Methods to Prevent the Stack Effect in High Rise Residential Buildings

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Abstract
The stack effect occurs always when there exits temperature difference between indoor and outdoor air and climate wind pressure even increases its strength. This stack effect acts like a chimney: natural convection of air entering at the lower floors, flowing through the building and exiting from the upper floors. The vertical movement of the air within the building will occur in the shafts and staircases as well as any other openings that exist at the slab edge or in vertical piping sleeves at various locations that are not perfectly sealed. Uncontrolled air movement over the building envelope and further through the building increases draft risk and energy consumption. Over the neutral pressure level point, exfiltration happens and outflowing air could be condensate inside building envelope and increase the risk of mold grow. Also, high uncontrolled air movement could increase noise and the risk of spread of pollutions between apartments. In this study, the effects of external and internal air tightness, air temperature control of shaft and outdoor environmental conditions on air pressure conditions were simulated in a high rise apartment building with a multi-zone simulation model. Based on the carried out analysis together with air tightness of envelope, internal air tightness of shafts is playing a significant role in the stack effect. Thus staircases and lifts should be provided with own airtight anteroom and airtightness of apartment doors should be improved.

Keywords - stack effect; infiltration; air tightness; ventilation

1. Introduction

As buildings get taller, there are different climatic effects which vary over the height of a building. The façade becomes important, not only because of the building size, but also because of how it responds to ambient conditions and contributes to the building’s heating and cooling loads. Together with U-value and solar shading, air tightness of the façade is one significant element of high performance façade.
With the increasing migration of people into cities, high rise buildings continue to be in demand. Every tall building will require a vertical transportation system. In tall buildings, the final core design generally results in one or more elevators confined within a single shaft. This creates significant challenges with respect to the vertical air movement caused by the cracks of doors of elevators.

The stack effect occurs always when there exits temperature difference between indoor and outdoor air and climate wind pressure even increases its strength. The stack effect, either positive or negative, depending on the time of year or climatic conditions of the region. This stack effect acts like a chimney: natural convection of air entering at the lower floors, flowing through the building and exiting from the upper floors.

The vertical movement of the air within the building will occur in the shafts and staircases as well as any other openings that exist at the slab edge or in vertical piping sleeves at various locations that are not perfectly sealed. Over the neutral pressure level point, exfiltration happens and outflowing air could be condensate inside building envelope and increase the risk of mold grow. In Fig.1, there is presented the stack effect forces and air flow within a building [1].

Airflow between spaces (rooms, storeys and shaft) in residential buildings is driven by pressure differences between these spaces. These pressure differences can exist between the exterior and the interior, or between internal building spaces. The pressure differences can be created by the wind, stack effect, and mechanical supply and exhaust fans.
As the building height and temperature difference between the indoor and the outside increases, the magnitude of the stack effect in buildings also increases. The stack effect could provoke a number of problems as follows [2]:

- draft through the doors in the building
- noise through gaps of doors
- malfunctioning of the elevators and doors
- increase the heating and cooling energy consumption

Even though the measures to minimize the stack effect in high-rise buildings were used including a revolving door on the lobby floor, additional barriers to the passage of air in the lower part of the building, and air-tightness reinforcement for elevator doors, the stack effect is still present during cold season.

In this study, the effects of external and internal air tightness, air temperature control of shaft and outdoor environmental conditions on air pressure conditions were simulated in a high rise apartment building with a multi-zone simulation model.

2. Methods

The effect of the stack effect was studied on a high rise apartment building in cold Finnish climate conditions. The analyzed building has 24 floors where room air temperature is fixed to be at 20 °C in apartments and 17 °C in corridor through the year. The supply and exhaust airflow rates were 0.5 l/s per m² in apartments. In corridor area, the supply airflow rate was 0.9 l/s per m² and exhaust was 1.0 l/s per m². The supply and exhaust airflow rate to elevator shaft were +160 l/s and -300 l/s and in stairwell +10 l/s and -60 l/s, respectively.

In the analyzed reference case, the airtightness of the envelope was 0.5 m³/h,m² (q₅₀). The following structural measures were analyzed to prevent the stack effect compared to the reference Case 1:

- Case 2) air-tightness reinforcement of apartment door,
- Case 3) compartment of elevator and staircase shaft and
- Case 4) decreasing of airtightness of building envelope.

Airtightness of the envelope and values of the effective leakage area (ELA4) of the analyzed cases are presented in Table 1. The ELA4- values of Table 1 are collected from ASHRAE Fundamentals [3] and the carried out validation with measurements in a Finnish high rise building [4].

The effect of control air temperature in shafts for the stack effect was also analyzed. By reducing the temperature difference between outdoor air and shaft air, the driving force of stack reduces. The efficiency of control stack air temperature depends on together with the temperature of the shaft and its
uniformity throughout the shaft height. In this study, the shaft was cooled to 10 °C.

Table 1. Indoor climate measurements.

