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# Office Tower Configuration and Control for Natural Ventilation

# 办公塔楼的构造和自然通风的控制

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## Abstract

The use of natural ventilation in office towers has been met with resistance and skepticism due to perceived and real issues relating to climate, comfort, cost, and complexity. However, the desire to provide occupants with this amenity has led to renewed thinking and recent innovations on the topic. Programs such as Singapore's GreenMark, China's Greenstar, and LEED have responded to this trend providing guidance and incentives to pursue natural ventilation. Additionally, the ability to simulate complex air flow patterns integral to building energy models has helped designers make intelligent decisions regarding the appropriateness of natural ventilation strategies. This paper will examine the integration of a solar assisted stack effect strategy with intelligent façade components as a holistic approach to natural ventilation in office towers.

**Keywords: Natural ventilation, operable façade, thermal chimney, stack effect, CFD, dynamic thermal model**

## 摘要

由于环境、舒适性、成本和复杂性等一些很实际的问题，办公塔楼中自然通风的应用遇到了层层阻碍和质疑。但是，对人员舒适性的需求引发了对这个话题的再思考并开发了一些创新技术。在处理自然通风应用这个问题上，很多绿色建筑评价体系如新加坡的绿标，中国的绿色星级体系，以及LEED评价体系都提出了指导和激励政策。此外，在建筑能耗模型中模拟复杂的通风形式也大大地帮助了设计师设计出巧妙的方案将适合的自然通风技巧运用到建筑设计中。本文将探索一种结合了太阳能辅助的烟囱效应和智能幕墙结构的自然通风技术。

**关键词：自然通风，可操作幕墙，热烟囱，烟囱效应，计算流体力学，动态热模型**

## Design Intent and Thermal Comfort

The delivery of fresh air to a tall commercial office building directly impacts energy consumption, air quality, and occupant productivity. The HVAC industry has responded to this design issue by providing guidelines such as ASHRAE 62.1, mechanical equipment like air side economizers, and mechanical control strategies. The result of these HVAC design solutions is the mechanically dominated delivery of fresh air via ductwork and air handlers with no need for the façade or occupants to directly intervene with the building to introduce fresh air to their environment. However, a number of buildings have challenged this notion in response to occupant desires for direct access to the exterior environment while reducing building energy consumption. Examples include the RWE Headquarters Tower, Deutsche Messe AG Building, and the Manitoba Hydro Building.

In response to this trend, a design team was assembled by PNC Bank to conceive an office tower in Pittsburgh, Pennsylvania that could provide occupants with a connection to the exterior through direct manipulation of the façade. This design goal was one of many energy efficiency strategies implemented to

## 设计理念和热舒适

将新风送入高层商业办公建筑直接影响到建筑能耗、室内空气质量和人员的工作效率。针对这个设计问题，HVAC领域提出了很多指导性设计方法，如ASHRAE 62.1、采用空气侧节能器和一些机械控制技术。这些HVAC设计都是采用机械主导的方法将新风通过管道和空调箱引入室内，不需要幕墙和室内人员的直接干预。但是，大量建筑开始挑战这种设计概念，考虑室内人员对室外环境的直接需求，同时减少建筑能耗，比如RWE 总部大厦、Deutsche Messe AG大厦和Manitoba水利大厦。

针对这样的趋势，PNC银行组建了一支设计团队，设计一幢位于宾夕法尼亚州匹兹堡的办公塔楼，可以让室内人员直接通过操作建筑幕墙实现与室外的接触。这个设计目标是采用的多项节能技术中的一项，用来降低建筑的全年能耗。这篇文章则侧重于这个项目的设计决策过程中对自然通风的考虑。

## 定义高层商业办公建筑中的自然通风

按照客户要求，摆在设计团队面前的挑战是如何设计一幢办公塔楼可以让室内人员有机会与外界环境直接接触，同时又要保证舒适的室内工作环境。这种人员与室外连接的设计是从模糊的概念开始的，需要

reduce the building's annual energy consumption. This paper focuses on the design decision-making process that informed the use of natural ventilation on this project.

