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Effects of Vertical Meteorological Changes on Heating and Cooling Loads of Super Tall Buildings

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Abstract

Vertical meteorological conditions encountered by super tall buildings, such as wind speed, temperature and humidity, vary due to their height. Therefore, it is necessary to consider these environmental changes to properly estimate the heating and cooling loads, and to minimize the energy demands for HVAC in super tall buildings. This paper aims to analyze how vertical meteorological changes affect heating and cooling loads of super tall buildings by using numerical simulation. A radiosonde, which observes atmospheric parameters of upper air such as wind speed, wind direction, temperature, relative humidity and pressure, was used to provide weather data for the building load simulation. A hypothetical super tall building was used for the simulation to provide quantified characteristics of the heating and cooling loads, comparing the lower, middle and upper parts of the building. The effect of weather data on the heating and cooling loads in super tall building was also discussed.

Keywords: Super tall building, Heating and cooling loads, Vertical meteorological change, Simulation

1. Introduction

Over the past few years, numerous tall buildings are under construction or are being planned mainly in Asia and the Middle East, and some of these buildings are designed as super tall buildings. The world's tallest building Burj Khalifa in Dubai, at 828 meters high, was completed in January 2010. Other super tall buildings that are higher than 600 meters, including Kingdom Tower in Zeda, Saudi Arabia, Nakheel Tower in Dubai, UAE, Burj Mubarak Al Kabir in Kuwait, and Lotte World Tower in Seoul, South Korea, are either under construction or are being planned.

A super tall building can provide a good landmark to represent a metropolitan city and its nation, as well as effectively using limited land area in a dense city. Intensive land usage can not only create more green space in the city, but can also save energy for transportation and prevent urban sprawl. However, despite the advantages that super tall buildings offer, a drastic increase in energy consumption occurs in this type of building. The increase in exposed area to the external environment, especially through providing more glazing for better views, results in poor energy performance. Vertical transportation for building users and materials also cause a much greater energy use compared to lower buildings. In fact, tall buildings can lead to an energy usage that is double that of a low-rise building of the same area (Roaf, 2005). Therefore, research which attempts to reduce building load is very important for enhancing the sustainability of super tall buildings.

External environmental conditions around the super tall building, such as wind speed, air temperature, humidity and solar radiation, differ according to the height, due to the vertical micro-climate change. Geiger (Geiger, 1973) describes all meteorological elements as being subject to change with vertical height and horizontal distance, due to the varying effect of the ground. Whereas the principle zone of micro-climatic influence in a low-rise building is horizontal, the principle zone for a tall building is vertical. Therefore, these differences of outdoor conditions have to be considered when the heating and cooling load is calculated. However, the meteorological information used for HVAC design of a building is typically obtained from standard surface metrological station data, or summaries of this data (~2 m above the ground) (Segal et al., 2000).

A few papers report meteorological information and performance guidelines for tall buildings. Ellis et al. (2005) evaluated Freedom tower in Manhattan, using EnergyPlus to compare the energy impacts of several environmental factors that vary with altitude. Results showed that environmental factors have a significant effect on the annual total building cooling and heating energy. Segal et al. (2000) used the archives of radiosonde meteorological data to calculate building load for tall buildings. They outlined procedures to use radiosonde data, and discussed the constraints involved with the

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utilization of these data. Coastal and continental locations in the US, as represented by San Diego and Oklahoma City radiosondes, were considered for illustration. Leung and Weismantle (2008) examined the application of temperature lapse rates to super tall buildings, showing reductions in energy usage through the use of Energy Plus modeling of multiple vertical and horizontal compartments. Whilst the focus of the paper is on HVAC design they conclude with suggestions for architectural treatments.

In this paper, the effect of vertical meteorological changes on heating and cooling loads of a hypothetical 1,000 meter, 200 storey building were analyzed using the Thermal Analysis Simulation (TAS) program. The hypothetical building was vertically divided into five zones each of 200 meters or 40 stories. Radiosonde weather data for the corresponding heights were used to compare how vertical meteorological changes affect the heating and cooling loads for each zone. Also, the differences between the loads with and without vertical atmospheric changes were evaluated.

