Thermal performance of a non–segmented and segmented tall atrium in hot and humid climate

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Abstract. The study was designed to quantify the thermal conditions in tall atria in office buildings to serve as a starting point towards understanding their performance. The simulation study of a non-segmented and segmented atrium of 250 m height reveals indoor air temperature, wind velocity contours and wind pressure coefficients at various heights of each atrium type. In a hot and humid climate like that of Singapore, the internal temperatures within each atrium stack remain constant at $27°$C. However, the wind velocity in the non-segmented atrium (of 0.5 - 0.7 m/s) is lower than acceptable (0.9 m/s) for human occupancy. Adding segments and a larger inlet to the atrium solves the problem of low wind velocity without increasing the effective ambient temperature within the atrium stack. Additionally, the segmented atrium offers the advantage of displaying lower buoyancy forces by lowering the pressure differential within a tall stack thereby providing better comfort conditions.

1. Introduction

In the past two decades, the world has witnessed an exponential growth in the number of tall buildings (greater than 200 m) [1]. This fact has been particularly true for the hot-humid climatic regions like Southeast Asia (SEA). Most tall buildings are completely air conditioned which causes significant environmental impact and operational cost. To provide acceptable thermal comfort standards for the climate, outdoor air needs to be cooled and dried before its introduction within a habitable space. Such climatic conditions exacerbate the energy-intensive characterization of tall buildings.

An alternative to active air-conditioning systems is natural ventilation, an effective passive strategy for energy efficiency and reduced operational cost [2], has the ability to improve indoor air quality [3] and to provide enhanced thermal comfort conditions if integrated correctly [4], [5]. However, introduction of natural ventilation in commercial buildings in a hot and humid climate zone is not a simple matter of operable windows. The problems are further pronounced in tall buildings due to fire safety laws and user safety regulations with increased height.

Although an atrium can be designed effectively to serve natural ventilation and day-lighting purposes, a tall atrium may fall short of providing effective day-lighting conditions [6]. Beyond the daylight related shortcomings, tall atria pose an additional challenge: With the increase in height, the air pressure and temperature differentials athwart the envelope increase along the height presenting difficulties in designing and sizing air inlets and controls for ventilation

strategies [5]. Hence there is a hesitance to adopt atrium design in tall office buildings in hot and humid climates. Therefore, in an attempt to establish an exemplary baseline study, the present article expounds on the design and thermal performance of non-segmented and segmented, tall (250 m) atria for the purpose of introducing natural ventilation in commercial office buildings in the hot and humid climatic conditions of Singapore.

2. Methodology

The details of the work flow undertaken for the study are presented in Figure 1. The Figure also lists the details regarding the input parameters used for modeling and simulations. Computational Fluid Dynamic method (CFD) using *Cham Phoenics* software was implemented to carry out the modeling and simulations.
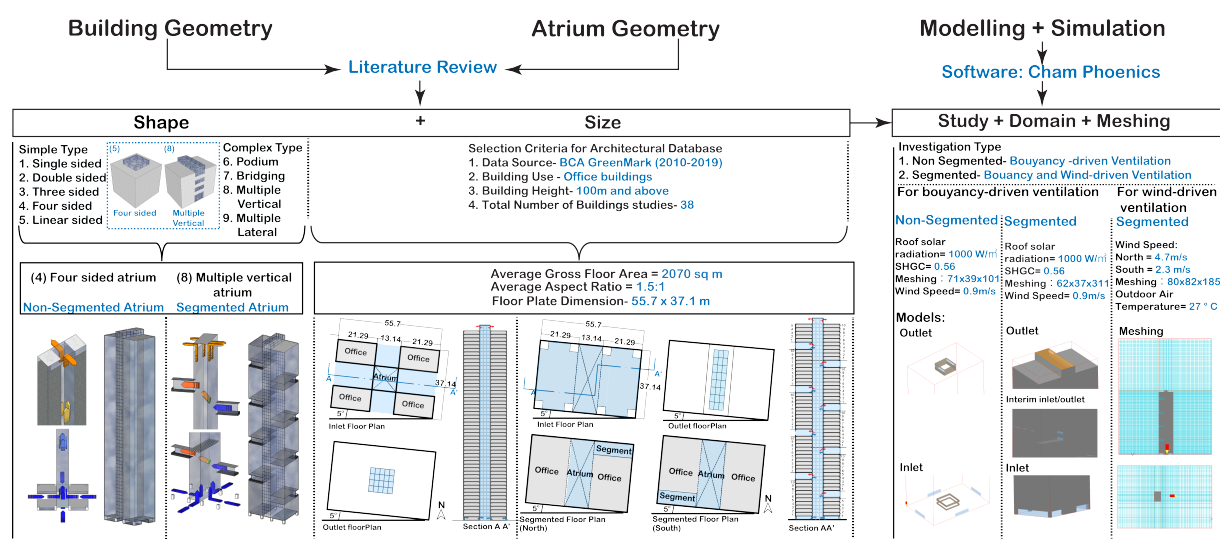

