Air-related problems in high-rise buildings: How can we cope with the problems due to stack effect?

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ABSTRACT

The construction of high-rise buildings began several decades ago in North America, and now high-rise buildings are common in East Asia and the Middle East. A high rise building usually entails various problems in areas such as energy consumption, IAQ, and stack effect, due to the great height of the building, most of which are related to the airflow and pressure in and around the building. In particular, the stack effect, which is driven by buoyancy forces through the vertical shaft of the core, is the most critical in severe winter climates. It has been reported that the stack effect in high-rise buildings causes many problems, including elevator malfunction, energy loss through the openings, excessive pressure differential across the door, and pollutant diffusion.

This article examines air-related problems associated with the stack effect and describes how to cope with the stack effect. In preventing problems caused by the stack effect, the most important tier of the strategy is architectural design (referred to as the passive approach), such as increasing the air tightness of all air passages including the exterior envelope and openings, and the separation/compartmentation of each zone. Problems caused by the stack effect can also be mitigated by the active approach, i.e. controlling the amount of air supplied and exhausted by mechanical systems, etc.

1. INTRODUCTION

High-rise buildings were first constructed in the early 20th century and until the 1980's had been mainly constructed in North America, especially in Chicago, and New York. Recently, however, a lot of high-rise buildings have been constructed in East Asia including Hong Kong, Singapore, Tokyo, Kuala Lumpur, Shanghai, and Seoul, in step with the growth of economy and the development of construction technologies. Eight of the ten tallest buildings in the world are located in East Asia, the tallest being the 'Taipei 101 (height: 508m)' in Taipei, Taiwan. Recently, Middle Eastern nations which have accumulated capital with the rise in the price of oil have invested in high-rise building development projects. Many high-rise buildings are currently under construction in the Middle East, such as 'Burj Dubai' in the United Arab Emirates and 'Abraj Al Bait Towers' in Saudi Arabia.

The high-rise building has become taller and taller, in accordance with progress in structural and construction technology. The maximum height is continuously being renewed in current high-rise buildings (in excess of 800 m, reaching over 1,000 m). Until 1990, there were only 9 buildings in the world that had heights of over 300 m, but now there are 89 such buildings built or under construction. These buildings having heights of over 300 m are defined by the Council on Tall Buildings and Urban Habitat (CTBUH) as "super-tall buildings."

The function of the high-rise building has also become diverse. Although the early high-rise buildings were used mainly as office areas, now their functions have become more complex and multi-purpose. High-rise buildings recently completed or under construction, are mostly for mixed-use, including two or more functions such as office, residential, hotel, and commercial business. These various functions have lead to unique characteristics in building aspects, for example, in the building plans and elevations, exterior envelopes, openings, doors and gates, mechanical systems, etc.

The evolution of the high-rise building, which is getting higher and multi-purpose use, is accompanied by more careful consideration in terms of the building environment, associated with providing comfort for the occupants while reducing energy consumption. In particular, as a high-rise building is more easily affected by outdoor air pressure and wind, it has become more important to deal with air-related problems caused by the airflow and pressure in and around the building.

In this article, the air-related problems in high-rise buildings associated with the building aspects are reviewed. Among such air-related problems, the stack effect is evaluated in greater detail. To cope with problems due to the stack effect in high-rise buildings, the basic theory and the principle of the stack effect, as well as problems that may be caused by the stack effect are presented, and various techniques for dealing with these problems are suggested.

2. AIR-RELATED PROBLEMS IN HIGH-RISE BUILDINGS

2.1 Cooling and Heating Energy Consumption

Most high-rise buildings have curtain walls for their exterior envelopes, due to their lightweight structure and desirable appearance. However, these also are causes of thermal and energy related problems, because of the large, transparent, and thermally weak glazing areas, and the metal frames having high thermal conductivity. Moreover, a high-rise building may receive greater levels of direct solar heat gain than does a low-rise building, because of the greater height over surrounding buildings and the greater exposure to radiation from the other building exterior surfaces. Besides, as the outside wind velocity is too high to open the windows, there are no windows that can be opened to allow natural ventilation and natural cooling. So, the cooling energy consumption for air-conditioning systems, particularly in summer, is greater in a high-rise building than in a low-rise building (Bang and Yu, 2006).

The increase in outside wind velocity and the wall pressure also increases the external wall surface convective heat transfer, so that more air infiltration/exfiltration will occur through the leakages of curtain wall (No et al., 2008). Therefore, the heating load is also higher in a high-rise-building than in a low-rise building during the winter season, and consequently the energy consumption for heating is also higher.

2.2 Ventilation for IAQ

Most high rise buildings have airtight envelopes to reduce air leakage, so that there are only small amounts of natural air exchanged between the inside and the outside. Moreover, because it is not convenient to provide natural ventilation through the openings, the high-rise building generally has fixed windows. Even if openable windows are installed in the exterior walls, the size and type of windows are limited for safety and other reasons, so that the scope of providing natural ventilation is limited. Therefore, in a high-rise building, mechanical ventilation systems should be used to guarantee acceptable indoor air quality. The use of mechanical ventilation systems is also a factor that increases energy consumption.