2. Vertical Micro Climate Change in Super Tall Buildings

In order to analyze the effect of vertical micro-climate change, weather data that has been measured by radiosonde was used. Radiosonde is a weather observing device, typically attached to weather balloons, that ascends to a higher atmospheric level to detect temperature, air pressure, wind speed, humidity etc. and transmits that data to the ground. Fig. 1 shows a radiosonde system. The University of Wyoming Department of Atmospheric Science provides weather data recorded worldwide by radiosondes (see http://weather.uwyo.edu). In this paper, weather data observed in 2009 by radiosonde in Osan, near Seoul metropolitan city, was used for the reference data. Table 1 contains monthly average data of temperature, humidity and wind speed for every 200 meters of height from ground level to 1,000 meters high. This shows that wind speed is positively proportional to height, while temperature and humidity are in general reversely related to height.

3. Simulation Conditions

The building load simulation modeled a hypothetical 1,000 meters high, 200 storey building. Six meters inside of the building envelope, which is greatly affected by external conditions, has been zoned as the perimeter zone. From the perimeter zone to the building core and inside of the building core has been zoned as internal zone and core zone, respectively. From ground level, intervals of 200 meters or 40 stories are vertically zoned

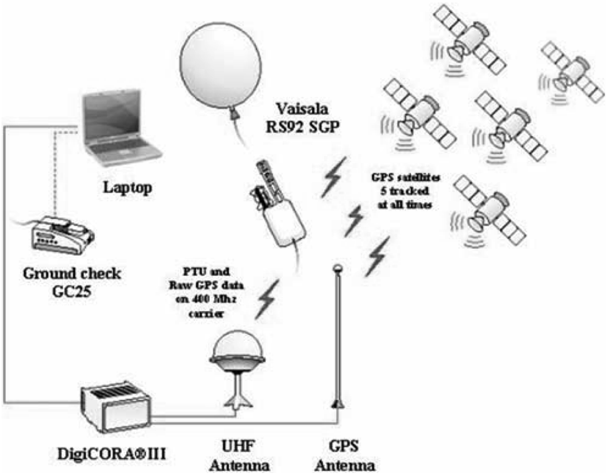

Figure 1. Radiosonde system.

Table 1. Monthly averaged vertical climate data of Osan 2009, observed by radiosonde

Height	January			February			March			April			May			June		
	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)
800~1000m	-7.0	50.4	7.7	-1.6	47.9	7.2	0.2	52.3	8.7	3.9	56.5	7.4	11.9	58.1	7.6	17.7	62.9	4.5
600~800m	-5.7	54.3	6.7	-0.9	55.5	6.0	1.7	54.6	7.8	5.2	54.5	6.6	13.4	58.7	6.7	19.2	61.2	4.0
400~600m	-4.1	54.0	5.3	0.3	60.9	4.7	3.2	55.8	6.5	6.6	55.4	5.4	14.6	59.1	5.3	20.5	61.1	3.2
200~400m	-2.3	53.6	3.2	1.5	65.1	3.4	4.6	57.4	4.9	8.0	57.6	4.0	15.7	62.1	3.7	21.6	62.4	2.4
0~200m	-3.2	67.7	2.1	1.9	74.0	2.1	5.4	64.2	3.4	9.1	62.7	2.7	17.0	68.0	2.1	23.2	68.7	1.6

