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Methods to Reduce Stack Effect and Improve Energy Efficiency in a Nordic High Rise Residential Building

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Abstract

The stack effect creates uncontrolled vertical air movement in buildings. This air movement over the building envelope and internal parts of the building creates noise and draft through gaps of doors and increases energy consumption. The wind and mechanical ventilation may also have a pronounced effect on the air pressure conditions and the movement of the air along the shafts of the building. The objective of this study was to find solutions to minimize the stack effect. The effects of air tightness, air leakage distributions, and outdoor environmental conditions on air pressure conditions and energy consumption in a high-rise residential building were simulated in cold climate conditions. The stack effect is possible to prevent with spatial arrangements and improved air tightness. Based on the analysis carried out, internal air tightness is playing the major role in the control of the stack effect.

Keywords: energy efficiency, high rise buildings, stack effect, cold climate

Nomenclature

q_{50} the air tightness of envelope with 50 Pa pressure difference, $m^3/h,m^2$

1. Introduction

With the increasing migration of people into cities, high-rise buildings continue to be in demand. The construction of the high-rise building has become more common at the northern and cold climates areas. As buildings get taller, there are different climatic effects which vary over the height of a building. The facade 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 facade is one significant element of high performance facade.

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The stack effect occurs always when there exist temperature difference between indoor and outdoor air and outdoor wind pressure even increases its strength. The stack effect is either upward or downward, depending on climatic conditions of the region. During the cold period the stack effect is usually stronger. This time the 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 exists 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 condensate inside building envelope and increase the risk of mold grow. In Fig.1, there are presented the stack effect forces and air flows within a building [1].

Airflow created by stack effect can exits between spaces (rooms, floors and shaft) in residential buildings and it 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 problems of the stack effect increase as the building height and temperature difference between the indoor and the outdoor increases. Also in a modern high-rise building with a well-sealed envelope, the stack effect can create significant pressure differences which have to be into account in architecture and ventilation design. The stack effect could provoke a number of problems as follows [2]: increase the heating and cooling energy consumption, noise and draft through gaps of doors, pollutions spreading inside of building and incorrect airflows.

Even though the measures to minimize the stack effect in high-rise buildings were taken into account 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.

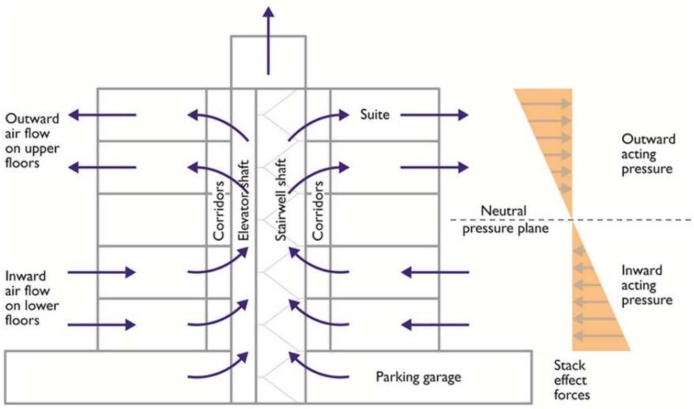

Fig.1 Illustration of GHE zoning

2. Methods

The influence of the stack effect was studied on a high rise apartment building in cold Finnish climate conditions. The analyzed building has 25 floors. The total floor area and volume are 13150 m^2 and 50385 m^3. The room air temperature is fixed to be at 20 ºC in apartments and 17 ºC in corridor through the year. The supply and exhaust airflow rates were 0.5 l/s per m^2 in apartments. In corridor area, the supply airflow rate was 0.9 l/s per m^2 and exhaust was 1.0 l/s per m^2. 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.

Table.1 Analyzed cases of the air tightness

Analysed Cases	**Air tightness** (q_{50})/ **ELA$_4$- values**
Case 1 (reference case)	
Building envelope	q_{50} = 0.5 m³/h,m²
Apartment door	0.0012 m²
Revolving door (entrance)	0.0015 m²

Door of elevator	0.0022 m²
Other doors	0.0075 m²
Roof of stairway enclosure	0.000752 m²/m²
Elevator shaft cable inlets	0.56 m² (15 x 0.037 m²)
Roof of elevator motor room	0.0033 m²/ m²
Case 2	
As Case 1 + improved inner air tightness	
Apartment door	0.0004 m²
Elevator shaft compartmentation door	0.0012 m²
Case 3	
As Case 1 + decreased air tightness	
Building envelope	q_{50} = 2.0 m³/h,m²

In the analyzed reference Case 1, the airtightness of the envelope was 0.5 $m^3/h,m^2$ (q_{50}). The following structural measures were analyzed to prevent the stack effect compared to the reference case: Case 2) air-tightness reinforcement of apartment door and Case 3) compartment of elevator and staircase shaft.

