Abstract
This paper presents an effective approach to mitigate stack effect in super high-rise buildings. With the great height of modern skyscrapers, the stack effect due to indoor and ambient temperature differential will be very strong and cause many adverse design and operation problems, such as increase in air-conditioning load, strong force acting on lift doors. This paper, based on an examination of the physics behind stack effect, proposes a new method which is low-cost, easy-to-use and effective for stack effect evaluation and subsequent design of mitigation measures. The physics behind the proposed method comes from real-life practice. The method, aiming at firstly analysing and optimizing the overall distribution of pressure difference between lift lobby and lift shaft, and then is coupled with ‘air locker’ to cope with local problems regarding high pressure difference. The simulation results confirmed that the stack pressure differential throughout the building can be entirely lowered, thus directly mitigating the stack effect.

Keywords: High-rise building, Stack pressure, Stack effect

1. Introduction
Stack effect is the ventilation inside buildings, which is driven by pressure difference across the building envelope by air density difference due to temperature differential between indoor and outdoor air [1], inter-connecting shaft of different floors (the stack) and the building height. It can be used to enhance natural ventilation to reduce energy consumption, improving indoor air quality [2-4]. Nevertheless, it leads to many adverse effects which are a great concern on building management, in particular for super high-rise buildings. For instance, excessive infiltration and exfiltration which lead to high energy cost on air conditioning; high pressure force on lift doors which may cause the lift to be inoperable [5-7].

Previous studies have focused on both the characteristics of stack effect-driven problems and the solution methods to alleviate the adverse effect. Tamura and Wilson [8] measured the distribution of pressure differences in high-rise buildings and analyzed their characteristics by the Thermal Draft Coefficient. Similarly, Tamura [9] investigated the characteristics of pressure difference distributions and air flows in high-rise buildings, and concluded that the pressure difference, subject to stack effect, is greatly affected by the distribution of leakage areas in the building envelop and the internal partitions. Other studies measuring the air-tightness of a single part of a building also exist [10-13].

With these measurements and relevant data, progress has been made in the understanding of the stack effect problem. Jacques [14,15] proposed using vestibules and air-lock doors to increase the air-tightness of the spaces. Tamblyn [16,17] introduced a mechanical ventilation system to control indoor pressure. The failure of these two approaches was addressed by Lee et al [18] as: the existing measures against stack effect generally solve local problems, i.e. they may solve the problems of certain parts, but the power which causes stack effect may be transferred to other parts, resulting in secondary problems. Based on this, Lee et al [18] suggested an elevator shaft cooling system and indicated that the system can evenly reduce the pressure difference and air flow rate throughout a
building. However, the proposed system, including sub-duct systems which further comprise additional sensors, is complex, making this active system difficult for practical installation and control.

In this study, an easy-to-use, cost-effective method is developed to control stack effect in high-rise buildings. It is put forward based on the nature and characteristics of the stack pressure distribution, and focused on minimizing the magnitude of the pressure difference resulting from stack effect.

2. Overview of Stack Effect

2.1. The physics of stack effect

The origin of stack effect comes from hydrostatic pressure differentials between building interiors and exteriors. Due to interior space heating or cooling of a building, different temperatures establish between the inside and outside of the building and thus result in air density variation in between.

For any building associated with leakage, a neutral pressure level (NPL) exists, i.e. where the indoor and outdoor hydrostatic pressure are equal. Consequently, different densities of air lead to different stack pressures, positive and negative, at different heights except NPL. Thus a pressure difference establishes across the building envelope at the same height. The magnitude of the pressure difference ($\Delta P$) at the height ($H$) is related to the height of NPL ($H_{NPL}$) and the indoor ($T_i$) and outdoor ($T_o$) temperatures by Eq. (1) [1]:

$$\Delta P = \rho_a \left( \frac{T_o - T_i}{T_i} \right) g (H_{NPL} - H) \quad (1)$$

Eq. (1) shows that once a temperature difference ($\Delta T$) occurs across the building envelope, a stack pressure difference ($\Delta P$) establishes, and the higher the $\Delta T$, the larger the $\Delta P$.

2.2. The characteristics of stack effect-driven problems

The problems driven by stack effect can be classified into two types. Type I is due to the presence of extremely high $\Delta P$ across a building element, such as door and window. It is generally required that the pressure differential across a single window or door shall not exceed 130 Pa so that it can be opened/closed by a person [1]. Type II problems are associated with a high airflow rate, which leads to the problems of noise, strong wind and excessive thermal load for HVAC systems.

