Title: **Methods to Mitigate Costly and Disruptive Stack Effect in Super and Megatall Towers**

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Methods to Mitigate Costly and Disruptive Stack Effect in Super and Megatall Towers

论超高层和巨高层建筑中降低烟囱效应的设计方法和相应措施

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Abstract | 摘要

Risks for developers of supertall and megatall towers come in many forms, as these developments are high profile and complex. One present risk is the financial and disruptive impact of stack effect. Stack effect is the movement of air into or out of buildings due to air buoyancy, caused by a difference in temperature and humidity between the indoors and outdoors. Uncontrolled airflow and pressure related to stack effect always exists – especially in supertall and megatall towers – but can be exacerbated by extreme outdoor conditions. This paper presents strategies for mitigating risks through simulated stack effect conditions of realistic configurations of megatall towers. Stack effect will be reviewed parametrically to establish a design basis considering a tower's response related to geographic design conditions, envelope construction, lobby configuration, and space pressurization. Stack effect can be effectively mitigated if analyzed holistically and addressed early in design, resulting in significant energy cost savings.

Keywords: Façade, Megatall, MEP, Stack Effect, Sustainability and Vertical Urbanism

超高层建筑由于建筑自身的复杂性和知名度给开发商带来了一系列的风险。其中之一即为由烟囱效应而带来的经济和运营风险。烟囱效应指由于空气浮力而造成的不受控的室外气流渗出或渗入于建筑内部。与烟囱效应相关的不受控的气流和气压总是存在的，在超高层和高层建筑中表现尤甚，对于严寒酷暑区的超高层，该现象更达到极至的表现。这篇文章阐述了减轻超高层建筑烟囱效应的措施。烟囱效应的参数由不同地理气候，建筑围护结构，大堂设置，建筑内部区域空调压系统等来相应调节超高层的设计。 烟囱效应可以通过全建筑系统全方面考虑和从早期设计方案入手被大大减轻，大大降低建筑能耗。

关键词：幕墙、巨型高层建筑、机电、烟囱效应、可持续性、垂直城市化

Introduction

Urban centers are expanding vertically, with now over 1,000 completed tall buildings greater than 200 meters (Gabel 2016). The pace of tall building completion also continues to quicken as 2015 broke the record for tall building (>200 meter) completion, previously set the year before. Additionally, the number of completed supertall buildings (>300 meter) is now twice what it was in 2010 (Gabel 2016). These trends have reshaped urban centers, but also presented new architectural and engineering challenges. Critical to consider as these trends continue is the impact of stack effect on tall buildings and best practice design methods to help mitigate stack effect related issues.

介绍

全球范围内现已竣工的200米以上的高层建筑已经超过1000栋（Gabel 2016），预示着城市中心正在纵向蔓延。继2015年打破上年度（200米以上）高层建筑的竣工记录以来，高层建筑仍然相继落成，保持旺盛的增长势头。与2010年相比，已竣工超高层建筑（300米以上）的数量现已翻番（Gabel 2016）。增长趋势不仅重塑了城市中心，而且给建筑和工程设计领域带来了新的挑战。面对垂直城市趋势的有增无减，如何考虑烟囱效应对高层建筑的影响和采用哪些最佳惯用设计方法来缓解烟囱效应的相关问题就成为超高层建筑和设计中心当务之急。

Uncontrolled Airflow Can Wreak Havoc on Tall Buildings

Stack effect is the movement of air in or out of a building, driven by the buoyancy of the

失控气流可对高层建筑造成严重破坏

烟囱效应是指由于室内外的空气的温度差或湿度差而产生空气浮力作用下，由压差产生的相对内外空气流动。设计中如不考虑烟囱效应，其产生的相关气流的渗入或

air due to the difference in temperature or humidity between the indoors and outdoors. If left unchecked, stack effect related airflow and pressures can lead to a host of problems for tall building owners, occupants, and operators.

Stack effect is characterized by vertical air movement inside buildings and an increased infiltration. Uncontrolled airflow through the building envelope is untreated air, which must be heated or cooled at the building air handling system, with significant energy cost implications.

The stack effect related uncontrolled air movement and pressure differences in buildings may also create comfort issues for occupants. Stack effect can lead to "windy" interior conditions, doors that are difficult to open or close, and whistling noises. In prestigious supertall and megatall buildings, this level of occupant discomfort is often considered to be unacceptable.

Building systems and operations can also be adversely affected by these conditions. Elevator shafts create a continuous vertical conduit for air movement, so there is typically significant stack effect air movement and pressure within, which may impede elevator door openings and cab travel. Elevators can create piston effect pressure in the shaft, which can be heightened by stack effect airflow. This is especially a concern in supertall and megatall buildings, where fast elevators and limited shaft clearance around the cab due to core space constraints are typical.

Stack effect pressures can also create significant back pressure on building fan systems, with air handling systems required to run at elevated fan static pressure to overcome stack effect, which leads to increased energy cost and operational complexity. This is especially critical for life safety systems such as stair pressurization or atrium exhaust systems, as the systems must be designed and controlled to operate against stack effect pressure under varying climatic conditions.

Ultimately, stack effect pressures are enhanced when coupled with increased air infiltration due to climatic wind forces imposed on supertall and megatall buildings causing undesirable and uncontrolled airflow within the buildings.

Stack Effect Will Always Exist in Tall Buildings

The uncontrolled airflow and pressures related to stack effect will always exist in buildings,

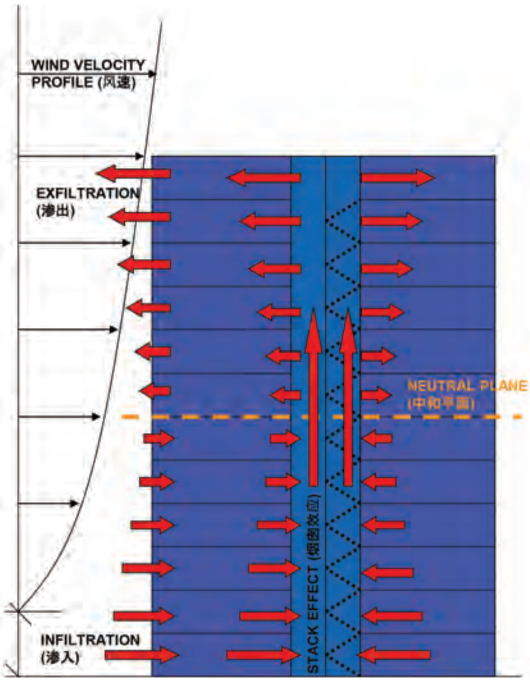

Figure 1. Stack effect schematic for winter design condition (Source: Environmental Systems Design, Inc.)
图1. 冬季烟囱效应（来源：Environmental Systems Design, Inc.）

exacerbated by extreme outdoor temperatures and wind, and will be especially prevalent in tall, supertall, and megatall buildings. While impossible to eliminate, stack effect can be appropriately managed and mitigated through careful building planning and design.

Air buoyancy occurs in either an upwards or downwards direction within a building depending on the temperature variation between indoors and outdoors. With warm outside conditions, downward air buoyancy (gravity driven drop of relatively cool, conditioned air molecules) leads to vertical air movement down through the building with uncontrolled infiltration (airflow into the building) at upper levels and exfiltration (airflow out of the building) at lower levels. The opposite occurs with cold outside ambient conditions as upward air (rise of relatively warm, conditioned air molecules) leads to vertical air movement up through the building with infiltration at the base of the building and exfiltration at upper levels. The winter stack effect condition is shown diagrammatically in Figure 1.