## Defining Natural Ventilation in the Context of a Tall Commercial Office Building

The challenge presented to the design team by the client was to deliver an office tower that could provide occupants with opportunities to experience a direct connection with the external environment while maintaining comfortable interior working conditions. This connection began as a vague design directive which required the design team to further define this connection. Issues such as acoustics, birds, insects, wind, rain, and thermal comfort were addressed and explored with the client's operational team. Additionally, the definition of natural ventilation was explored with the user group. Terms such as fresh, not stale, cool, and refreshing were mentioned as qualities of naturally ventilated buildings. It was clarified that the perception of natural ventilation was of air coming in to the office space through operable elements of the façade rather than exhausting. These statements from the client's user group were translated by the design team to a set of specific design targets.

## What Natural Ventilation Meant to the User Group?

There are three principles of natural ventilation that were derived from the client/user group:

- First was the option for manual control. This statement fits well with the client's desire to impact user behavior as it related to thermal comfort and energy consumption patterns. While some user control was desired, it was agreed that automated control was also needed to maximize potential energy savings.
- Second, that the natural ventilation system be conceived as a means for bringing air into the building rather than exhausting as experienced during visits to some existing naturally ventilated buildings.
- Third, the creation of a "porch" meaning an interstitial space that had a connection to the exterior without being outside. It was understood that thermal control in these spaces required an expanded range of temperature and humidity levels.

## Natural Ventilation Design Targets

- The qualitative definition of natural ventilation described above was translated to quantitative metrics and design targets: Maximize the number of hours per year that the façade system can be used to provide fresh air to the space while maintaining comfort conditions as defined in ASHRAE Standard 55 (temperature, relative humidity, and $CO_2$). This goal is directly influenced by the reduction of solar gain and internal thermal gains on each office floor plate.
- Prevent overheating of cavity space during summer time operations. As a design target, the design team strived to limit the increase in cavity air temperature to less than 10°F compared to the outside ambient air temperature during hot summer days by flushing the cavity with sufficient air exchanges through passive venting.
- Provide redundancy and resilience to the operable surfaces

设计团队进一步明确。设计团队提出了一些像噪声、鸟类、昆虫、风、雨和热舒适等问题，并与客户的运行团队共同探索。此外，也与用户团队探讨了自然通风的定义。一些相关概念如新鲜的、不陈旧、冷却的和净化等在探讨自然通风建筑品质时经常被提及。并且要明确的是，自然通风是要把空气通过幕墙的可操作结构从外界引入到办公区域中，而不是排出空气。客户团队的这些描述由设计团队翻译成了一系列特定的设计目标。

## 对使用者来讲，自然通风意味着什么

从客户/使用者角度，对自然通风的应用有三点原则：

- 第一是人工控制。这一点与客户要求的人员参与很吻合，它涉及到热舒适和能耗形式。虽然期望看到一些人员控制，但自动控制也是需要的，并且可以最大化的节约能耗。
- 第二，自然通风系统是要作为一种将外界空气引入到建筑中的方法，而不是像参观一些现有自然通风建筑时感受到的排出空气。
- 第三，建立起"走廊"的概念，表示通过一个间隙空间就能接触到外部环境而不用真正到室外去。需要明确的是，这些区域的热环境控制需要对温度和湿度水平范围进行扩展延伸。

## 自然通风设计目标

以上对于自然通风定性的描述被翻译成为以下定量指标和设计目标：

- 最大化幕墙系统一年中可被用来提供新风的小时数，同时按照ASHRAE标准55号保持室内舒适性（温度、相对湿度、二氧化碳浓度）。这个目标直接受到每一个办公楼层太阳得热和室内得热减少的影响。
- 防止幕墙通道区域在夏季开启时出现过热的现象。作为一项设计目标，设计团队要努力控制通道中空气温度的升高，在很热的夏季利用被动通风的形式、使充足的室内换气通过通道，限制通道中温度低于室外温度10华氏度。
- 为可操作的幕墙表面提供富余和弹性，使全年可用来为办公楼层通风的自然通风小时数达到最多。
- 通过建筑自动化系统提供足够的控制点、传感器和幕墙的自动控制，使得可以在办公楼层使用低能耗辐射HVAC系统。

