.9 W/m$^2$. This adds the total heat loads to 44.4 W/m$^2$. This amount of heat source presumably happens in formal office area, where the occupants are seated and wouldn't do much activity. The analyzed areas take place in the public areas near atrium (stack ventilation area). In public area, occupants do more activity than the formal office area. Activities like walking, running, or moving the equipment provide more heat around 60% [12] makes it increase to 70 W/m$^2$. Thus, maximum heat source in this simulation is set up at 70 W/m$^2$ and minimum at 40 W/m$^2$.

### *C. Boundary and Domain Setting*

The simulations use standard k-eps model for its turbulence calculation. Opening is set up in all boundary, from front-behind (x boundary), left-right (y boundary) and also the top boundary (upper z boundary). Top boundary is opened due to the buoyancy effect which air will flows from below to upper side. "Zero-wind" condition is set up in this boundary condition, purposed to analyze the model purely based on buoyancy effect only.

The CFD domain is given extra length especially in the top boundary. Despite at "zero-wind" condition, airflows are assumed going from inlet (lower part) to outlet (upper part) due the buoyancy effect. And the extra length make the calculation become more accurate.

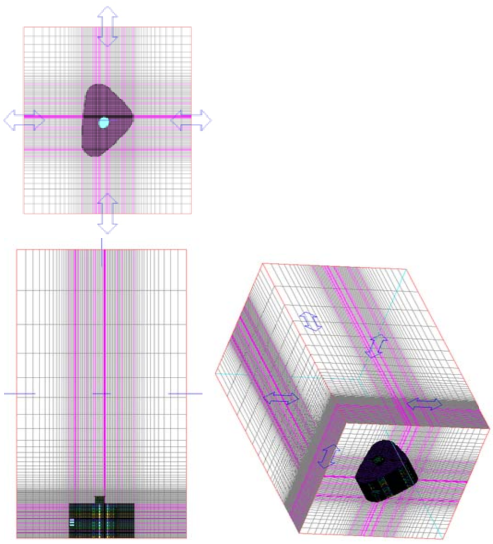


Fig. 7 Boundary opening and gridding domain condition (left to right: plan, elevation, axonometric)

The domain is being grid to represents the calculated space. To save computation expense, domain grids are not generated too dense. Roughly the element grid amount for the building is around 1.000.000 elements. The simulation is set up to converge after reach steady state analysis. The converge criteria for temperature and flow is $10^{-4}$.

## III. Simulation Validation

By using CFD for analyze the subject, user can get calculation result and also predict the airflow inside the building. The results are relatively fast compare using real model experiment. Even it is fast, the result's accuracy still needs to be proven. To prove that the used setting is accurate, the setting must undergo a series of validation process.

### *A. Setting Validation*

The validation for the setting is based on equation by **Linden** [6] as in

$$Q = A^*(g'H)^{\frac{1}{2}} \quad (1)$$

The values for the airflow equation are characterized by the uniform buoyancy flux, which driven by heat flux from the heat source.

$$g' = \left(\frac{B}{A^* H^{\frac{1}{2}}}\right)^{\frac{1}{2}} \quad (2)$$

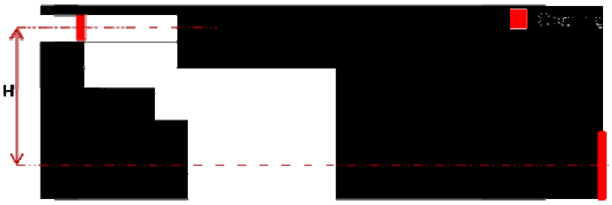
$$B = \frac{g\gamma W}{\rho C_p} \quad (3)$$

The heat source in this validation model is put in the middle of inlet height. The middle of the inlet height also represents the starting point of the stack height [6].