Fig. 1 illustrates the vertical distribution of static pressure for a high-rise building during wintertime. It is shown that with ideally airtight rooms, the pressure difference between the rooms and ambient is minimal due to the limited headroom, and the stack effect associated with each floor acts independently and has its own NPL. In contrast, the pressure difference between the lift shaft and ambient is the maximum, due to its great height. In real condition, i.e. the room partitions are not totally airtight, various airflow paths establish from the shaft to ambient or vice versa, and the maximum pressure difference in Fig. 1 would be shared by the individual partitions/leakages along each flow path. The pressure difference shared by a particular partition/leakage or the distribution of the pressure difference along the flow path is subject to the building’s constitution and the leakage area of each component [8-13].

It is commonly recognized that the vertical shafts, including elevator shafts and stairwells, contribute significant stack effect because they provide a direct vertical path for airflow [1, 14-17]. The physics for the role of the shafts is generally understood in two ways. Firstly, due to the large height of the column of air in the shaft, a large pressure difference exists between the indoor and outdoor environment that is to be shared by individual partitions/leakages residing between the shaft and envelope. Secondly, large airflow rates tend to occur inside the shaft. In wintertime, air flows from the ambient, across the room spaces into the shaft at low floor level, and flows from the shaft towards ambient at high floor level. In summertime, just the opposite case occurs. Hence, inside the shaft is an upward flow in winter and a downward flow in summer. The airflows across the floors carry and redistribute air pollutants and contaminants, forming a serious concern for indoor air quality.

To sum up, the nature for occurrence of stack effect and the relevant adverse problems is due to the presence of a pressure difference between the indoor and outdoor environment, and this pressure difference is mainly due to the presence of the vertical shaft.
2.3. The solution for stack effect mitigation

In this section, the solutions for stack effect mitigation are discussed. The existing methods for solving stack effect-driven problems involve air-lock [14,15], mechanical ventilation [16,17] and shaft cooling [18]. The former two methods are positive approaches, with the objective of alleviating the pressure difference shared by each building element. Specifically, air-lock method, by adding additional partitions such as door or enhancing the flow resistance of the existing partition, the pressure difference shared by other partitions is thus lowered, say, to meet the requirement of a maximum pressure difference of 130 Pa across a single door or window. However, this method only solves the local problem because it only changes the distribution of pressure difference. As for as the entire building is considered, the stack effect problems still exist here or there. The second method, mechanical ventilation, is meant to provide slightly positive pressurization in the room spaces. Take wintertime for example, positive pressurization at low floor level counteracts with the high hydrostatic pressure outside the building, thus reducing the pressure difference between the spaces and ambient. But, an even worse condition occurs at high floor level where the pressure difference between the room spaces and ambient is enhanced. Listburek [19] pointed out that the ventilation / pressurization unique to each room should be provided, instead of providing uniform ventilation by central systems to solve the stack effect problem. However, developers rarely select systems that are more expensive. The third method, shaft cooling, is rather aggressive. In theory, it can essentially solve the stack effect problem, because it directly lowers the pressure difference occurring between the shaft and ambient, by minimizing the indoor and outdoor temperature difference. However, the shaft cooling system, as proposed by Lee et al [18] is difficult to service and high in cost to maintain by skilled personnel. It may have limited application in newly designed buildings, but may not be applicable for those buildings constructed already.

3. A New Method for Stack Effect Mitigation

To overcome the drawbacks of existing measures against stack effect, the pressure difference arising between the shaft and ambient must be minimized. This study suggests a new method, which can uniformly rearrange the distribution of the pressure difference between the shaft and ambient at all floor levels in the whole building.

As known, in wintertime the vertical shaft is associated with a negative pressure at low floor level, i.e. below NPL and a positive pressure at high floor level above NPL when compared to the ambient hydrostatic pressure at the low and high levels, respectively. Further, an upward airflow establishes along the height of the shaft. These are the two main reasons contributing to stack effect-driven problems, as afore-discussed.

The new mitigation method consists of two steps. The first step is associated with installation of mitigation holes on the lift shaft well, which alters the overall and/or local pressure difference between the shaft and ambient. The purpose of this strategy is to lower the high pressure difference in the regions where stack effect is most serious. After the first step where the pressure difference for the whole building is optimized, i.e. local extreme high pressure difference problems may be solved by other mitigation method, and ‘air locker’ is used as the second step in the current study.

The proposed mitigation method is adopted into a numerical model for a tall building over 400m as illustrated in Fig.2. In total, the building has 90 floor levels. The winter weather conditions are simulated, with the interior temperature of 20°C and outdoor ambient temperature of 6°C. The objective of the simulation analysis is to alleviate the pressure difference on the lift. Both the wind effect and the urban wind profile have been taken into consideration in the simulation. The simulation is conducted by using the multi-zone model software CONTAM developed by NIST.

Fig. 2 Analyzed building (left) and lift topology, OE: Office Express, HE: Hotel Express, FS: Fire Service.