## 指导原则和设计参数

当自然通风设计目标已经被细化完成，设计团队则开始提出一些建筑和工程方案来实现通过高层建筑幕墙引入新风并同时保持室内热舒适性。匹兹堡的气候参数表明，由于适宜的室外温度和湿度水平，全年有充足的小时数可以采用自然通风。这些数据被提取出来提供给客户并在讨论中展示，讨论中还探讨了空气节能器作为可操作幕墙替代选择的效果。在这次讨论之后，一系列结合了空气流动网络的动态热模型被建立起来，进行初步的全年逐时能耗模拟。热舒适模拟也包含在内，因为它与自然通风密切相关。这个阶段的模型被用来探索其他会影响到自然通风的设计元素，包括建筑布局密度、办公楼层构造、室内家具布局、自然采光、公共空间和中庭的结合，以及中心布局。最终的建筑布局参考了建筑南立面与太阳路径和街道网格之间的关系，使得建筑中庭面向一个城市广场，这是客户和建筑团队所期望看到的。一系列概念性的草图考查了在给出了场地限制的情况下这些元素是怎

of the façade to maximize the number of hours per year that natural ventilation can be utilized to ventilate office floors.

- Provide sufficient control points, sensors and automation of the façade through the Building Automation System to allow the use of low energy radiant HVAC systems in the office floor plate.

## Guidelines and Design Parameters

Once natural ventilation design goals were defined, the design team set out to develop architectural and engineering design solutions capable of delivering fresh air through the façade of a tall building while maintaining thermal comfort. Pittsburgh's climate data indicated that there are sufficient hours during the course of the year when natural ventilation could be used due to appropriate external air temperatures and humidity levels. This data was extracted for the client and presented in a discussion that included the impact of an air side economizer as an alternative to an operable façade. Following this discussion, a series of dynamic thermal models with integrated air flow network models were constructed to conduct preliminary annual hourly simulation of energy consumption and thermal comfort as it related to natural ventilation. This level of modeling was used to investigate other design issues influencing natural ventilation including building massing, office floor plate configuration and furniture layout, daylight penetration, integration of common spaces and atria, and core configuration. The resulting building massing addressed the relationship of the south façade to the sun path and street grid while allowing the atria to face an urban plaza which was desired by the client and architectural team. A series of conceptual sketches examined how these elements could inform and be informed by natural ventilation design issues given the opportunities and restrictions of the site (see Figures 1 and 2). The resulting form of the building included a centralized core with surrounding office floor plates spanning an average of 40 feet from the core to the façade.

The building's massing and orientation are the result of carefully negotiated design issues, of which natural ventilation is only one component. The resulting floor plates and massing of the tower represent the optimal balance between form, function, budget, site, and climate for the particular client. Though not the focus of this paper, it is worth mentioning that the dynamic thermal and air flow modeling included a thorough investigation of HVAC system options. The conclusion of the HVAC studies resulted in the selection of an active chilled beam system with dedicated outdoor air handling units containing dual enthalpy heat recovery wheels. The advantages of this system met the needs of the users/client, the energy reduction goals of the project, and the desired floor-to-floor height. The limited capacity of the chilled beams to manage sensible thermal loads reinforced the need to control solar gain and internal thermal loads to maximize periods of natural ventilation. The combination of a radiant system to condition the floor plate with the desire to maximize the use of natural ventilation heavily influenced the design of the building façade and the sequence of controls between the HVAC system and the natural ventilation elements of the building.

The resulting massing and configuration is a response to the building's climate and desire to implement natural ventilation during parts of the year when exterior conditions are favorable. To maximize the opportunities for implementing natural ventilation, additional refinement was needed. Early climate studies indicated that Pittsburgh experiences fairly low wind speeds on average. The winds do have seasonal patterns but there is no significant prevailing