The magnitude of the air buoyancy and stack effect is driven by the hydrostatic pressure variation created by the weight of a column air inside the building compared to outside. The hydrostatic pressure depends on the height of the air column and the air density, a function of temperature and humidity ratio. Stack effect pressure differential is proportional to the temperature difference between interior and exterior and to the building height, so therefore will be most pronounced in tall buildings and in locations with extreme outside air ambient conditions.

渗出和压力可为高层建筑的业主、使用者和管理者带来不少麻烦。

烟囱效应的显著特征就是空气在建筑内的垂直移动从而增加围护结构的渗透作用。这股未经过处理的空气气流穿过建筑围护结构必须经大楼空调处理系统加热或冷却，从而带来显著的能源损失。

由于烟囱效应引起的建筑内的失控气流与压差还可影响建筑使用人员的舒适度。烟囱效应可导致室内条件中的“风道”现象，造成开门关门困难、气流噪音等。对于精良的超高层建筑和摩天楼宇中，使用人员是无法接受该室内舒适度水平。

楼宇其他工程系统及运行也会受到负面影响。垂直电梯井不可避免的形成了许多空气垂直通道，因此电梯井内一般都会有显著的烟囱效应所带来的气流运动和压差，从而妨碍电梯门开启和梯厢行进。由于活塞效应的缘故，电梯可在竖井内产生压力，而烟囱效应产生的气流运动会使活塞效应恶化。在超高层建筑和摩天大楼中，电梯高速运行，再加上核心筒空间局限性等问题较为普遍，导致轿厢四周的电梯井净空较为有限，这一问题显得尤为突出。

烟囱效应产生的压力还造成建筑风机系统中背压现象，从而迫使空调机组在升高风机静压下运行，以抵消烟囱效应的影响，从而导致运行成本增加，运行操作系统更为复杂化。这在楼梯增压或中庭排烟系统等消防系统中尤为关键，上述系统的设计和操控必须保证系统能够在任何气候条件下产生的烟囱效应下的环境压力下运行。

最终，由于室外风速等气候现象在超高层建筑和摩天大楼中产生风压，使建筑内部形成不可避免的失控气流，加剧室外空气渗透，烟囱效应产生的压力也随之增强。

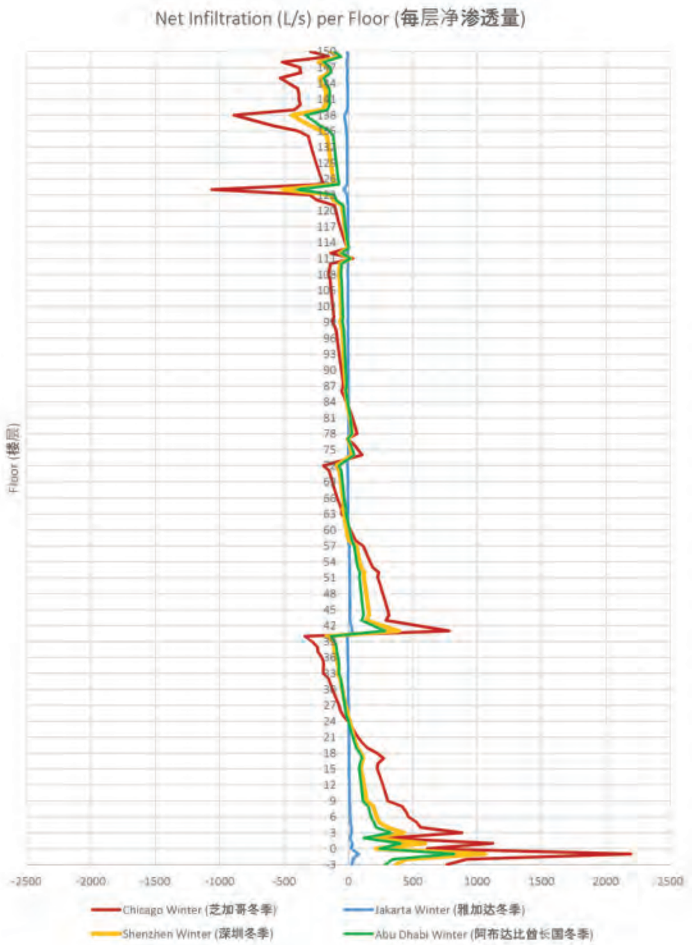

Figure 2. Stack effect variation due to climatic location, winter design condition (Source: Environmental Systems Design, Inc.)

图2. 冬季不同地理气候位置的烟囱效应比较（来源：Environmental Systems Design, Inc.）

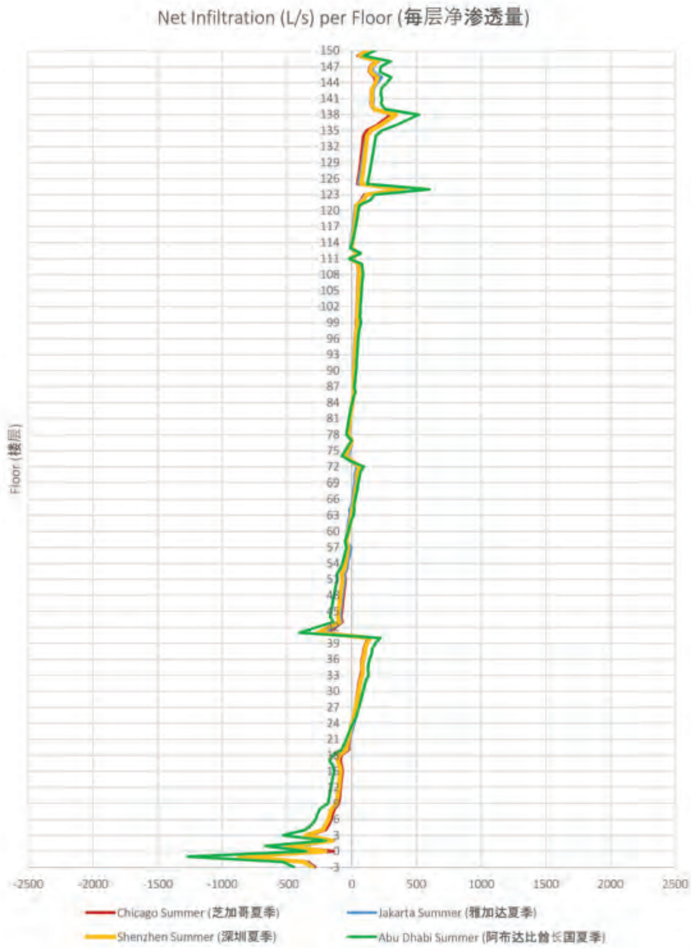

Figure 3. Stack effect variation due to climatic location, summer design condition (Source: Environmental Systems Design, Inc.)

图3. 夏季不同地理气候位置的烟囱效应比较（来源：Environmental Systems Design, Inc.）

The effect of climate on stack effect can be seen in Figures 2 and 3, where the simulated net infiltration per floor is plotted for a representative 150-story, 570-meter, megatall building. The net infiltration is the sum of all air leakage into the building less all air leakage out of the building for a given level. The air leakage may be through cracks or joints in the curtain wall or through exterior doors. Positive infiltration values indicate airflow into the building and negative infiltration values indicate airflow out of the building.