<table>
<thead>
<tr>
<th>Analyzed Cases</th>
<th>Airtightness / ELA₄- values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case 1</strong></td>
<td></td>
</tr>
<tr>
<td>Building envelope</td>
<td>q₅₀ = 0.5 m³/h, m²</td>
</tr>
<tr>
<td>Apartment door</td>
<td>0.0012 m²</td>
</tr>
<tr>
<td>Revolving door (entrance)</td>
<td>0.0015 m²</td>
</tr>
<tr>
<td>Door of elevator</td>
<td>0.022 m²</td>
</tr>
<tr>
<td>Other doors</td>
<td>0.0075 m²</td>
</tr>
<tr>
<td>Roof of stairway enclosure</td>
<td>0.000752 m²</td>
</tr>
<tr>
<td>Elevator shaft cable inlets</td>
<td>0.56 m²</td>
</tr>
<tr>
<td><strong>Case 2</strong></td>
<td></td>
</tr>
<tr>
<td>As Case 1 + improved airtightness</td>
<td></td>
</tr>
<tr>
<td>Apartment door</td>
<td>0.0004 m²</td>
</tr>
<tr>
<td><strong>Case 3</strong></td>
<td></td>
</tr>
<tr>
<td>As Case 2 + Compartmentation</td>
<td></td>
</tr>
<tr>
<td>Additional door</td>
<td>0.0012 m²</td>
</tr>
<tr>
<td><strong>Case 4</strong></td>
<td></td>
</tr>
<tr>
<td>As Case 1 + decreased airtightness</td>
<td></td>
</tr>
<tr>
<td>Building envelope</td>
<td>q₅₀ = 2.0 m³/h, m²</td>
</tr>
</tbody>
</table>

Air pressure conditions and internal airflow rates were simulated with a multi-zone simulation model using IDA Indoor Climate and Energy (IDA ICE) simulation software [5] in a high rise apartment building. The measured and simulated air pressure conditions with IDA-ICA are compared in an earlier study [6]. This carried out study indicated that IDA-ICA is reliable tool for the stack effect analysis.

This simulation tool is capable of modeling multi-zone building with HVAC systems, and is suitable for dynamic simulation, thermal comfort IAQ and energy assessment. IDA ICE’s performance, accuracy and reliability as a dynamic simulation tool has been validated and proved in numerous studies before, such as tests against measurements and several independent inter-model comparisons for different energy analysis applications.

Depending on the ratio of supply and return air flow rates in each zone, the air mass is balanced with air flows through the leaks in exterior walls or openings between zones, fulfilling the principle of mass conservation. The mass flows are simulated as a function of the air pressure difference between the zones and the outdoor environment. The air flow between the spaces, floors, and outdoors caused by the pressure differences is simulated by means of the principle of a nodal network, where the flow paths, cracks, or openings between the zones or outdoors are described as flow resistances.
Wind pressure distribution around the house is simulated using the normal assumption in building engineering that the wind flow is horizontal and an atmospheric boundary layer is neutral without vertical air flow. The wind conditions of the environment were approximated using the wind profile equation reported in ASHRAE Fundamentals [3].

This driving pressure difference of infiltration is calculated for every air leakage opening in the model, combining the effect of mechanical ventilation, wind, and stack effect. The air leakage openings were distributed over the building model according to airtightness and ELA-values shown in Table 1.

3. Results

Together with minimized leakage in building envelope, internal airtightness of apartment doors and compartmentation of shafts are playing a significant role in controlling of infiltration and exfiltration. With IDA-ICE, the effect of external and internal airtightness on air flow rates between the spaces, floors and outdoors were simulated.

In Fig. 3, there is presented plans of the ground floor with the reference buildings (Case 1) and the airtightness reinforcement solution (Case 3). In Fig. 3, there is also marked the modelled air leakage routes in the ground floor.

In Table 2, there is presented exfiltration and infiltration airflow rates at the ground floor with Cases 1 and 3. In Table 2, there is not shown the supply and exhaust airflow rates in the spaces. In the space 1, the supply and exhaust airflow rates were 0.5 l/s,m$^2$. In the space 5, the supply airflow rate was 0.9 l/s,m$^2$ and exhaust was 1.0 l/s,m$^2$.

The compartments of the shaft decreased the total airflow rates with in the building. Also, it should be noted that compartmentation change the direction of airflow rates in the entrance lobby and vestibules. As in spite of airtightness
reinforcement, the pressure difference between indoor and outdoor remains the same. This pressure difference can exist between the exterior and the interior, or partly between internal building spaces when compartments of the shafts are introduced.

Table 2. Infiltration and exfiltration airflow rates (l/s) with two internal airtightness levels at the ground floor.