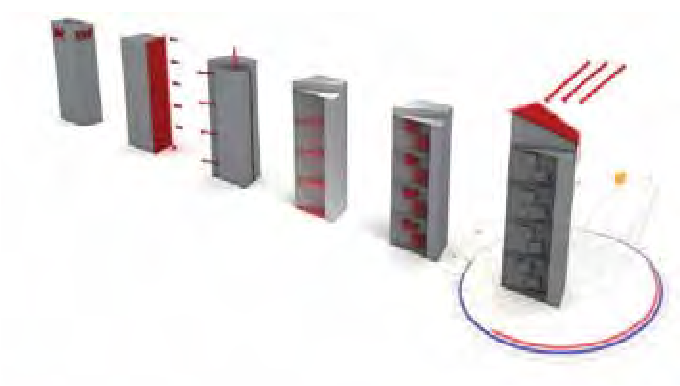

Figure 1. Initial massing and solar orientation responses (Source: Gensler)
图1. 最初的布局和太阳朝向的关系（来源：Gensler）

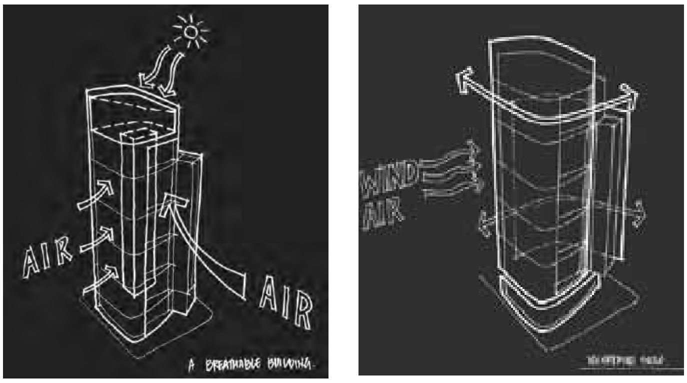


Figure 2. Sketch showing concept of the double skin façade wrapping the building for wind speed and solar control (Source: Gensler)
图2. 草图显示了包围整个建筑的双层皮幕墙的概念，用来进行风速和太阳光控制（来源：Gensler）

样与自然通风设计联系起来的（见图1和图2）。建筑的最终形式包含了一个中心区域，周边由办公层包围，从中心到建筑外表面跨度平均为40英尺。

建筑布局和朝向是设计过程中经过仔细讨论过的，在所有的设计议题中，自然通风只是其中一个元素。最终的平面形式和塔楼的布局是平衡了形式、作用、预算、场地和气候的最优方案。虽然这不是这篇文章的重点，但有必要提一下动态热模型和空气流动模型包括了对HVAC系统选择的全面考虑。HVAC系统最终选择了主动式冷梁系统，配以包含了全热转轮的独立新风机组。这种系统满足了用户/客户的需求、项目中降低能耗的目标和预期的层高。冷梁系统处理显热负荷的局限能力增强了控制太阳得热负荷和室内得热负荷的需求，要最大化地延长采用自然通风的时间。楼层采用的辐射系统，结合着最大化采用自然通风的需求，很大程度上影响了建筑围护结构的设计和HVAC与自然通风部件的控制顺序。

最终的建筑布局和构造是根据建筑所处的气候条件和在外部条件适宜时采用自然通风的需求决定的。为了最大化利用自然通风，还需要一些额外的细化。最初的气象条件研究表明匹兹堡的平均风速很低，风向有季节性特征但没有主导风向。但是这幢塔楼的高度高于其周围大部分建筑，导致在塔楼高层会有升高的风速。对风速另外的分析表明在春季和秋季风速会有小幅升高，特别是在建筑高层这种现象会更加明显，在这期间可以采用自然通风。围护结构周围风速和风压差需要表示出来，以避免在开启了的幕墙结构附近出现高速流动的空气。最终的解决方法是采用双层皮幕墙。这种方案达到了以下几个目标：

- 由于幕墙通道的影响，在可开启幕墙新风入口处风速会下降。
- 建筑布局使得建筑南向在夏季被很好地遮阳。

direction. However the height of the tower makes it taller than most of the surrounding context resulting in some periods of elevated wind speeds at the upper floors. Additional analysis of wind speeds indicated that periods of natural ventilation tend to occur in the spring and fall when wind speeds are slightly elevated, especially at the upper floors. This required that wind speed and pressure differential across the façade be addressed to prevent high velocity air movement near the operable surfaces of the façade when open. The resulting solution was the implementation of a double-skin façade. This solution achieved several goals:

- The reduction of the wind speed at the entry point of fresh air through the operable element of the façade due to double-skin façade cavity.
- The massing of the building allowed the south façade to be well shaded during summer months.
- The cavity of the double-skin façade protects operable shades located in the cavity
- The double-skin façade included the integration of manually operated doors to allow occupants access to the "porch like" conditions referenced by the client as a desirable link to the external environment.
- The double-skin façade reduces the heating load by creating a thermal buffer between the inner and outer layers of the façade.