Figures 2 and 3 compare the stack effect response for the same building simulated in four different climatic locations for winter and summer conditions. The general response pattern is similar for all locations, but it is apparent that stack effect airflows are greatly exaggerated in extreme climates. Considering the Chicago winter condition (nearly 70 °F or 38.9 C variation from inside temperature), there is significant infiltration into the building at the lower levels, with strong exfiltration at the top of the building. For the Jakarta winter design condition (less than one °F or 0.5 C variation from inside temperature), there is almost no airflow in or out of the building at any level.

The summer and winter conditions are also seen to be mirrors of each other (refer to

烟囱效应将与高层建筑形影不离

建筑中总是会存在由烟囱效应而产生的相关失控气流和压力，而严寒或酷暑地域的室外温度和室外高风速地区又会使其加剧，这种现象在高层建筑、超高层建筑和摩天大楼中尤其明显。虽然无法消除这一现象，但在成熟的建筑规划设计中可适当控制和减缓烟囱效应。

建筑内无论是上方向还是下方向都会产生空气浮力差，具体取决于室内外的温茶变化。如果外界条件较为炎热，下风向的空气浮力（重力驱动，炎热外界空气于较经过空调处理的凉爽空气相比，室内空气密度较高）导致空气垂直向下穿过建筑，建筑上部的空气渗入（流入建筑的气流）与建筑下部的空气渗出（流出建筑的气流）。当外界环境条件较为寒冷时，情况则恰恰相反，上行气流（相对在室内经过处理的炎热空气密度较高）导致空气向上垂直穿过建筑，建筑基底发生空气渗入现象，而上层发生空气渗出现象。冬季的烟囱效应条件示意图如图1所示。

空气浮力和烟囱效应幅度的原驱动力为建筑室内外温差度而引起的流体静力压差。流体静压取决于空气密度差，是一项温度与湿度比的函数。烟囱效应压差与室内外温差与建筑高度成正比，因此在高层建筑顶部于基部和外界空气环境条件较为严酷的环境处所中最为显著。

从图2和图3可以看出气候对烟囱效应的影响，图中以150层570米高的摩天大楼为例，描绘了每层楼的模拟净渗透量。净渗透量是指某一给定的楼层中用渗入大楼中的空气总量减去渗出大楼的空气总量求得的差值。渗透现象可能发生在幕墙中的裂缝或接缝处，也可能发生在通向室外的大门处。空气渗透值为正，则表明空气流入建筑物，渗透值为负，则表明空气流出建筑物。

图2和图3比较了冬夏两季在四个不同的环境气候下计算机模拟的同一栋建筑物的烟囱效应反应。虽然四个气候环境下的整体反应模式大同小异，但显而易见，在极端气候条件下烟囱效应所产生的气流明显加大。考虑到芝加哥市入冬后的气候条件（与内部温度相比温度变化将近70华氏度或38.9摄氏度），在较低楼层空气渗透进入大楼的现象较为显著，而大楼顶部的空气渗出十分强烈。针对雅加达冬季的设计条件（与内部温度相比温度变化低于1华氏度或0.5摄氏度），各楼层基本上不存在空气流入或流出大楼的现象。

在夏季和冬季条件下可以镜面相反的表现模式相互对照（图4），其气流模式刚好

Figure 4), with reverse airflow patterns. The building response to both the summer and winter condition includes neutral planes with zero net infiltration at identical levels, but the magnitude of the winter airflow is much greater, proportional to the difference between inside and outside temperatures.

Integrated Design as a Means to Minimize Stack Effect

Current trends include the construction of increasingly tall buildings, often located in extreme climates, so stack effect must be managed and mitigated by providing vertical compartmentalization (such as elevator and stair transfers) and by providing continuity of the air barrier boundary. Vertical compartmentalization effectively creates a series of shorter stacked buildings where the magnitude of stack effect is reduced. A robust air barrier between inside and outside helps limit uncontrolled airflow through the building envelope. It is especially important to separate the building exterior from vertical pathways such as stair and elevator shafts, so tight-sealed elevator lobbies or similar air barriers can be helpful.

Compartmentalization and multiple layers of tight air barriers are the two most effective tools to combat stack effect, but may not always be feasible architecturally or programmatically. The most effective means to mitigate stack effect is to establish an integrated, holistic design process that incorporates these features into the building from early design stages. Appropriate vestibules, stair or elevator transfers, proper elevator shaft size/design, effective HVAC system zones/air risers configuration, and other features are easiest to incorporate when integrated into the program early.

Building response to stack effect conditions can be simulated during design to identify "hotspots," or areas where airflows and pressures will be especially problematic due to the architectural configuration. These areas can then be addressed with additional levels of air barrier protection or specialized pressurization systems to reduced uncontrolled air exchange between indoor and outdoor.

The holistic design process should also include effective detailing of the curtain wall enclosure, especially at corners, setbacks, and other areas where construction anomalies can provide an air leakage path. Figure 5 shows

表现相反。建筑物对夏季和冬季条件的反应包括相同楼层净渗透量为零的理想中性平面位置，但冬季空气流动的幅度明显加大，其幅度与内外温差成正比。

通过整体设计最大限度减少烟囱效应

当下兴建高层建筑已蔚然成风，高层建筑的高度亦与日俱增，许多超高层也往往位于极端气候区内，因此对烟囱效应的遏制更加需要控制体现于设计。例如提供垂直分区（即电梯与楼梯中转）和间断的气流障界来管控。该方式通过垂直分区有效打造出一系列较矮的叠加建筑，使烟囱效应的幅度随之减小。另外在建筑内部与外部之间设置一道严密的空气屏障，有助于限制穿过建筑围护结构的失控气流。建筑室外与楼梯和电梯井等垂直通道的分隔尤为重要，因此严缝侯梯厅或类似的空气锁的在减缓烟囱效应作用不言而喻。

垂直分区隔断和设置多道气密性屏障是抵制烟囱效应最为有效的两大工具，但这两项物理措施无论从建筑学还是从业态的角度分析，都很难有效的在实践实施。减轻烟囱效应，最有效的手段莫过于创建一套综合全面的设计流程，从初期就将上述功能整合到建筑中。从早期改建方案入手，