Height	July			August			September			October			November			December		
	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)	T (°C)	H (%)	W (m/s)
800~1000m	18.9	76.0	6.4	20.8	68.2	6.2	16.3	61.7	3.9	11.2	55.7	6.5	2.1	68.4	7.8	-4.7	54.7	8.6
600~800m	20.1	75.8	5.7	20.9	68.4	5.5	17.7	61.6	3.6	12.6	56.1	5.8	3.2	67.9	7.0	-4.1	59.9	7.8
400~600m	21.3	77.5	4.7	22.3	69.4	4.7	19.3	62.5	3.0	14.0	56.8	4.8	4.7	65.7	5.9	-2.8	60.6	6.2
200~400m	22.6	80.3	3.4	23.7	72.4	3.6	20.7	65.2	2.3	15.3	58.4	3.6	6.1	63.6	4.3	-1.4	60.4	4.3
0~200m	24.0	85.7	2.0	25.1	79.0	2.5	21.7	73.1	1.6	15.3	68.9	2.3	6.5	69.6	2.8	-1.0	69.0	2.4

(T: Temperature, H: Humidity, W: Wind speed).

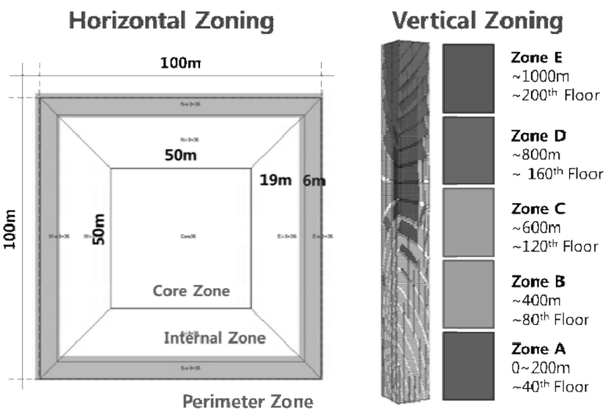

Figure 2. Zoning plan.

to divide the whole building into five zones. Fig. 2 shows the horizontal and vertical zoning of the analyzed building. Tables 2, 3 and 4 show the information and conditions used for the simulation.

Since most high-rise buildings are exposed to higher wind speed and higher infiltration, these factors should be considered to calculate heating and cooling loads properly. Infiltration is assumed as a constant value in conventional heating and cooling loads simulations. However, the infiltration rate is proportional to wind speed, and super tall buildings are exposed to strong wind. Therefore, the infiltration rate should be set as inconstant (ASHRAE, 2009). The infiltration rate was thus set at 0.5 ACH when the external wind speed is 3 m/s; for other wind speeds in this study the infiltration is then direct proportional to the wind speed. The internal heat gain, occupancy, and operation schedule for equipment were based on ASHRAE 90.1 (ASHRAE, 2010).

Table 2. Modeling building information

Height	1,000 m	
Floors	200 stories	
Typical Floor Area	Center Zone	2,500 m^2
	Perimeter Zone	554 m^2 for each direction
	Interior Zone	1,308.5 m^2 for each direction
Gross Floor Area	2,000,000 m^2	
Ceiling height	3.5 m	
Usage	Office	

Table 3. Modeling building materials

Component	Material	Thickness (mm)	U-Value (W/m^2)
Glazing	Low-E (6CL + 12Air + 6LE)	24	1.592 (SHGC: 0.319)
Frame	Metal/Thermal break	100	3.115
Opaque Wall	Al sheet/Glass Wool	50	1.95
Internal Wall	Reinforced Concrete	500	2.5
Internal Floor	Reinforced Concrete /Air gap/Acoustic Tile	180	1.3

We calculated heating and cooling loads for each of the five vertical zones using the thermal program TAS. TAS is a software package for the thermal analysis of buildings. It is a complete solution for the thermal simulation of a building, and a powerful design tool in the optimization of a building's environmental, energy and comfort performance (see http://www.edsl.net). TAS is Building Energy and Environmental Modeling (BEEM) software that is recognized as being suitable for calculating building performance and predicting energy usage