Airtightness of the envelope (q_{50}) and values of the effective leakage area (ELA_4) of the internal structure are presented in Table 1. The ELA_4- values of Table 1 are collected from ASHRAE Fundamentals [3] and the carried out validation with measurements in a Finnish high rise building [4,5].

Air pressure conditions and internal airflow rates were simulated with a multi-zone simulation model using IDA Indoor Climate and Energy simulation software [6]. Depending on the ratio of supply and exhaust air flow rates and temperature in each zone, the air mass is balanced with air flows through the leaks and openings 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, and openings between the zones or outdoors are described as flow resistances.

Wind pressure distribution around the building 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 [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.2, there is presented simulated pressure difference over the envelope of the building in Cases 1, 2 and 3. Figure 3 shows, that the improved air tightness of envelope (Case 1) raised the neutral pressure two floors higher level than less airtight envelope (Case 3). Also, raised neutral pressure level increase the pressure differences over the envelope at lower parts of the building. Increased pressure difference over the envelope at lower parts of the building caused malfunctions at regular entrance doors, creates noise, draft and increases energy consumption. Recommended entrance door type is revolving door to reduce uncontrolled air movement.

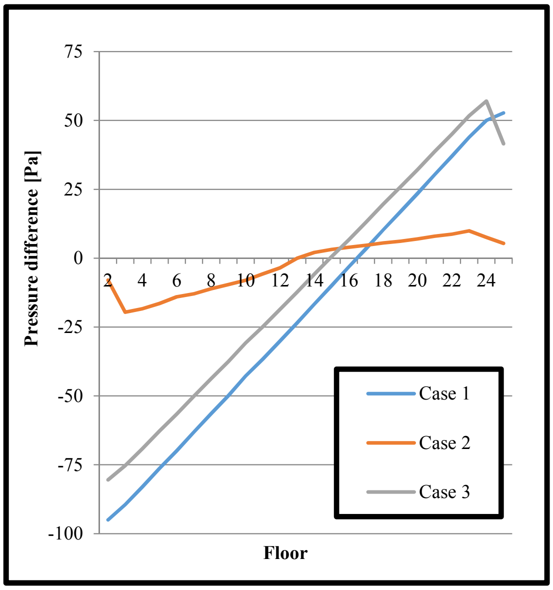

Fig.2 Pressure difference over the envelope at outdoor temperature -5°C.

In Case 2, compartments of the shaft decreased the pressure differences over the envelope in all levels. With airtight compartments, the majority of the pressure difference happens between the compartmentations and the corridors. In that conditions, compartmentations doors needs to be automatic sliding doors to guarantee proper function at the high pressure difference conditions.

In Fig.3, there are presented plans of the ground floor with the reference building (Case 1) and the airtightness reinforcement solution (Case 3). In Fig. 3, there are also marked the modelled air leakage routes in the ground floor. In Table 3 there are presented exfiltration and infiltration airflow rates at the ground floor with Cases 1, 2 and 3. 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.

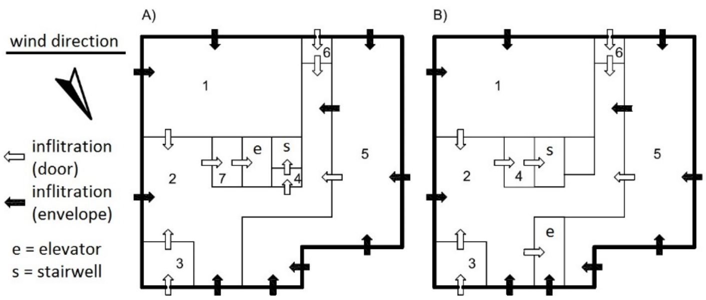

Fig.3 Modelled airflor routes in the ground floor: a) tight apartment doors and compartments (Case 3) b) reference building (Case 1).

Table.2 Infiltration and exfiltration airflow rates (l/s) at the ground floor (-5°C).

	Envelope		**Inner wall**	
	infiltration	**exflitration**	**infiltration**	**exflitration**
2: lobby				
Case 1	69	0	119	216
Case 2	0	59	0	72
Case 3	224	0	334	449
3: vestibule				
Case 1	10	0	0	18
Case 2	0	25	12	0

Case 3	8	0	0	16
4: stairwell compartmentation				
Case 1	0	0	27	29
Case 2	0	0	19	21
Case 3	0	0	38	40
6: vestibule				
Case 1	63	0	0	81
Case 2	0	57	52	0
Case 3	57	0	0	63
7: elevator compartmentation				
Case 1	-	-	-	-
Case 2	0	0	19	22
Case 3	-	-	-	-