<table>
<thead>
<tr>
<th>T_{outside} (°C)</th>
<th>infiltration envelope</th>
<th>exfiltration envelope</th>
<th>infiltration inner wall</th>
<th>exfiltration inner wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>-26</td>
<td>-5</td>
<td>-26</td>
<td>-5</td>
</tr>
</tbody>
</table>

1: space
- Case 1
  - infiltration: 1
  - exfiltration: 1
- Case 3
  - infiltration: 0
  - exfiltration: 0

2: lobby
- Case 1
  - infiltration: 119
  - exfiltration: 269
- Case 3
  - infiltration: 0
  - exfiltration: 72

3: vestibule
- Case 1
  - infiltration: 10
  - exfiltration: 18
- Case 3
  - infiltration: 0
  - exfiltration: 0

4: stairwell compartmentation
- Case 1
  - infiltration: 27
  - exfiltration: 29
- Case 3
  - infiltration: 0
  - exfiltration: 21

5: space
- Case 1
  - infiltration: 42
  - exfiltration: 46
- Case 3
  - infiltration: 73
  - exfiltration: 82

6: vestibule
- Case 1
  - infiltration: 63
  - exfiltration: 71
- Case 3
  - infiltration: 0
  - exfiltration: 57

7: elevator compartmentation
- Case 1
  - infiltration: -
  - exfiltration: -
- Case 3
  - infiltration: 0
  - exfiltration: 0

To get the view of air flows inside the building, total infiltration at ground floor and exfiltration at 24 floor levels should be reviewed. In Fig. 3, there is shown the directions of the main air flow at low and high levels. The observation point of 3 is important for energy consideration and thus, higher value at point 3 indicates higher heating demand in the building because of air leakage.
In Table 3, there is shown the infiltration airflow rate at ground level, airflow rate in the shafts at 23 floor level and exfiltration airflow rate at the 24 floor level. The airflow rates in elevator and staircase shafts are shown separately. The airflow rate within building are calculated with -5 °C and -26 °C outdoor air temperatures.

<table>
<thead>
<tr>
<th>$T_{out}$ ($^\circ$C)</th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>898</td>
<td>932</td>
<td>185</td>
<td>1134</td>
<td>488</td>
</tr>
<tr>
<td>-26</td>
<td></td>
<td></td>
<td>338</td>
<td>1341</td>
<td>534</td>
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<tr>
<td>Shafts-Elevator</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Case 1</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>898</td>
<td>932</td>
<td>185</td>
<td>1134</td>
<td>488</td>
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<tr>
<td></td>
<td>214</td>
<td>228</td>
<td>25</td>
<td>587</td>
<td>69</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>29</td>
<td>674</td>
<td>67</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>366</td>
<td>457</td>
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<tr>
<td>Case 3</td>
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<tr>
<td></td>
<td>214</td>
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<td>167</td>
<td>217</td>
</tr>
</tbody>
</table>

By improving internal airtightness, it is possible reduce significantly airflow rate within building. Total airflow rate through elevator shaft (point 3) reduced 48 % at -5 °C from 1134 l/s to 587 l/s. Also, enhanced internal airtightness reduced exfiltration airflow rate at top level of the building (points 4 and 5). All this demonstrate possibility to enhance energy efficiency and to create draft-free conditions by reducing internal airflow movement.

In Fig. 4, there is presented the relative airflow rate in the elevator shaft with different airtightness. In Fig. 4, there is also shown the effect of cooled
ventilation shaft (constantly 10 °C) on the shaft airflow rate (point 3 in Fig.3). The outdoor air temperature was -5 °C in this simulation case.

Fig. 4. Airflow rate in the elevator shaft with different measures to reduce stack effect.

The airflow rate was increased 40 % when the envelope airtightness (q50) decreased from the value of 0.5 m³/h·m² to 2.0 m³/h·m². The improvement of airtightness of apartment doors (Case 2) did have any effect on the airflow rate in the shaft compared the reference case. Compartments of shafts reduced 48 % of the air flow rate. By introducing shaft air cooling (Case 5) together with compartments has slightly improvement on airflow rate. The airflow rate with compartments and shaft cooling reduced airflow rate 52 % compared the reference case.

4. Discussion and Conclusion

The stack effect occurs always when there exits temperature difference between indoor and outdoor air. Even though the measures to minimize the stack effect were taken, the stack effect is still present during cold season. Airflow within building and between spaces is driven by pressure differences. These pressure differences can exist between the exterior and the interior, or between internal building spaces. Thus, the compartmentation and improvement of internal airtightness is just distributing the pressure difference in a new way inside the building.

In this study, the effects of external and internal air tightness, air temperature control of shaft and outdoor environmental conditions on air pressure conditions were simulated in a high rise apartment building with a
multi-zone simulation model. Based on the carried out analysis together with air tightness of envelope, internal air tightness of shafts is playing a significant role in the stack effect. By decreasing airtightness of envelope from the value of 0.5 m$^3$/h,m$^2$ to 2.0 m$^3$/h,m$^2$ was increased 40 % of airflow rate through elevator shaft. When compartments of elevator shaft was used, the airflow rate of shaft reduced 48 % compared with the reference case.

Acknowledgment

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References