3.1. Introduction of CONTAM

The magnitude of the pressure difference between the shaft and ambient can be predicted by Eq. (1) which is widely used within the building community [1,20]. Further, the multi-zone model, CONTAMW, developed by the National Institute of Standards and Technology (NIST) USA, was capable of predicting the pressure difference magnitude caused by stack effect.

In multi-zone models, the rooms of a building are typically represented as zones, with homogeneous air properties in each zone. And air flows passing through the paths interconnect the various zones. Each flow path has user-defined leakage characteristics to represent its aerodynamics performance. The air flow rates through the paths are calculated based on the mass balance equation.
For the simulations in current study, the reliability of the numerical results is subject to the leakage data chosen for the building mode. This source of uncertainty was minimized by considering multiple calculations adopting various leakage data, and the results showed good repeatability.

3.2. Simulation results & discussions

For the simulation results in this study, i.e. the pressure difference acting across the door, window and etc. are dependent on the leakage data adopted. To assure the reliability of the simulation, various leakage data were used and the results showed good repeatability.

Fig. 3 is the distribution of pressure difference that acts on lift doors for lift shaft (OE) which is, relatively speaking, located at the lower part of the 400m-high building, serving floor levels from B1 (basement) to Level 45. Fig. 3 indicates that the neutral pressure level (NPL) for OE occurs at the upper section of the lift height, namely around Level 38 or Level 39. Such location of NPL for OE can be related to the fact that the NPL for the whole building generally occurs at the middle height of the building, i.e. at around Level 45 for the 90-Level buildings.

Fig. 3 Lift door pressure difference for OE

Fig. 4 shows the distribution of lift door pressure difference for lift shaft HE. HE serves floor levels from B3 to L71. The NPL of HE resides at around L42.

Fig. 4 Lift door pressure difference for HE

Fig. 5 is the lift door pressure difference for lift shaft for fire service lift FS, which serves all floor levels from B3 to L89. For FS, the NPL occurs at around L51 or L52, also in proximity of the NPL of the whole building, which is generally at half building height.

Fig. 5 Lift door pressure difference for FS

The high pressure difference exerted on lift doors would incur difficulty in lift door opening/closing. Such difficulty may induce severe problems regarding to human safety. Thus, alleviating the lift pressure difference becomes the objective of many research efforts and also the present study. In this study, the strategy adopts installation of mitigation hole and addition of door to solve the problem.

First, relief openings are proposed to be installed on the lift shaft OE to shift its NPL from Level 38 to lower level, thus decreasing the lift door pressure difference at L1 and simultaneously increasing the lift door pressure difference at L44 and L45. The effect of relief opening is twofold. On the one hand, it balances the pressure difference across the lift doors that are located at the levels nearby the opening, thus solving local high pressure problems. On the other hand, it changes the NPL position, thus altering the distribution of lift door pressure difference.

In total, two relief openings with effective leakage area of 0.25m² are adopted for OE, one at L1 and the other one at L45. The lift door pressure difference after installation of relief openings is given in Fig. 6.
Similarly, two relief openings are proposed to be installed for HE, one at L1 and the other at L3. The simulation result after installation of two holes is shown in Fig. 7.

It can be seen that installation of relief openings for shafts OE and HE has changed the lift door pressure difference by relocating NPL to a middle position or by reducing the pressure difference on lift doors that are near to the relief openings. For the present building model, no relief opening is installed for FS, as its NPL is already at the middle of the levels spanned by FS, namely around L51 or L52. However, there is a high pressure difference across the lift door at L3, which exceeds 100Pa. This local problem can be well coped with the traditional ‘air locker’ method. After adding an additional door to the lobby of lift shaft FS, the high pressure can be shared by the lift door and additional door, thus lowering the pressure difference exerted on the lift door at L3. Fig. 8 shows the pressure difference distribution for FS after mitigation.

4. Conclusion

A new mitigation strategy is proposed in this study to solve the stack-effect-driven high-pressure-difference problem that associates with lift door. In high-rise buildings, the stack effect due to indoor/outdoor temperature differential is so strong that it results in high pressure difference across the lift door. This may lead to difficulty in lift door operation, and further other severe safety issues. Through numerically modeling a 400m building, the vertical distribution of pressure difference exerted on lift door is found to be optimized by proper installation of a few relief openings. At the same time, the pressure difference magnitude can be reduced. After optimization of the overall pressure difference distribution, local high-pressure-difference issue can be solved by adding ‘air locker’.

The proposed strategy, i.e. relief opening together with ‘air locker’ is better than traditional methods which can only solve local problems. It is low-cost, easy-to-use. More importantly, it has the capability of evenly alleviating the stack pressure differential throughout the whole building. The new strategy can be applied to both newly designed buildings and to those already constructed ones.

References