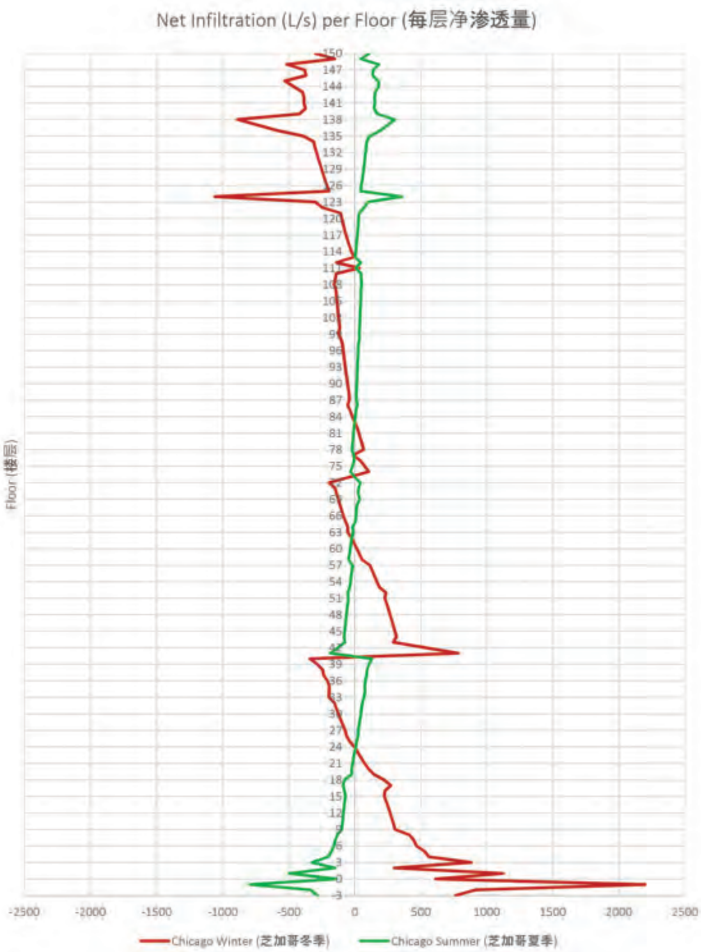

Figure 4. Stack effect comparison of Chicago summer and winter design conditions (Source: Environmental Systems Design, Inc.)
图4. 芝加哥地区冬夏季烟囱效应比较（来源：Environmental Systems Design，Inc.）

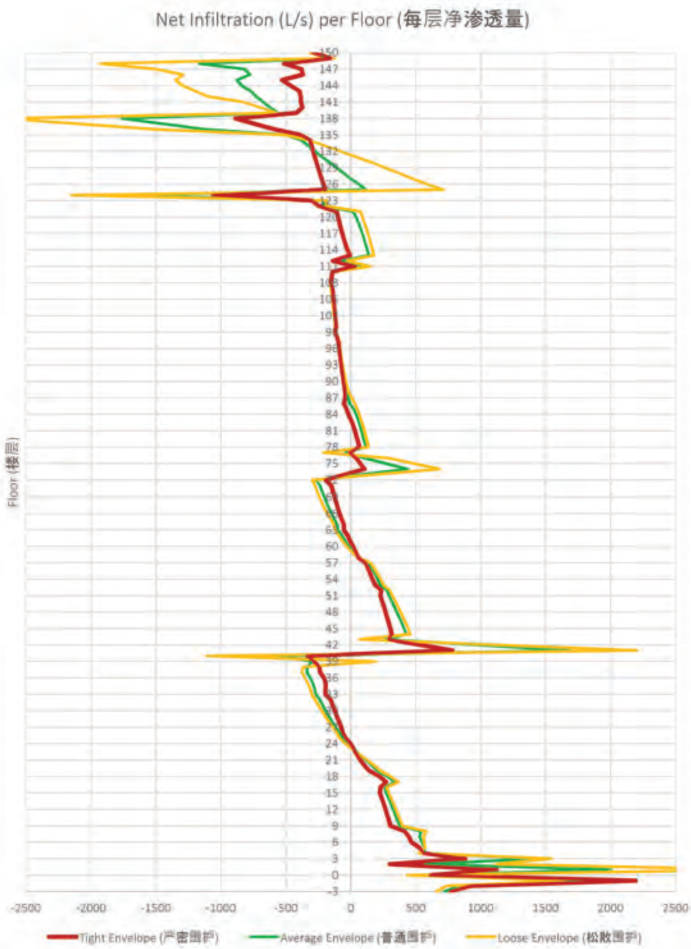

Figure 5. Stack effect variation due to envelope tightness (Source: Environmental Systems Design, Inc.)
图5. 围护结构紧密度对烟囱效应变化的影响（来源：Environmental Systems Design，Inc.）

the importance of a tight building envelope as infiltration due to stack effect increases dramatically for average and loose envelopes. Note that the definition of tight, average, and loose construction is based on curtain wall leakage rates from a dated study of mid-rise buildings. While not necessarily applicable for modern tall building construction, which are all typically designed to be tight or better, the relationship still applies.

Construction anomalies will always exist, even in a well-designed, well-detailed building, so it is important to have a strong construction phase quality control and oversight and commissioning of the building envelope to confirm the design intent and design criteria are fully met. Small anomalies, such as unsealed conduit penetrations to façade lighting through the curtain wall, can have a tremendous effect on the overall curtain wall leakage rate, and in turn, the magnitude of stack effect.

When not fully addressed through an integrated design process, stack effect is significantly more costly and disruptive to mitigate post construction. Problems in existing buildings can still be addressed, but not to the same extent. For example, it is likely not economically feasible to add vertical compartmentalization. A more robust air barrier can be provided by adding vestibules and sealing envelope openings, but even this may be expensive and difficult if the building is occupied.

Simulating Stack Effect Conditions to Establish Best Practices

To help establish a stack effect design basis, a software tool was used to simulate airflows and pressures within a representative, megatall building. With the software, a simplified theoretical building model can be created that consists of the primary building zones and the airflow leakage paths between those zones. The pressures created by external wind at various elevations derived from wind tunnel evaluations, ambient design temperatures at various elevations, and building air handling systems can be imposed on the model, with calculated theoretical pressure and airflow within each zone and across each airflow path as an output.

The software is a powerful tool that enables analysis of complex airflow and pressure relationships in buildings, but also provides a mountain of data. Parametric studies on climatic variation and envelope tightness were discussed previously, with net infiltration charted as indicator of building stack effect response. The climatic variation study

<table>
<tr><th>Reference
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比较项目</th><th>Simulation
计算机模拟参数</th><th>Design Temperature (C) | 外界设计温度</th><th>Total Positive Infiltration (L/s) | 净渗透量</th><th>Heat Load at Design Condition (kW) | 热负荷</th><th>% Difference
误差/百分比</th></tr>
<tr><td rowspan="4">Figure 1
图1</td><td rowspan="4">Climatic Location - Winter
气候地区
（冬季）</td><td>Chicago | 芝加哥</td><td>-15.7</td><td>21724</td><td>–</td><td>–</td></tr>
<tr><td>Jakarta | 雅加达</td><td>22</td><td>1289</td><td>–</td><td>-94%</td></tr>
<tr><td>Shenzhen | 深圳</td><td>8.6</td><td>11738</td><td>–</td><td>-46%</td></tr>
<tr><td>Abu Dhadi
阿布Dhadi</td><td>12.8</td><td>7502</td><td>–</td><td>-65%</td></tr>
<tr><td rowspan="4">Figure 2
图2</td><td rowspan="4">Climatic Location - Summer
气候地区
（夏季）</td><td>Chicago | 芝加哥</td><td>31.5</td><td>11359</td><td>–</td><td>–</td></tr>
<tr><td>Jakarta | 雅加达</td><td>33.1</td><td>11351</td><td>–</td><td>0%</td></tr>
<tr><td>Shenzhen | 深圳</td><td>33.1</td><td>9106</td><td>–</td><td>-20%</td></tr>
<tr><td>Abu Dhadi
阿布Dhadi</td><td>43.3</td><td>12655</td><td>–</td><td>11%</td></tr>
<tr><td rowspan="3">Figure 5
图5</td><td rowspan="3">Envelope Performance
围护结构情况</td><td>Tight | 严密围护</td><td>-15.7</td><td>21724</td><td>995</td><td>–</td></tr>
<tr><td>Average | 普通围护</td><td>-15.7</td><td>49166</td><td>2251</td><td>126%</td></tr>
<tr><td>Loose | 松散围护</td><td>-15.7</td><td>156990</td><td>7187</td><td>623%</td></tr>
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空调系统正压</td><td>Neutral Pressure
中和压</td><td>-15.7</td><td>21724</td><td>995</td><td>–</td></tr>
<tr><td>-10% Pressurized
−10%负压</td><td>-15.7</td><td>27250</td><td>1248</td><td>25%</td></tr>
<tr><td>+10% Pressurized
+10%负压</td><td>-15.7</td><td>18019</td><td>825</td><td>-17%</td></tr>
<tr><td rowspan="3">Figure 8
图8</td><td rowspan="3">Freight Elevator Vestibule Configuration
货梯前室</td><td>Tight | 严密货梯前室</td><td>-15.7</td><td>21724</td><td>995</td><td>–</td></tr>
<tr><td>Loose | 松散货梯前室</td><td>-15.7</td><td>23571</td><td>1079</td><td>9%</td></tr>
<tr><td>No Vestibule
无货梯前室</td><td>-15.7</td><td>27156</td><td>1243</td><td>25%</td></tr>
<tr><td rowspan="3">Figure 9
图9</td><td rowspan="3">Core Elevator Lobby Configuration
核心筒电梯厅构型</td><td>Tight | 严密货梯前室</td><td>-15.7</td><td>20788</td><td>952</td><td>–</td></tr>
<tr><td>Loose | 松散货梯前室</td><td>-15.7</td><td>23571</td><td>1079</td><td>13%</td></tr>
<tr><td>No Vestibule
无烟囱效应大堂</td><td>-15.7</td><td>27156</td><td>1243</td><td>31%</td></tr>
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四层特殊层（直联）</td><td>-15.7</td><td>21724</td><td>995</td><td>–</td></tr>
<tr><td>Additional Vestibule at Critical Levels
四层特殊层（保护）</td><td>-15.7</td><td>20487</td><td>938</td><td>-6%</td></tr>
</table>