The inclusion of a double-skin façade supported the goals of the project on several levels; however, the configuration of the typical floor plates with a central core was such that cross ventilation through the double-skin façade alone would not provide sufficient air exchanges to cool the open office space during periods of natural ventilation. This fact, combined with the efficiencies of a central core and the preference that fresh air be introduced though the façade as incoming air during times of natural ventilation, required the design team to conceive a passive means to extract air from the center of the building.

## Incorporating the Stack Effect with the Natural Ventilation Strategy

Initial concepts investigated interior atria; however, the cost, acoustics, fire/smoke issues, and space efficiency reduced the appropriateness of such a configuration. As an alternative, oversized return air shafts located in the central core were proposed. These shafts connect the office floors and served the dual function of HVAC return air path during times of the year when floor plates were outside the comfort zone and as a stack effect induced exhaust path of air during times of natural ventilation. To utilize the stack effect, it is necessary to understand the influence of pressure across the building's height. Preliminary calculations proved favorable using the stack effect to augment air exchanges on the floor plate during periods of natural ventilation. However, the relatively small temperature difference between the exterior air and interior air during these periods initially created a challenge.

The stack effect relies on the buoyancy of warmer air relative to adjacent air temperatures creating a pressure differential. In a typical tall building, the stack effect induced pressure differential varies from negative pressure at the bottom to positive pressure at the top creating neutral condition in the middle of the building. This mid-point is referred to as the neutral pressure layer. The pressure differential between the top and the bottom of this stack is directly influenced by

- 双层皮幕墙的通道保护了通道中可开启的叶片
- 双层皮幕墙结构结合了可人工开启的门，使得人员可以来到像客户提出的“走廊”一样的结构，作为与外部环境的连接通道。
- 双层皮幕墙通过在内层和外层幕墙间创造热缓冲区域，减少了得热量。

双层皮幕墙的应用从不同的层次上支持了项目的设计目标；但是由于标准层带有中心区域的设计，在可利用自然通风期间，单单通过双层皮幕墙所形成的前后对流通风不能提供足够的换气来冷却开放式办公区域。这个问题，结合着中心区域的利用效率和在自然通风期间通过围护结构引入新风的需求，需要设计团队采用一种被动式技术从建筑中心引入空气。

## 结合烟囱效应的自然通风技术

最初的想法是去探索内部的中庭区域；但是，投资、噪声、排火排烟以及空间的利用效率问题降低了这个方案的可执行性。另一种方案是在中心区域采用稍大尺寸的回风竖井。这些竖井与办公层连接，起到了两方面作用，一是在室内条件不在舒适区的时间下作为HVAC系统的回风通道，另一方面是在利用自然通风期间起到烟囱效应的作用诱导排风路径。为了利用烟囱效应，有必要了解随建筑高度变化压力变化的影响。最初的计算表明在自然通风期间利用烟囱效应增加办公层的换气是可行的。但是，在这段时间期间，室内外较小的温差是一个挑战。

烟囱效应是靠着较热空气相对于周边较低温度的浮力产生了压力差而形成的。在典型的高层建筑中，烟囱效应诱使的压力差由底部的负压差变到顶部的正压差，在建筑中间部位形成中性情况。这个中点所指的就是建筑的中性压力面。这种烟囱效应顶部和底部的压差是由室内温度和室外温度的温度差直接影响的。这种现象对于自然通风的概念是很重要的，原因有两个：

1. 在采用自然通风期间，室内温度（68至75华氏度）和室外温度差相对较小，因此也就减小了烟囱效应产生的压力差。
2. 在采用自然通风期间，通过幕墙将外部新鲜空气引入的目标对于高于中性层的楼层会有一些损失，因为这些楼层内部空间的压力会相对高于较低的楼层和外部环境压力，这会导致空气会由幕墙的开口渗出。