Figure 1. Work flow, modeling and simulation details

Two types of atria, each 250m tall, were modelled: One continuous atrium with an inlet on the ground floor and a roof outlet and one segmented atrium, with one inlet on the ground floor and multiple auxiliary openings (apertures) to the main ventilation shaft. The apertures for the segmented atrium were modeled with a double height (9 m) tall "sky-court". Therefore, each segment spans over the two normal storeys of the building. The double height segments were designed to allow better air flow as compared to a conventional full height window opening. The first segment aperture is located on the north facade and spans across level 5 and 6. The subsequent segments are oriented on the north and south side of the building as recommended for tall office buildings in dense urban settings [7]. The details of the design can be seen in Figure 1 under the heading "Shape". Figure 1 also shows the orientation of the buildings that have been tilted 5° to maximize the natural ventilation opportunities for the tropics [8].

While evaluating the thermal performance of an indoor space, three parameters are to be quantified. The internal temperature profile, the wind velocity contour (WVC) and the wind pressure coefficients (WPC). The results for the temperature profile and WVC with the two atria stacks are as presented in Section 3.1. For the WVC performance at the various segments, the results are presented in Section 3.2. The results presented in Section 3.2 for the segmented atrium are simulated based on scenarios when North and South direction act as windward directions to the segments.

Wind pressure coefficients (WPC) play a decisive role in determining the ventilation performance of a tall atrium shaft. Depending of the design of the atrium shaft WPC were

Table 1. $p - p_\infty$ Values for internal atrium walls and exterior segment walls

Non - Segmented Atrium (internal)			Segmented Atrium (internal)			Segmented Atrium (external)		
Wall Orientation	height position (m)	p -p_∞	Wall Orientation	height position (m)	p -p_∞	Wall Orientation	height position (m)	p -p_∞
South	1.5m	-1.22	South	75m	-0.47	North	Lvl 1.5	-0.74
	75m	-0.59		175m	0.5		Lvl 5	-0.8
	175m	0.48		225m	1.02		Lvl 6	-0.77
	225m	1.04					Lvl 18	-0.4
							Lvl 19	-0.35
North	1.5m	-1.22	North	75m	-0.45		Lvl 30	0.11
	75m	-0.59		175m	0.48		Lvl 31	0.16
	175m	0.5		225m	0.99		Lvl 42	0.65
	225m	1.05					Lvl 43	0.7
							Lvl 56	1.5
West	1.5m	-1.03	West	75m	-0.47	South	Lvl 1.5	-0.68
	75m	-0.58		175m	0.44		Lvl 10	-0.59
	175m	0.49		225m	1		Lvl 11	-0.43
	225m	1.03					Lvl 23	-0.16
	250m	1.6					Lvl 24	-0.15
East	1.5m	-1.05	East	75m	-0.46		Lvl 35	0.29
	75m	-0.59		175m	0.49		Lvl 36	0.43
	175m	0.49		225m	1		Lvl 47	0.8
	225m	1.03					Lvl 48	0.86
	250m	1.6					Lvl 56	1.5

computed at different locations: For the non segmented atrium, WPC are calculated at 1.5, 75, 175, 225 and 250 m on the internal wall. The non-segmented atrium has four inlets at 1.5 m on each of the four walls and two outlets at 250 m on the East and West Wall of the roof. For the segmented atrium WPC are determined at 75, 175 and 225 m on the internal wall of the segmented atrium. No WPC were computed at the inlet (1.5 m) for segmented atrium as there are no walls at these levels. The WPC was also recorded at the apertures of various segments (on the external facade) in the North and South direction. Refer to Section 3.3 for details. The values for WPC were calculated using Equation 1.

$$C_p = \frac{p - p_\infty}{0.5 * \rho * U_\infty^2} \tag{1}$$

Where C_p is the WPC, p is the pressure at the point of interest, p_∞ is the pressure in the free-stream, ρ is the free-stream air density, and U_∞ is the free-stream wind velocity at the building height [9].