Table 4. Simulation conditions

Condition	Value	
Weather data	Conventional data : Experimental data and SAREK weather data for Seoul, Korea (SAREK, 1998) Radiosonde data, Osan, 2009 (Temperature, Wind speed, Humidity, Wind direction) + Seoul climate data (Solar radiation)	
Latitude	37.3	
Longitude	127.0	
Heating set point	22ºC, 40%	
Cooling set point	26ºC, 60%	
Heat gain (ASHRAE, 2010)	Occupancy	Sensible heat gain: 15 [W/m^2], Latent heat gain: 11 [W/m^2]
	Lighting	Office: 12 [W/m^2]
	Equipment	Office: 21.5 [W/m^2]
Infiltration	0.5 ACH when external wind speed is 3 m/s, infiltration rate is direct proportional to the wind speed or wind pressure.	
Cooling schedule	9 a.m. ~ 8 p.m.	
Heating schedule	8 a.m. ~ 8 p.m.	
Cooling and heating period	01/01 ~ 12/31 (Mon-Fri only)	
Simulation period	8760 hours	

(see http://www.edsl.myzen.co.uk/downloads/misc/BEEM%20check%20list%20AM11.pdf)

The total simulation cases were 6. Using radiosonde weather data, the heating and cooling loads for each of the five vertical zones were analyzed. Also, the basic case of using conventional weather data was compared to the case of using radiosonde weather data.

4. Results

4.1. The heating and cooling loads for the five vertical zones

Monthly heating and cooling load differences in the perimeter zone for the vertical zones are shown in Fig. 3. These indicate that the cooling load decreases while the heating load increases from the lower part of the building, Zone A, to the higher part of the building, Zone E.

Table 5 compares the building load of the perimeter and the internal zones between Zone A and the other zones. The highest Zone E requires 736% of the heating load and 52% of the cooling load compared to Zone A; the other zones show similar tendencies.

Fig. 4 indicates the annual cooling and heating load per square meter of the perimeter zone that is critically affected by external conditions. On average, from lower to upper zone, the increased rate of heating is about 600%, while the decreased rate of cooling load is about 50%. Heating load rapidly increased according to the height, while cooling load gradually decreased when compared to heating load.

Fig. 5 shows the heating and cooling difference between the conventional method of simulation, which is based on single weather data at near ground level, and the new method using radiosonde data, which reflects the changes that occur in vertical climate. Even though annual total building loads have a slight difference of about 3%, the heating and cooling load profiles shows great differences between the two. When vertical climate changes are considered, the cooling load decreases 27%, and the heating load increases 290%. Therefore, if, HVAC systems for the building envelope are designed based only on single weather data that are measured near ground level, this results in inappropriate design of HVAC system capacity, and an indoor environment that is out of control.

Fig. 6 analyzes load elements of the perimeter zone of the lower Zone A and the higher Zone E. Internal heat gains from occupancy, equipment and lighting are the same in whole zones; also, solar heat gain shows no significant difference, since we are not concerned with the shading effect of surrounding buildings.

The highest part of the building, Zone E, shows a radical increase of 213.7% from infiltration gain when compared to Zone A, because of faster wind speed. Also, energy loss caused by conduction rises 21.5% from glazing and 33.3% from opaque surfaces in Zone E. These results indicate that air tightness and conduction

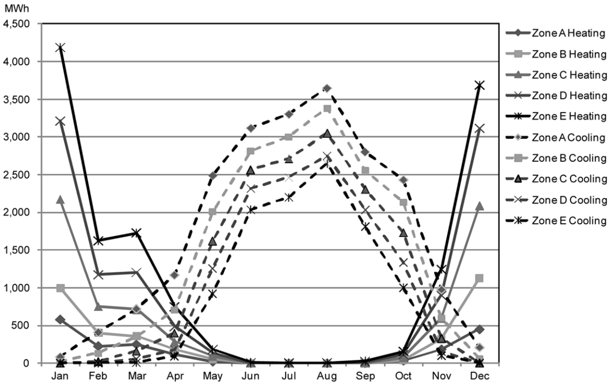

Figure 3. Monthly heating and cooling loads.