Figure 6. Summary table of stack effect variation studies (Source: Environmental Systems Design, Inc.)
图6. 烟囱效应比较研究总表（来源：Environmental Systems Design, Inc.）

considered four locations to demonstrate the effect of outdoor ambient temperature on stack effect, but all other parametric studies consider the Chicago winter design condition only, as it represents extreme climatic case.

As another indicator of whole building stack effect response, the cumulative positive infiltration into the building can be considered. A positively pressurized building with airflow out of the building is generally desired as controlled, conditioned air flows out through the curtain wall. Positive infiltration introduces untreated, uncontrolled, unconditioned outside air into the building, all of which eventually gets conditioned by the building air handling systems, adding to the building heating or cooling load. For the Chicago winter design condition, the cumulative positive infiltration is presented in air volume (L/s) as well as the additional heat load imposed on the building (kW). A summary of the results from all studies is shown in Figure 6.

恰到好处的前室、楼梯或电梯中转、合理的电梯井尺寸/设计，以及有效的暖通空调系统分区/送平排风立管配置及其他功能都是最易于整合的到实际并有效方案中的。

在设计阶段就可以通过计算机模拟建筑物对烟囱效应工况的反应，例如确定问题楼层，从而推断出哪些区域的气流和压力由于建筑配置显得尤为棘手。这些可通过提高空气屏障保护等级或区域性增压系统解决该区域气流的渗入渗出问题。

整体设计过程还应包括对幕墙围护的有效细化，尤其是结节、退界及其他由于施工不当造成空气渗漏漏气隐患的区域。图5表明当由于烟囱效应引起的空气渗透显著增加时，施工过程严密的建筑围护结构与施工过程较为普通和松散的围护结构相比，其优越性可见一斑。在此对施工严密、普通和松散的定义是基于现有的中层建筑研究中的幕墙实际漏气率。尽管这一指标不见得适用于现代高层建筑施工，因为后者的设计与施工一般都相对严密，甚

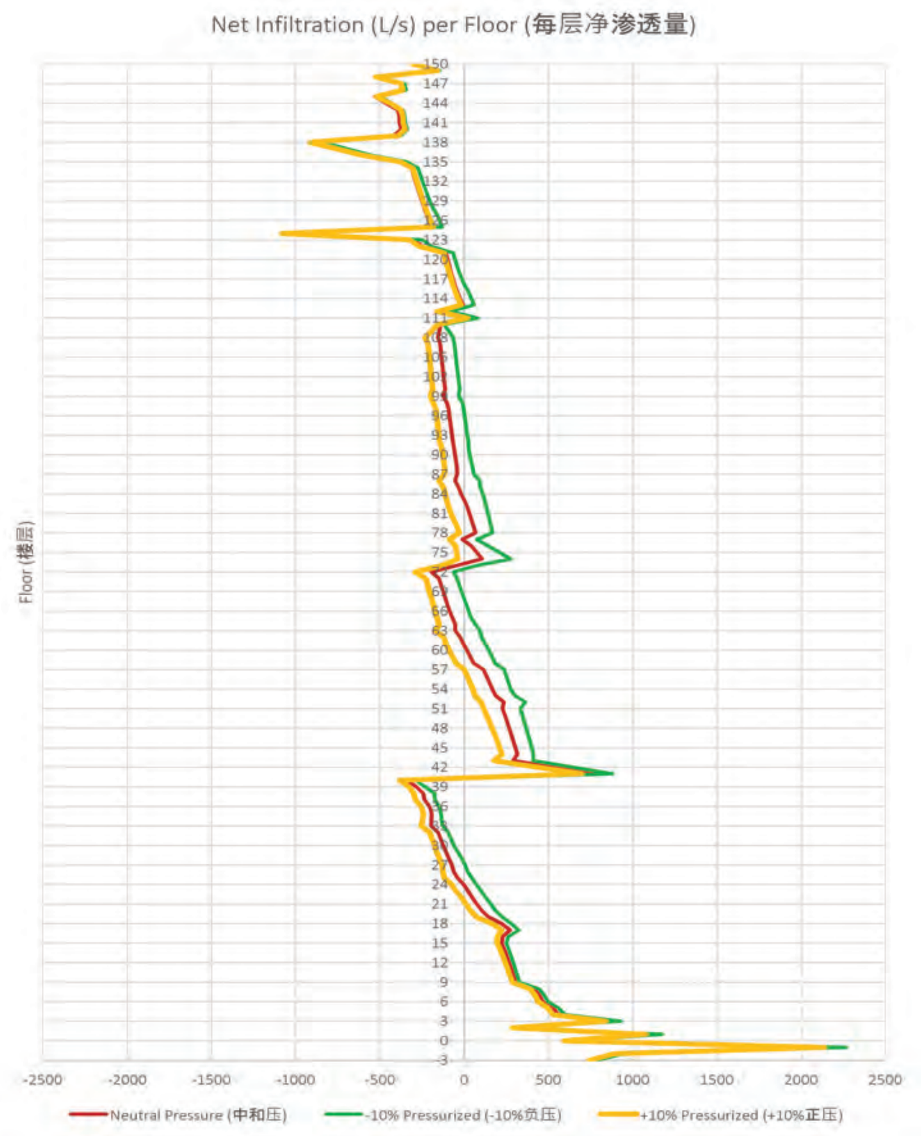

Figure 7. Stack effect variation due to HVAC system pressurization (Source: Environmental Systems Design, Inc.)
图7. 空调系统增压对烟囱效应变化的影响 （来源：Environmental Systems Design, Inc.）

The impact of mechanical system pressurization on stack effect is represented in Figure 7, which compares building air handling systems that are -10 percent pressurized (10 percent more exhaust than outside air intake), neutral pressurized (equivalent exhaust and outside air intake), and +10 percent pressurized (10 percent more outside air intake than exhaust). The positively pressurized building can be seen to outperform the other two cases, with less positive infiltration at each level and overall.