TABLE II
Units for Linden Equation

| Symbol | Quantity | Definitions |
|---|---|---|
| $Q$ | cubic meter per second (m$^3$/s) | Airflows rate |
| $A*$ | square meter(m) | Effective Area of the inlet and outlet enclosure |
| $g'$ | meter per square second(m/s$^2$) | Uniform buoyancy / reduced gravity |
| $H$ | meter (m) | Stack height (measured from the middle of inlet height until the middle of outlet height) |
| $B$ | m$^4$/s$^3$ | Total buoyancy flux into the space |
| $g$ | meter per square second (m/s$^2$) | Acceleration of gravity |
| $\gamma$ | - | Coefficient of expansion |
| $W$ | Watts per square meter (W/m$^2$) | Heat flux |
| $\rho$ | kilogram per cubic meter (kg/m$^3$) | density |
| $Cp$ | - | specific heat capacity at constant pressure |

All of validation model's setting condition is set up the same as the analysis model's setting condition. This includes the same initial temperature and the same heat source value. The only difference is in this validation model, inlet and outlet have same opening area size.

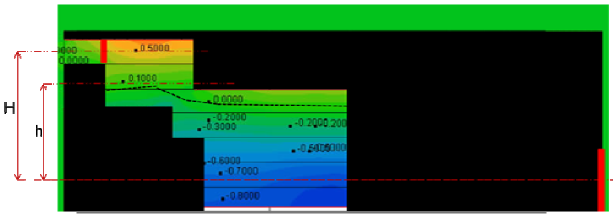



VARIABLES PROPERTIES

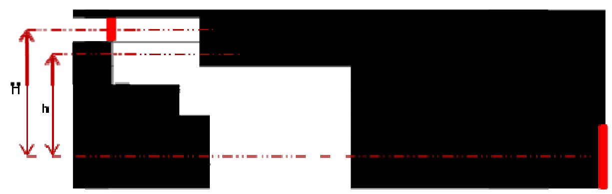
| Variable | Value |
|---|---|
| *W* | Total heat flux = 28,950 W/m$^2$ |
| *A** | Inlet area = 22.23m$^2$ |
| | Outlet area = 22.23m$^2$ |
| | →Effective area = 15.72 m$^2$ |
| *H* | Stack height = 15.3 m |

Fig. 8 Schematic figure and variables in the validation model

Simulation results that airflow rate in the Validation model is 10 m$^3$/s, whereas airflow rate based on Linden equation is 8.5 m$^3$/s.




(a) Validation model result; h = 11.4 m




(b) Equation result; h = 12.24 m

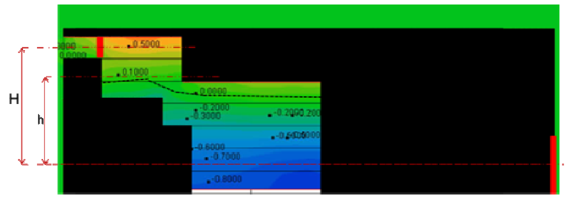
Fig. 9 Comparison of h between validation model result (a)with equation result (b)

Fig. 9 shows, the NPL height (symbolize with h) in the Validation model happens at 11.4 m. With equation, h results in 12.24 m. Both shows that the NPL located 4 floors higher from the heat source, with result from the simulation just slightly lower (7% difference) than the equation result. Thus, the results from the simulation and equation both have almost the same value.

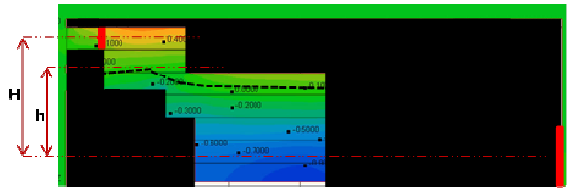
### *B. Grid Sensitivity Validation*

Grid Sensitivity validation model also applies the same setting as analysis model's setting condition. However, Grid Sensitivity Validation raised grid amount in validation model twice from the analysis model's amount.