The values for U_∞ are indicated as wind speeds in Figure 1 under the section "Study + Domain + Meshing". The values for $p - p_\infty$ for internal walls of non- segmented and segmented atrium as well as for the external apertures of the segments are as indicated in Table 1. The value for ρ is the free-stream air density was considered as 1.1521 kg/m^3 [9] .

3. Results and Discussion
3.1. Temperature and Wind Velocity in the Atria
The CFD simulation results for the temperature and wind velocity contours (WVC) for non-segmented and segmented atria are presented in Figure 2. The temperature profile in both atria remains constant at 27°C except at the roof level of the atria where temperatures vary between 28.5°C and 33°C. The wind velocity through the vertical shaft of the non-segmented atrium lay between 0.5 m/s and 0.7 m/s, only changing at the inlet and outlet. For the segmented atrium the wind velocity remains constant at 0.9 m/s through out the atrium shaft except. This velocity, unlike the lower velocity in the non-segmented atrium, fulfils the minimum indoor thermal comfort standards specified in ASHRAE 55 [10], and is therefore acceptable for comfortable human habitation. However, the wind entering the atrium shaft at 1.5 m reaches a velocity of up to 1.5 m/s. Although there is additional air movement observed at the various segment

levels, it does not significantly alter the WVC within the atrium shaft. Refer to Section 3.2 for
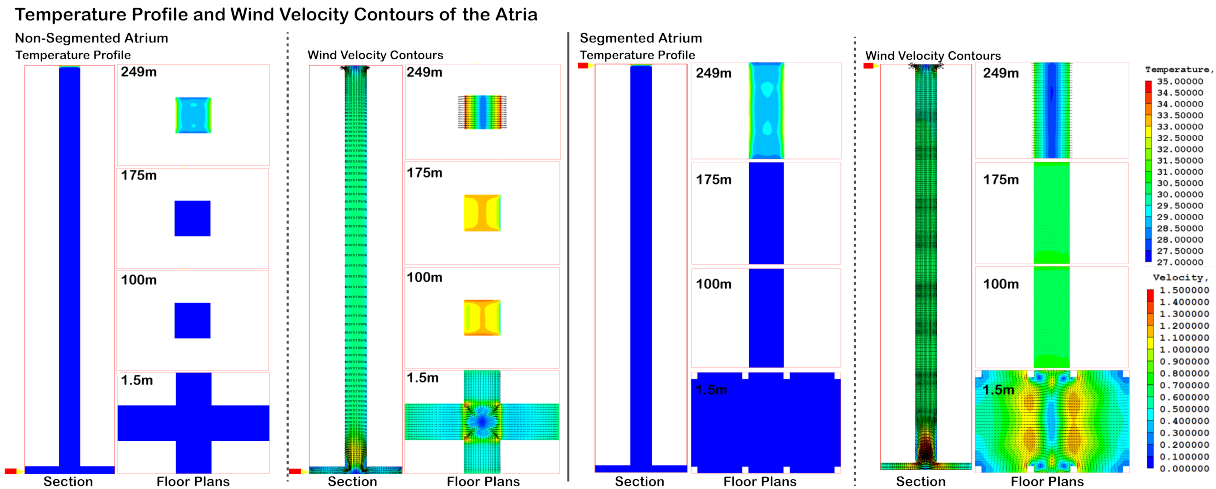more details.