Especially in cold climates, many buildings shut outside air dampers in winter in an effort to save on heating energy costs, but this practice only exacerbates stack effect and creates more issues than it solves. The best practice is to positively pressurize the building lobby and other areas on lower floors of the building that are especially prone to stack effect related infiltration. Positive pressurization using the building air handling system will provide controlled introduction of conditioned outside air into the space, and will help minimize stack effect as shown in Figure 7.

至更甚一筹，然而上述气流关系仍然可参照适用。

施工不当在所难免，甚至出现在设计和深化设计都很合理的建筑中，因此对建筑围护结构进行有力的施工阶段质量控制、监督和调试，以确认是否完全符合设计意图和设计准则，其重要性可见一斑。即使小小的施工问题，如建筑外立面照明管线穿越幕墙的穿管处未经过气密封处理等，都会对整体幕墙漏气率产生巨大的影响，并波及到烟囱效应的幅度。

如果通过整体设计过程仍然无法完全解决上述科研问题，则建筑竣工后再进行治理烟囱效应的代价和对建筑系统的破坏性都会更高。对于现有建筑物的烟囱效应问题仍可解决，只是收效程度不一。例如，增加垂直分区从经济的角度考虑不太可行。通过增加前室和密封围护结构孔洞可以提供加强空气屏障密闭性，但即便如此，建筑物一旦入住后，也会面改造临造价不菲和施工困难重重等问题。

模拟烟囱效应工况确立最佳做法

为建立明确烟囱效应的设计依据，我司采用了软件工具来模拟某一栋代表性摩天大楼内的气流和压力。通过软件创建简化理论建筑模型，包含主要建筑分区和上述分区之间的气流漏气途径。通过风洞数值评价推算出来的各标高外界风压、各标高环境设计温度。建筑空调系统亦可以输入到模型中，从而模型计算输出每个分区 内和贯穿每个空调系统的计算理论压力和气流。

这款软件工具可以分析大楼中错综复杂的气流和压力关系，但输出数据的数量也同样惊人。前面探讨了气候性变化和围护结构严密性的参数化研究，并列表说明净渗透量作为衡量建筑烟囱效应反应的指标。气候性变化研究考虑了四个不同外界地理气候，论证了室外环境温度对烟囱效应的影响，而其他各项参数化研究都只考虑了芝加哥市的冬季设计条件，因为后者代表了严寒端气候案例。

渗出建筑的累计正渗透量可作为另一项衡量整体建筑烟囱效应反应的指标。一般来讲为使建筑物增压后保持正压，通过幕墙渗出的气流为受控调节空气。而正渗入气流将外界未经处理和调节的失控空气引入空间，最终全部由楼中空气处理系统再转化成为调节空气，该过程增加大楼的制热或制冷负荷。就芝加哥市的冬季设计条件为例，累计正渗入的空气流量（升/秒）以及建筑物新增热负荷（kW）表征等。各项研究结果汇总如图6所示。

机械系统增压对烟囱效应的影响如图7所示，图中比较了负压-10%的大楼空气处理系统（排气量比室外新风进风量多10%）、零增压（排风量与新风进风量等同）以及增压+10%（新风进风量比排风量多10%）等三种情况。可以看到增压正压运行大楼的性能优于另外两种情况，每个楼层和整座大楼的正渗入值量均低于另外两种情况。

尤其在寒冷的气候条件下，很多大楼都会在冬季关闭新风风阀，以节省采暖的能源成本，但这种做法只能加剧烟囱效应，滋生出更多问题。最佳做法是给大楼大堂及其他较低楼层区域增压，使其保持正压，因为上述区域尤其容易发生与烟囱效应相关联的空气渗入。通过大楼空气处理系统正向增压可将调节新风量从而有组织的引导空间气流，从而最大限度地减少烟囱效应，如图7所示。

图8和图9突出显示了有效的空气屏障设计对烟囱效应所产生的影响，图中表明了货梯前室配置和核心筒候梯厅配置所产生的烟囱效应变化。就超高层建筑和摩天大楼而言，在大楼的主要垂直通道（楼梯、电梯等）与建筑室外之间尽量多设置几道空气隔离（防御层）就显得至关重要。高度

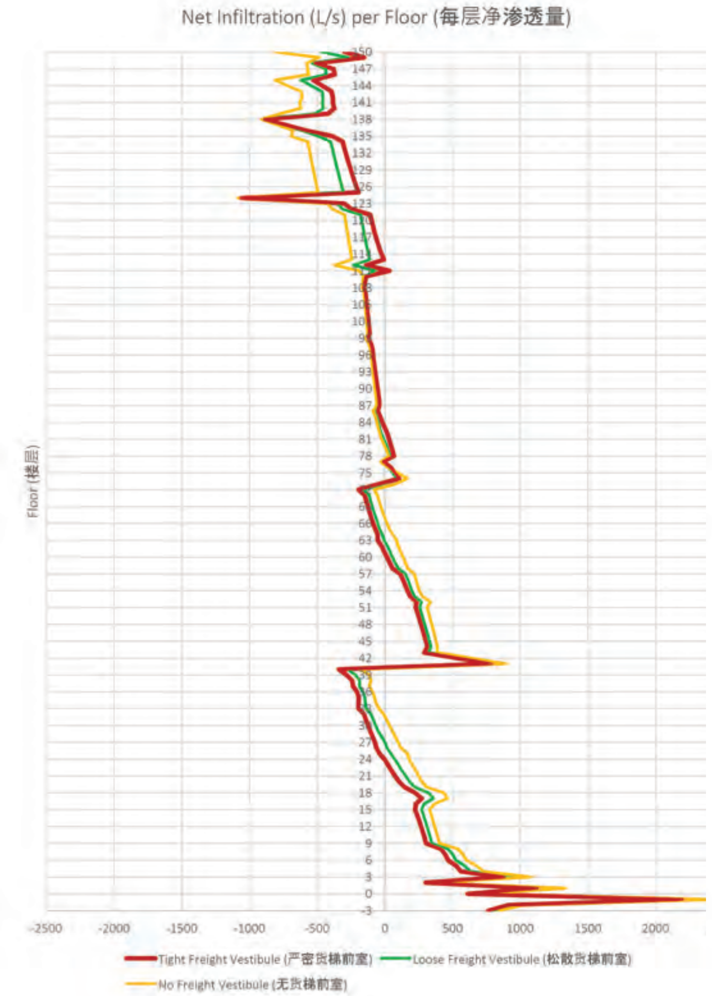

Figure 8. Stack effect variation due to freight vestibule configuration (Source: Environmental Systems Design, Inc.)
图8. 货梯前室构型对烟囱效应变化的影响（来源：Environmental Systems Design，Inc.）