Based on simulation results, the higher grid amount model has slightly higher airflows rate (10.9 m$^3$/s) and the lower grid amount model have lower airflow rate (10 m$^3$/s).Both result have almost the same result (the difference is under 10%)




(a) Lower grid amount result; h = 11.4 m



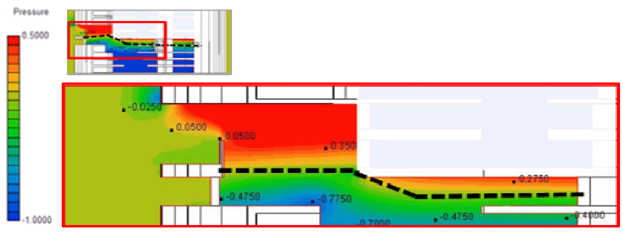

(b) Higher grid result; h = 11.6 m

Fig. 10 Comparison of h between lower grid amount model (a) with higher grid amount model (b)

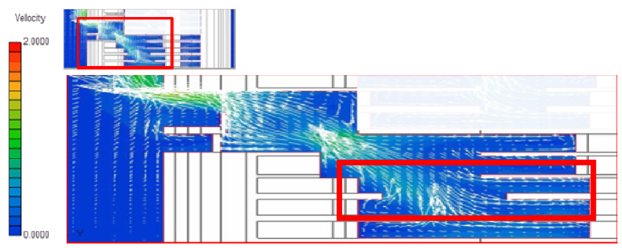
Fig. 10 shows that h in both results are almost at the same height. The most apparent difference between two models is in higher grid, the resolution is better and smoother image produced. This proves that the grid that used in the analysis model is good enough to be used for the simulation.

## IV. RESULTS AND DISCUSSION

### *A. Design Verification*




(a) NPL location

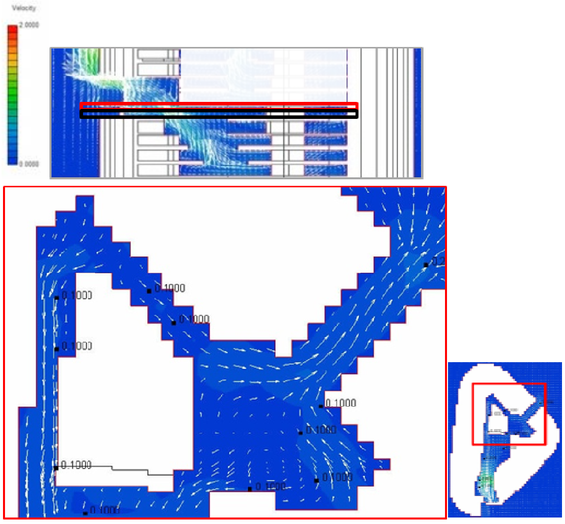



(b) Airflow direction

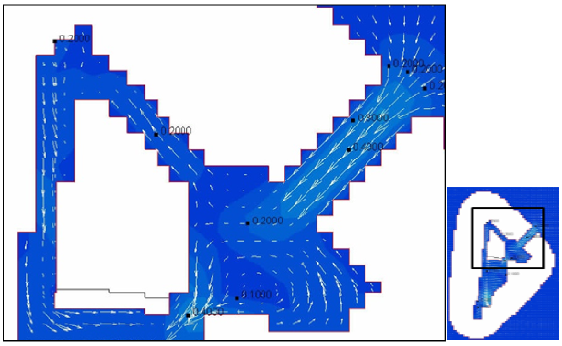
Fig. 11 Vertical air distribution condition. Simulation shows separated NPL location (a) and reverse airflow (b)

Fig. 11 displays that the NPL is separated between two segments. One is located in the chimney neck whereas the other is in the middle of the top floor. The latter causes reverse flow on the top floor (top floor have inflow and outflow).

The secondary NPL creates two airflows on top floor. Airflows at 1.5 m height examination are inflows, whereas airflows at 2m examination are outflows. Fig. 12 presents reverse flow that happens on the top floor.



(a) 2 m cut from the slab



(b) 1.5 m cut from the slab

Fig. 12 Detail images of the reverse flow in the top floor. (a) and (b) happen in the same floor, but results in different air direction

Reverse flow on top floor forms turbulences, which create stagnant area in the corner. Since the air is not moving in uniform direction, the heat can't be evacuated. Fig. 13 shows accumulated heat occurs on the top floor.