2.3 Stack Effect

High-rise buildings generally have central cores that include vertical shafts, such as elevator shafts and stairwells, where the air may easily flow upwards. When the indoor–outdoor temperature difference is large, a high-rise building can experience severe problems due to the stack effect; problems such as sticking elevator doors, difficulty in opening doors, and noise resulting from air flowing through cracks. These stack effect problems were first recognized in North America but are frequently reported in countries in Northeast Asia, all of which have severely cold climate conditions marked by an indoor–outdoor temperature difference of over 30 K.

The greater the length of a vertical shaft, the more complicated the stack effect problems. Thus, for taller buildings, the problems due to the stack effect become more severe.

3. STACK EFFECT IN HIGH-RISE BUILDINGS

3.1 Principles of Stack effect

The stack effect is the movement of air into and out of buildings, chimneys, flue gas stacks, or other containers, and is also referred to as the "chimney effect." The stack effect is driven by buoyancy forces which occur due to a difference in indoor-to-outdoor air density, resulting from a difference in temperature. The result is either a stack effect or a reverse stack effect. The reverse stack effect, in most cases, is not as critical an issue as the stack effect.

There is a pressure difference between the outside air and the inside air of the building, caused by the difference in temperature between the outside air and the inside air. That pressure differential is the driving force of the stack effect, and it is also a function of the building height and the airflow resistance in the building, i.e., the draft coefficient. The greater the thermal temperature difference and the height of the building, the higher the buoyancy force.

The stack effect pressure differential is maximized at both the top and bottom of the building, and the inflow from the bottom shifts across the neutral pressure level of the building to the outflow through the envelope.

The characteristics of pressure distribution in real buildings are very complicated, depending on the floor plans and sections of the building, the airtightness of the slab/envelope, gate/door/openings, and so on. To prevent severe problems due to stack effect and to propose effective methods for solving the various stack effect problems, it is very important to analyze the pressure gradient profiles of the building.

3.2 Problems due to stack effect

The induced airflow from the gates, cracks and windows at the bottom portion of the building, and rising airflow through the vertical shaft of the building caused by stack effect, generate problems such as the following:

- Malfunctioning in elevator operation and elevator doors
- Noise resulting from air flowing through cracks (through tiny openings)
- Difficulty in opening and closing doors
- Increased heating energy consumption, due to infiltration and exfiltration
- Diffusion of pollutants and smoke
- Backflow and choking of ventilation and exhaust systems
- Occupant discomfort due to higher levels of air draft inside building

3.3 Ways to Prevent Stack Effect

For preventing and solving problems due to the stack effect, both the passive and the active approach will be applied in actual practice. The former is a strategy of using careful architectural design considerations, and the latter is a strategy of using mechanical equipment and devices.

The architectural design considerations are based on the idea of increasing the resistance to airflow through all airflow passages (separation and compartmentation). One example is to increase the airtightness of the exterior envelope to prevent both infiltration and exfiltration, and another is to divide the building into several zones to control airflow. If the exterior envelopes are airtight, even though the stack pressure differentials across the exterior envelopes are high, the amount of infiltration/exfiltration will be decreased, and consequently the stack effect can be reduced. To make the exterior envelopes airtight, the openings at the bottom of the building should be made airtight, such as by minimizing the number of entrance gates, using revolving doors, and installing vestibules. Doors at the rooftop and openings for ventilation in machinery rooms should also be airtight.

To minimize airflow going up in buildings, horizontal and vertical zoning are needed. When the inner space of a building is divided by various partitions, barriers, and doors, the maximum pressure differential caused by the stack effect will be mitigated across the exterior walls, partitions, barriers, and doors. In terms of vertical zoning, ensuring the airtightness of vertical shafts and vertically zoning elevator shafts are the most effective ways.

The active method of using mechanical equipment and devices is to control the distribution of pressure differential in a building through the control of airflow, i.e. air supply and exhaust rates, or the temperature of the air, in order to provide lower buoyancy. However, this active approach typically needs additional systems and consumes extra energy, so that the passive approach should be the first consideration.

To prevent the stack effect and to solve problems caused by the stack effect, different ways can be adopted during the design and construction stages. In the design stage, a design guideline for preventing stack effect can be consulted. In the construction stage, a construction checklist and various methods for increasing building airtightness can be utilized. After construction, diagnosis and commissioning for follow-up measures may be required. That is, an integrated and holistic solution is required to manage stack effect problems throughout the overall building construction process.

4. CONCLUSIONS

Among air-related problems in high-rise buildings, the stack effect is the most critical. Problems resulting from the stack effect are described, and methods of preventing such problems are suggested. The conclusions of this article can be summarized as follow:

1) In high-rise buildings, it is highly likely that there will be air-related problems, caused by inward and outward airflow and pressure difference. These problems can increase energy consumption for heating and cooling, and exacerbate ventilation problems and stack effect problems.
2) The stack effect causes many kinds of problems in high-rise buildings; malfunctioning in elevators, increased energy consumption, and increased diffusion of pollutants. The stack effect can be solved using a passive approach of using careful architectural design considerations, such as for zoning, separation, compartmentation, and increasing airtightness. The stack effect can also be reduced by an active approach of using mechanical equipment and devices for controlling such factors as the amount of air supplied and exhausted, and the temperature of the air.
3) To prevent the problems from the stack effect, an integrated and holistic solution is required that spans throughout the overall building construction process.

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