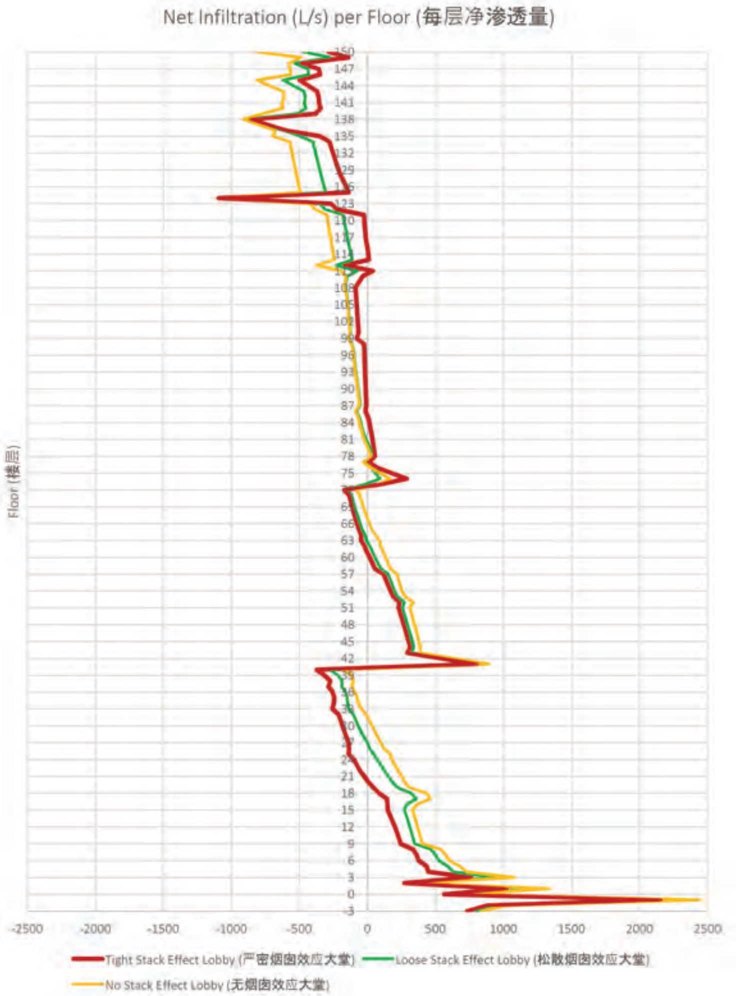

Figure 9. Stack effect variation due to core elevator lobby configuration (Source: Environmental Systems Design, Inc.)
图9. 核心筒大堂构型对烟囱效应变化的影响（来源：Environmental Systems Design，Inc.）

The impact of effective air barrier design is highlighted in Figures 8 and 9, which show variation due to freight elevator vestibule configuration and core elevator lobby configuration. For supertall and megatall buildings, it is critical to provide as many layers of air separation (defense) between primary vertical pathways (such as stairs or elevators) and the building exterior. Typical stairs or elevators that transfer and have shaft heights of less than approximately 40 floors should have two lines of defense between the shaft and exterior: for example, a gasketed elevator lobby door and a tight-sealed curtain wall.

Critical shafts that connect more levels such as those for freight or observation deck service will require even more protection. Freight elevator vestibules are especially important to help limit vertical shaft airflow, which can intensify elevator piston effect as discussed previously. The simulated peak shaft airflow was shown to be 40 percent greater with a loose freight vestibule and 70 percent greater with no freight vestibule, compared to a tight freight vestibule. Access hatches at the top of elevator shafts and in the elevator pit also need to be properly gasketed and sealed to combat stack effect .Some authorities having jurisdiction may require shaft ventilation, in which case special consideration needs to be given to controls and operation so that the ventilation system doesn't serve to amplify stack effect.

In all studies, there are a handful of airflow spikes that occur at consistent levels as a result of the specific building architecture. The large spikes at the base of the building are due to the exterior entrances, which are always a path for infiltration even when vestibules and revolving doors and vestibules are utilized. Revolving doors were actually invented in 1888 as a means to prevent air inrush at building entrances due to stack effect and have since become the standard for tall building entrances. Additional spikes in the figures represent elevator and stair transfers as well as mechanical floors. The top of one elevator shaft develops a strong exfiltration path, while the bottom of a separate shaft immediately above develops a strong infiltration path, seen in the charts as a rapid spike. Additionally, the mechanical floor configuration includes an additional freight elevator opening, which is not vestibuled for ease of access and

低于约40层的楼层承担中转职能层竖井的典型楼梯或电梯应在竖井与室外之间设置两道防御锁，例如防风侯梯厅门与气密性幕墙之间就应如此。货梯或观光平台服务等衔接更多楼层的关键竖井的保护要求甚至更高。货梯前室对于限制垂直竖井气流的作用尤其重要，如前文所述，前者可以使电梯活塞效应变得集中化。如图所示，与施工严密的货梯前室相比，货梯前室较为松散时的模拟高峰竖井气流高出40%，而未设置货梯前室时高出70%。电梯井顶部和电梯坑的检修门也需要采取合理的气密措施，以减轻烟囱效应。有些国家地区规范可能要求采取竖井通风措施，在这种情况下，就需要特别考虑控制和运行环节，保证不会因通风系统加剧烟囱效应。

在大量统计了许多具体楼宇建筑的运行测试各项研究后，我司发现许多系统现象发生在相同的楼层。于建筑基底如气流渗透量降值发生，由于室外入口产生，甚至当采用前室和旋转门及其前室时，室外入口也总是成为空气渗透的通路。旋转门实际上是1888年发明的，当时是为了防止烟囱效应导致空气从大楼基底侵入而采取的一种手段，后来就演变为高层建筑标准入口。图中新增的标记代表电梯和楼梯中转以及设备层。例如电梯井的顶部发展为渗出通路，而正上方的独立竖井的底部发展