Fig. 14 shows that in 1st through 4th floor, temperatures in point 2,3,4,5 fall within comfort zone. The temperatures vary between 21°C to 26°C, with average 22.3°C. On point 6, temperatures steadily increase with 4°C to 6°C rise. Point 6 is located near the outlet, where heats bought by airflow pass toward the outside.

In the top floor there are heats accumulated. The temperature in top floor varies from 26°C to 32°C. However, the highest temperatures on the top floor are not near the outlet area just like other floors, but located on point 2, 3 and 4. This likely caused by high dense occupation on points 2, 3 and 4. Heat from the occupants can't escape because of the reverse flow.

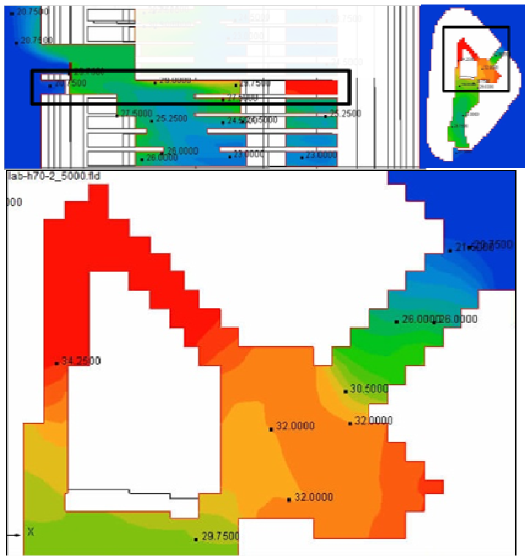


Fig. 13 Detail images of the top floor's temperature condition

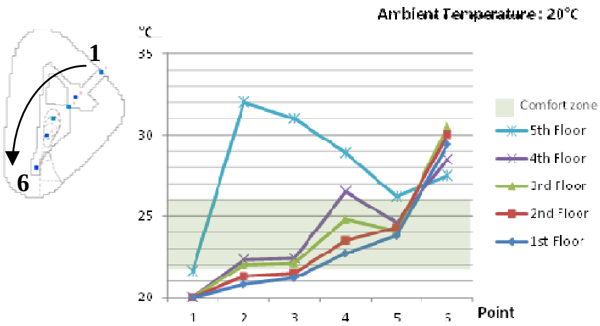
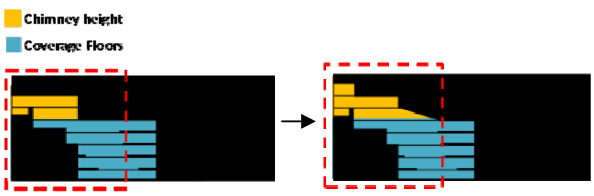



Fig. 14 Temperature value in points of each floor. This illustrates the temperatures difference condition between top floor with other floors

To provide more effective result in provide thermal comfort, modifications for the stack is needed. The modifications need to raise secondary NPL, in order to resolve the reverse flow.

*B. Design Modifications*

Modification for the stack consists of two actions, add extra chimney height and modify the ceiling of the upper floor of the lower stack.

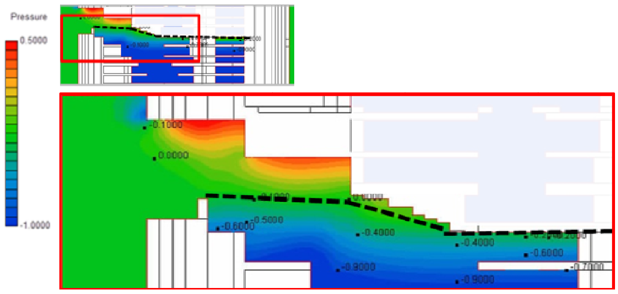



(a) before (b) after

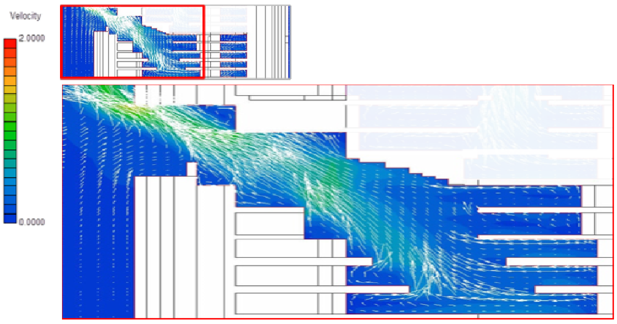
Fig. 15 Schematic section of the modifications