Figure 2. CFD results of air temperature profiles and wind velocity contour within the atria

3.2. Internal and External Wind Velocity Contours (WVC) at the Segments
Figure 3 shows the internal and external WVC of each of the segments. The internal wind
velocity at the aperture is observed between 0.2 and 0.3 m/s. The external wind velocity at
the aperture is observed at an average of 4 m/s, it is normalized to 1 m/s as it passes through
the atrium shaft. On an average, the speed of the air entering from the North apertures of the
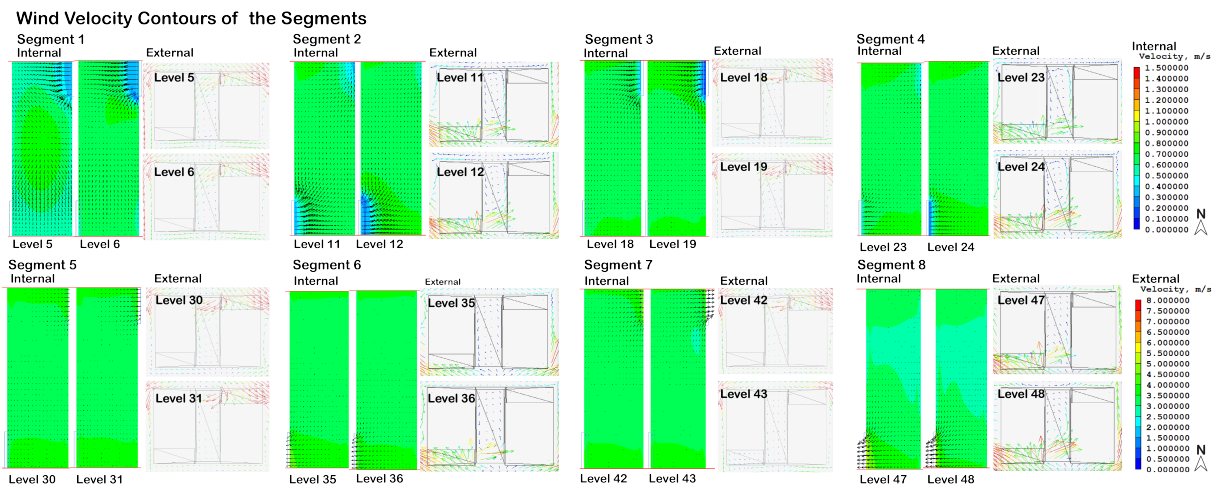segments is higher than the one from the South.

Figure 3. CFD results for internal and external wind velocity contours of the segments

3.3. Wind Pressure Coefficients (WPC)
The WPC is denoted by C_p and the calculated values for the two atria are as shown in Figure
4. The C_p on the internal surface of the inlets of segmented atrium is quantified at -2.61 (North
and South walls), -2.21 (West wall) and -2.25 (East wall). The quantified C_p at both the outlets
was 3.43. For the segmented atrium, there are no walls or openings at the inlet level, therefore

there are no C_p values at 1.5 level. The values at level 75, 175 and 225 m are as presented in Figure 4.

The C_p values for segment apertures are as stated in Figure 5. The C_p value range for the north segment was observed between -0.06 and 0.12 and for the south segment was -0.22 and 0.49. From the results it was also observed that C_p values on the north facade are lower than those on the South facade supporting the WVC results presented in Section 3.2.
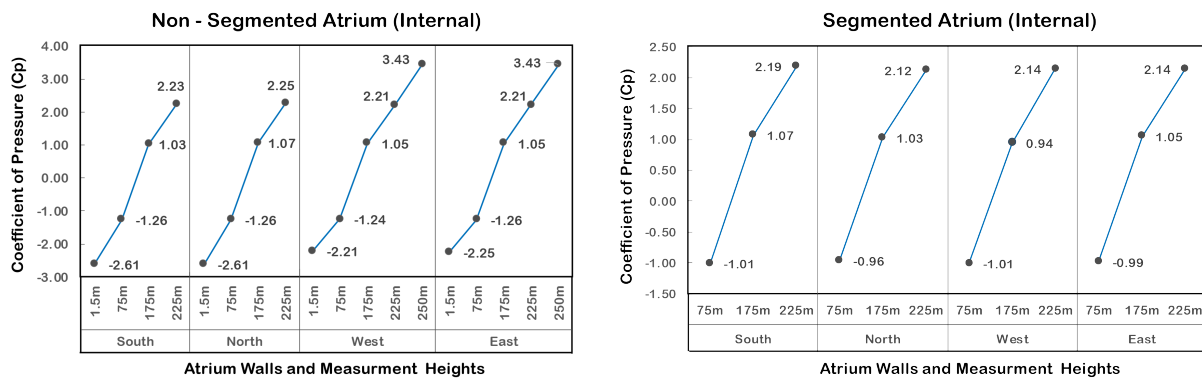

Figure 4. Computed results for WPC at the atrium walls

3.4. Discussion

In nature, the cause of air movement is the pressure differential. Air always moves from areas of high pressure to areas of low pressure. When buildings can create and maintain a consistent pressure differential through their design, natural ventilation occurs effectively. Natural ventilation in buildings is normally categorized as wind-driven and buoyancy-driven.