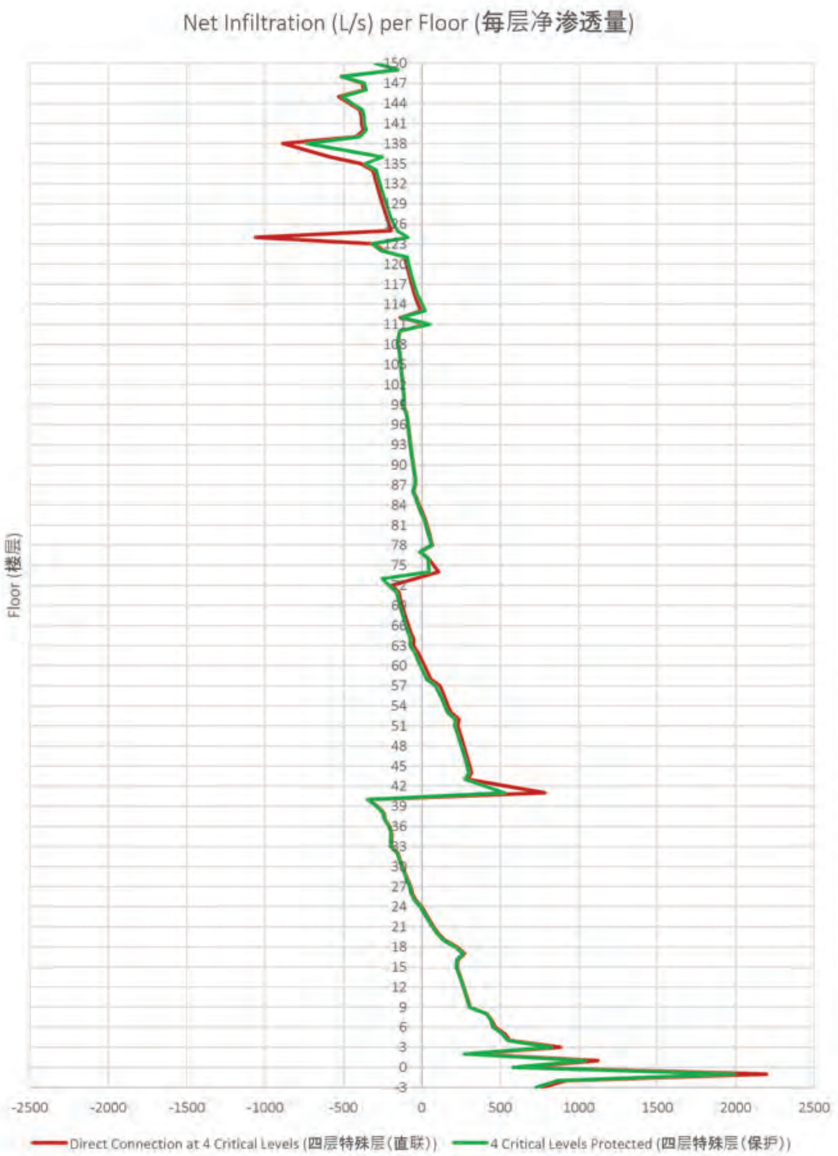

Figure 10. Stack effect variation due to critical-level air barrier configuration (Source: Environmental Systems Design, Inc.)
图10. 重要楼层空气锁障构造对烟囱效应变化的影响（来源：Environmental Systems Design, Inc.）

operational functionality. Adding a freight vestibule at these four critical levels reduces the total positive infiltration by six percent, charted in Figure 10. This result underscores the importance of stack effect analysis to determine and address "hotspots."

Energy and Financial Impact of Stack Effect Mitigation

There are distinct sustainability and economic benefits to urbanization and tall building construction, such as improved access to goods and services and thus occupant transportation reduction, the reduction of total building materials per occupiable area, efficient use of land, and increased occupant density; however, stack effect is one issue that pushes the needle in the wrong direction. If not appropriately mitigated, stack effect can lead to significant energy penalties for tall buildings.

Using the Chicago winter design conditions, Figure 6 includes the simulated heating load imposed on the representative megatall building. In this scenario, the baseline building with tight envelope and tight elevator lobby configuration requires nearly one MW of heat to offset the stack effect infiltration on a design day.

Stack effect cannot be eliminated in tall buildings, but even a small reduction would have significant sustainability implications. Considering the entire tall building stock over 200 meters (quantity 1,040), the approximate order of magnitude annual heating load as a result of stack effect is nearly 100 GWh. Even a 10 percent reduction would provide nearly 10 GWh of heating load savings, equivalent to the annual power consumption of approximately 10,000 homes. Additional annual savings would be also achieved due to reduced infiltration cooling load in summer with stack effect mitigation measures in place.

为高渗入通路，在图中显示为气流高峰值标记。此外，设备层配置还包括新增货梯开洞，为了易于检修和运行功能之便，没有设置前室。在上述四个关键楼层增设一间货梯前室可以使总正渗透量减少6%，如图10所示。该结果强调了烟囱效应分析对于定性和定位“问题楼层” 的重要性。

减少烟囱效应的能耗及经济影响

城市化和高层建筑有着显著的可持续及经济效益，比如人们可以更容易获得商品和服务，从而相应减少所需交通量，人均使用面积的总建筑材料，用地的高效以及居住密度的提高。然而，烟囱效应却可能让一切朝着错误的方向发展。如果不正确地减轻烟囱效应，将导致高层建筑能耗大大增加。

采用芝加哥冬季设计条件。图6为代表性超高层建筑的模拟制热负荷。在该场景中，拥有密封围护和电梯间配置的底线建筑需要接近1MW热能以抵消烟囱效应。

高层建筑中无法完全根除烟囱效应，但稍微减轻就可获得非常大的可持续益处。以主体建筑高度超过200米的高层为例，其每年制热负荷约为100 GWh。烟囱效应减少10%，就会节约将近10 GWh的制热负荷，在夏季，借助烟囱效应缓和措施，制冷负荷渗入降低亦会减少制冷负荷，每年可以实现额外的能耗节省。

建筑设计行业对烟囱效应缓和措施改进的下一步行动

烟囱效应以及相关的运营和经济风险将持续影响高层建筑运行负担，但通过采用一些业内优化设计，可以有效减少风险。

对现有建筑我司，还需要进行更多的研究和数据采集，这对于业主、运营方以及设计都从实际数据中获益匪浅。幕墙渗透量设计标准一般于实验室标准模块测试，但事实上大量的空气渗透量是经过非标准的施工结节和其他特殊情形。整个楼层甚至整个建筑幕墙压力和气流数据有助于验证目前业内认可的、将作为未来分析和设计基础的泄露水平。

获取现有建筑的数据可能有实际操作困难，其中原因可能由于业主对分享烟囱效应问题方面的数据很不情愿，因为这可能会导致负面的媒体曝光。然而，全球高层建筑都难逃烟囱效应，只有当相关信息透明以次相互借鉴，现有建筑和新建建筑的烟囱效应才可有效缓解措施方案方能制定。也许，类似于美国现有建筑能源基准有助于鼓励业主分享烟囱效应数据。额外的数据有助于业内更好地理解烟囱效应和

Next Steps to Improve Stack Effect Mitigation Industry-wide

Stack effect and its associated operational and financial risks will continue to impact tall buildings, but these risks can be reduced with the help of some recommended industry advancements.

Additional research is needed to collect real data from existing buildings, which would be beneficial for building owners, operators, and designers to see how real buildings behave. Design criteria for curtain wall leakage is typically based on a standard module tested in a lab, but the bulk of the actual air leakage path once constructed will be through atypical joints and other anomalies. Data for whole floor or even whole building curtain wall pressures and airflows could help validate current industry-accepted leakage rates, to be used as the basis for future analyses and designs.

Data from existing building may prove difficult to extract as building owners may be hesitant to share data relating to stack effect issues due to potential negative publicity; however, stack effect is pervasive across the entire world's tall building stock and effective solutions to mitigate the impact in existing and new buildings will be more readily available if the information is available. Perhaps something similar to energy benchmarking programs would help encourage the sharing of data related to stack effect issues. Additional data will help the industry better understand stack effect and the best practices to help design, build, and operate tall buildings to mitigate the negative impacts of stack effect.

Further focused research is also needed to develop best practice guidelines and standards for stack effect mitigation in new buildings. Some publications exist with limited broad stack effect principles and mitigation measures, but the industry would benefit from a more concentrated research effort on the subject.

As new tall buildings continue to push the envelope on maximum height, stack effect will be an enduring challenge. With an integrated design process, mitigation measures, and more research into real building stack effect response, the industry can reduce stack effect issues.

相应应对措施，有助于更好地设计、建造和运营高层建筑。

此外，也需要采取进一步的专业研究，以找到新建高层建筑烟囱效应缓解的最佳设计标准。目前有一些出版物给出了一些宽泛的烟囱效应原则和缓解措施，但是就整个行业来说，还需要对这一业主进行更加深入、集中的研究行动。

由于新建高层建筑围护高度越来越高，烟囱效应将成为持续的挑战焦点。只有有了整体化的设计流程、缓解措施、更多的专业研究，建筑行业才能有效应对烟囱效应问题。

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