Lengthen chimney height makes h (height of the stack) become higher. Thus, airflows can come out more freely. This modification makes chimney height become higher from 2 floors to 3 floors (Fig. 15).

Fig. 16 shows that NPL become higher, improving heat evacuation on the top floor. Thus, more airflow goes through the inlet. And because the outlet chimney becomes higher, more airflow comes out through the outlet. As Fig. 17 displays, in top floor more heat can be evacuated.



(a) NPL location



(b) airflow direction

Fig. 16 NPL condition (a) and airflow direction (b) in improvement model

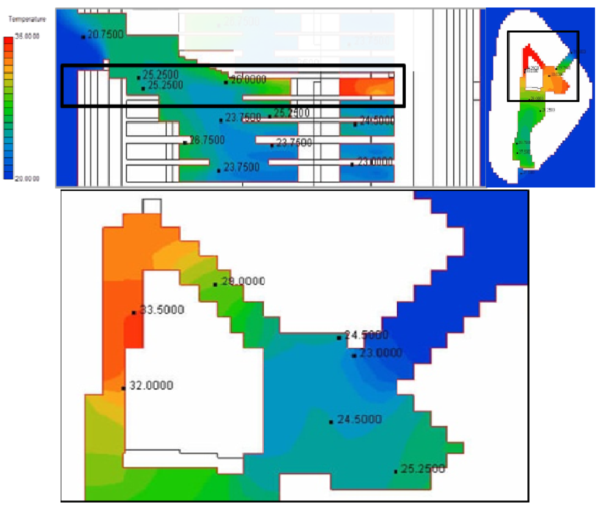


Fig. 17 Detail images of the top floor's temperature condition, for improvement model

Fig. 18 illustrates the temperature reduction on the top floor. Compare to previous design, point 2 is 7.5°C lower, and point 3 is 6.4°C lower. Temperature in point 4 decreases only 1.7°C. However, it falls just slightly over the comfort zone, which still acceptable.

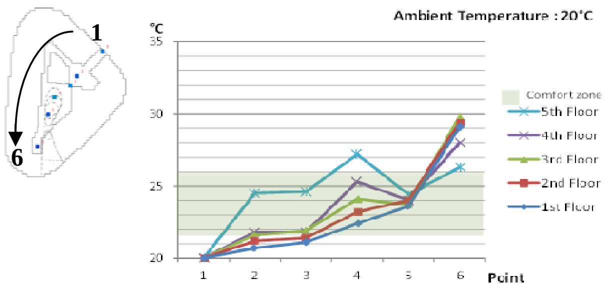



Fig. 18 Temperature value in points of each floor of lower stack (improvement model)

## V. Conclusion

CFD simulation is applied to a high-rise office building with two separate stacks to assist natural ventilation. The simulation is performed considering only buoyancy with ambient temperatures set to 20°C, representing spring condition of Taipei. The public area surrounding the atrium is analyzed to verify whether satisfactory thermal comfort can be achieved.

The NPL of the lower stack with a 2-story chimney over the 5-story atrium is right near the bottom of the stack. Also because the chimney as a courtyard is not direct above the atrium the accumulated heat from the top of the atrium forms a secondary NPL. Both facts together cause reverse flow on the top floor, resulting in stagnant area with unacceptable high temperature.

Extra chimney height is then extended from 2-story to 3-story with modification on top floor's ceiling makes NPL steadily higher. Higher NPL manages to minimize reverse flow, resulting in more airflow coming through the inlets and substantially reducing temperatures on the top floor.

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