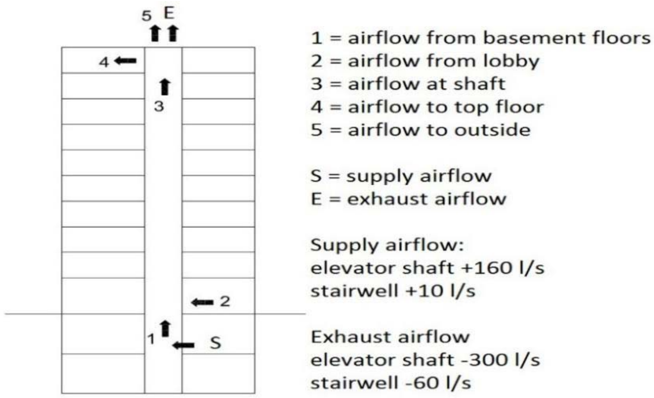

Fig.4 Directions of infiltration and exfiltration air flows at the ground and top levels of the building

Table.3 Airflow rates (l/s) with two airtightness levels through elevator and staircase shafts.

	Point 1		**Point 2**		**Point 3**		**Point 4**		**Point 5**	
T_{out} (ºC)	-5	-26	-5	-26	-5	-26	-5	-26	-5	-26
Shaft-Elevator										
Case1	898	932	185	338	1134	1341	488	534	602	751
Case 3	214	228	25	29	587	674	69	67	366	457
Shaft-Staircase										
Case 1	215	242	28	34	448	488	153	156	145	182
Case 3	76	91	22	24	285	339	118	122	167	217

In Fig. 5, there is presented the effect air tightness of building envelope and tightness of apartment and elevator doors on the heating energy consumption. The air tightness of the building envelope has a clear effect on heating energy consumption when the leakage of the apartment door is high (ELA_4= 0.01 m^2). By improving air tightness of the envelope from 3.0 $m^3/h,m^2$ (q_{50}) to 0.5 $m^3/h,m^2$ (q_{50}), it is possible to reduce energy consumption about 10 % (reduction from 55 $kWh/m^2,a$ to 49 $kWh/m^2,a$). With apartment and elevator doors of high leakage, the energy consumption is not possible further improve from the value of 49 kWh/m^2,a when the air tightness of the envelope is better than 0.5 m^3/h,m^2 (q_{50}).

The effect of the apartment and elevator doors on the energy consumption is higher than envelope. With the air tightness of envelope 0.5 m^3/h,m^2 (q_{50}), it is possible to reach around 20 % energy saving in the heating energy consumption (from 49 kWh/m^2,a to the level of 40 kWh/m^2,a) when air tightness of the apartment and elevators doors are tight (ELA_4= 0.0012 m^2).

All this demonstrate that high energy efficiency and the controlled air movement inside a high rise building is not only possible reach with airtight building envelope. Internal airtightness is also playing as significant role as envelope in a high performing high rise building.

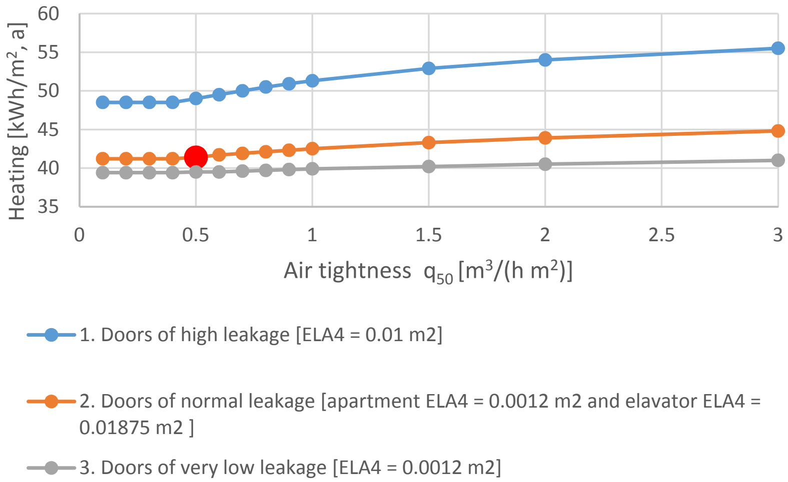

Fig.5 The effect of internal leakage and air tightness on energy consumption.

4. Discussion

The pressure difference always occurs when there exists temperature difference between indoor and outdoor temperatures. Air movement within building and between spaces is driven by pressure differences. Depending on the design solution, 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.

Against common believe, the air tightness of building envelope is not the only issue to control uncontrolled air movement in the building. Internal airtightness is playing much significant role that is commonly recognized. In a modern high-rise building with a well-sealed envelope, the stack effect can create significant pressure differences that must be taken into account in building design. To improve the performance of ventilation, the airtightness of the building envelope and the apartment and elevator doors should be analysed simultaneously.

5. Conclusions

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. When compartments of elevator shaft was used, the airflow rate of shaft could be reduced 48 % compared with the case where compartments were not used. With the air tightness of envelope 0.5 m^3/h,m^2 (q_{50}), it is possible to get 20 % energy saving in the heating energy consumption when air tightness of the apartment and elevators doors were improved.

Acknowledgment

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