Buoyancy-driven natural ventilation is the movement of air due to the pressure differential brought about by the variation of temperature and height between indoor and outdoor air. It is therefore also known as chimney effect or stack effect [5]. The pressure differential is mainly dependent on the height of the stack (the difference of height between the inlet and outlet openings) as well as the density of air which is a result of ambient temperature and humidity. In order to ensure an inward airflow when wind velocity is low or absent, buoyancy - driven ventilation is effective only when the outdoor temperatures are lower than the indoor temperatures. Therefore, as seen in the results presented in section 3.1, buoyancy driven natural ventilation does not occur in the atria. Although the stack height

Figure 5. WPC performance of North and South Facade apertures of the segmented atrium building

is significant, the atrium design fails to experience the temperature differential due to the climatic conditions of the region. Buoyancy-driven ventilation may still occur in some cases as the indoor air temperatures may be higher due to space utility and functions of the building giving rise to the necessary temperature differential. However, in order to achieve effective buoyancy - driven
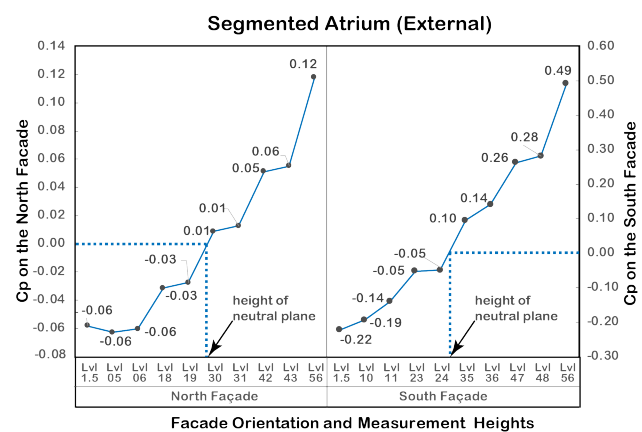
ventilation, there has to be a significant temperature difference between the indoor and outdoor air and minimal internal resistance to the air movement [5].

Wind-driven natural ventilation occurs when a localized pressure system is created around the building by the wind with respect to the existing atmospheric pressure at the site [5]. Due to the internal and external pressure differences the air flows into the building on the windward side and out through the leeward side. The top of the building is an over-pressured zone (i.e internal pressure is greater than external pressure), which validates the results presented in Section 3.3 . At a certain height of the building, an equilibrium is achieved between the indoor and the outdoor pressure. This level is known as the "neutral plane". As seen in Figure 5, the neutral plane is located at 121.5 m or level 27 of the building. The scope of the present study was limited only to the thermal performance of the atrium stacks without the considerations of internal loading. The result may differ when such loads are taken into consideration.

4. Conclusion

Natural ventilation has the potential to reduce the cooling loads of the building. Air movement in naturally ventilated spaces can increase the thermal comfort of the occupants and reduces the energy consumption. One of the most effective manners of introducing natural ventilation in tall buildings is through an atrium space. While designing an atrium for natural ventilation, it is important to understand that although thermal buoyancy is considered a dominant driving force on a windless day, in case of tropical regions like Singapore wind-driven forces will take a precedence as temperature differential between indoor and outdoor air is not significant enough to allow for a stack effect. The study shows clear advantages of a segmented atrium for the region and the prevalent building typology of the region. It is therefore advisable to design atria with features that act as wind- scoops and wind-catchers to achieve both user comfort and effective natural ventilation. The quantified thermal performance has also made it evidently clear that air from an (segmented) atrium can be used to ventilate office spaces at such heights where it is simply not possible to intake fresh air by opening the windows. However, it is also important to quantify the indoor thermal comfort of occupants in such a space along with the energy benefits of such a strategy.

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