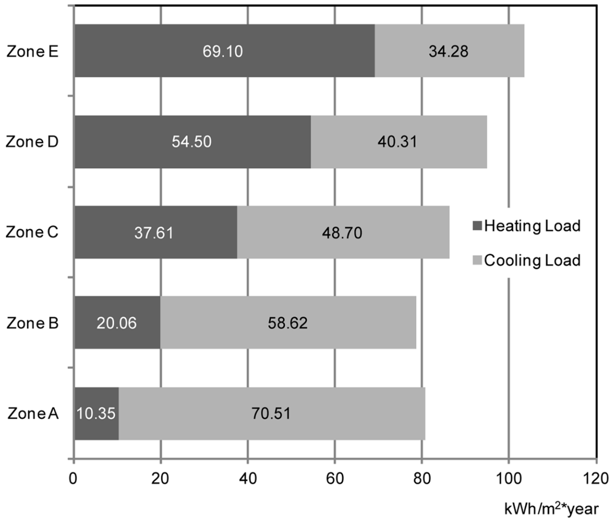

Figure 4. Annual heating and cooling loads of perimeter zone.

Table 5. Load comparison between Zone A and other zones

	Heating		Cooling		Total	
	[kWh/m^2·year]	[%]	[kWh/m^2·year]	[%]	[kWh/m^2·year]	[%]
Zone A	6.20	100	71.61	100	77.80	100
Zone B	11.65	188	59.53	83	71.18	91
Zone C	22.68	366	49.92	70	72.60	93
Zone D	34.71	560	42.05	59	76.77	99
Zone E	45.62	736	36.89	52	82.51	106

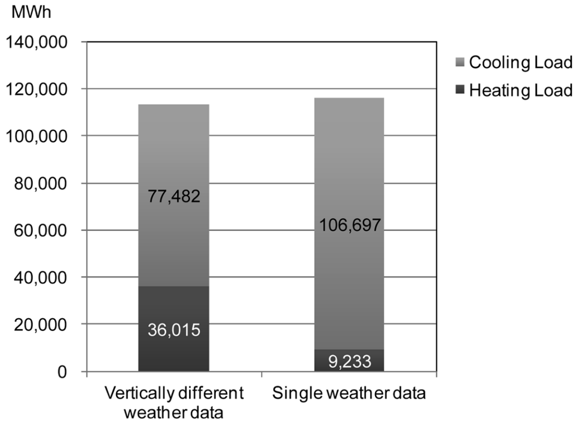

Figure 5. Total building load difference from weather data source.

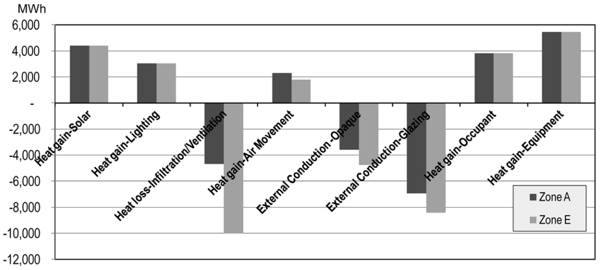

Figure 6. Load breakdown of Zone A and Zone E.

performance is more important for the higher part of a super tall building than for the lower part.

5. Conclusion

In this study, the effects of vertical micro-climate changes on heating and cooling load of a super tall building were analyzed by simulation. The results of this study are as follows.

In super tall buildings, the simulation method should reflect the vertical changes in wind speed and temperature, because these dominantly affect heating and cooling loads. In this study, the vertical climate changes were considered using radiosonde weather data for Osan, near Seoul, Korea.

From the results of cooling and heating load for the perimeter zone, which is mainly influenced by external environment changes, cooling load is decreased while heating load is increased in the higher part of the building, Zone E, compared to the lower part of the building, Zone A. These effects are because of the low temperature and increasing heat loss from high infiltration caused by escalating wind speed.

For the dependence of the heating and cooling loads on weather data, the cooling load is decreased by 27% and heating load is increased by 290% when vertical climate change is considered, compared to the conventional way of using single weather data.

From the results of the building load factors, infiltration and conduction are the main factors that result in heating and cooling load differences among the vertical zones. Therefore to minimize the energy consumption in super tall buildings, it is critical to enhance insulation and airtightness performance, especially in the higher part of the building.

Acknowledgements

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