塔楼的构造使得建筑南面具有较大的围护结构面积。建筑师团队根据这种朝向特点在建筑屋顶设计了一个向南倾斜的顶棚冠，因此建立了一大片太阳光收集表面。在这个屋顶表面上又封闭了一层玻璃屋顶，太阳得热被用来加热这个腔内的空气—有效地形成了暖房效应。早期的计算结果表明有足够的太阳辐射（直射和散射）可以把这部分空气温度加热到140华氏度。最终的设计方案将其与扩大的回风竖井相结合形成太阳能通风通道（见图3）。这个设计方案很有效的建立了太阳能驱动的烟囱效应，排风沿回风竖井向上，在排出楼外之前在屋顶腔体内被加热。这一过程将腔体的热量传递给排风。这种传递升高了腔体内排风的温度，因此增加了楼层顶部的浮力。这种现象的结果就是使建筑的中性压力面由建筑中间变到建筑顶部。这使得每层办公层在回风竖井处形成负压，因此在建筑高层空气可以由围护结构引入楼中而不是排出。

## 分析指导设计—设计指导分析

对于任何建筑的设计，考虑到自然通风技术，大量的有争议的因素需要被探讨。有很多分析工具和技术被用来处理上面所描述的自然通风技巧的风险和潜力。没有一个工具可以完整地把握环境影响和建筑物理之间的复杂关系，但是有一些工具可以很出色地

the temperature differential between the interior air temperature and the exterior air temperature. This phenomenon is important in terms of natural ventilation for two reasons:

1. During periods of natural ventilation the temperature differential between the inside air temperature (68 to 75°F) and the exterior air temperature are relatively small; thus, reducing the pressure differential created by the stack effect.
2. The desire to bring fresh air in through the façade during periods of natural ventilation could be compromised on floors above the neutral pressure layer as the interior air pressure on those floors is positive relative to the lower floors and the exterior environment resulting in exfiltration through the façade openings.

The massing of the tower had been configured to provide a large façade with a southern exposure. This orientation allowed the architectural team to shape the penthouse crown with a south facing slope; thus, creating a large solar collection area. The solar gain on this surface area was used to passively heat an area of thermal mass on the roof by enclosing it with a second glass roof – effectively creating a greenhouse-like configuration. Early calculations indicated that there is sufficient solar radiation (direct and diffuse) to heat the thermal mass to temperatures up to 140°F. The resulting design integrated this assembly, referred to as the solar ventilation cavity, with the enlarged return air shafts (see Figure 3). This effectively creates a solar driven stack effect where the exhaust air moving up the return air shafts is passively heated prior to being exhausted at the top of the roof cavity. This is accomplished through the transfer of heat from the thermal mass to the exhaust air. This transfer increases the temperature of the exhaust air in the cavity; thus, increasing buoyancy at the top of the building. The result of these phenomena is the relocation of the neutral pressure layer from the middle of the building to the top. This creates a negative pressure in the return air shafts at each office floor level; thus, allowing air to be drawn in through the façade in the upper floors rather than exhausted.

## Design Driven by Analysis – Analysis Driven by Design

As with any building design, a number of competing factors had to be negotiated along with the natural ventilation strategy. A wide range of analysis tools and techniques were employed to manage risks and opportunities of the natural ventilation strategy described above. None of the available tools fully captures the complex interactions of environmental influences and building physics; however, there are some tools that do an excellent job at providing insight to the potential impact of various design issues and decisions. To determine the effectiveness of this natural ventilation strategy a five step design process was executed.

### Step 1: Preliminary sizing of shafts and openings using stack effect equations

This was accomplished using *CIBSE Applications Manual 10 – Natural Ventilation in Non-domestic Buildings* as a reference. While none of the simplified equations in this manual were intended for the exact application proposed the manual was still very useful. The relevant equations were combined into a calculation tool for initial assessments of sizes and effectiveness of the concept. A wide range of calculations were used during schematic design from this useful manual. A few of the key calculations are included below for reference:

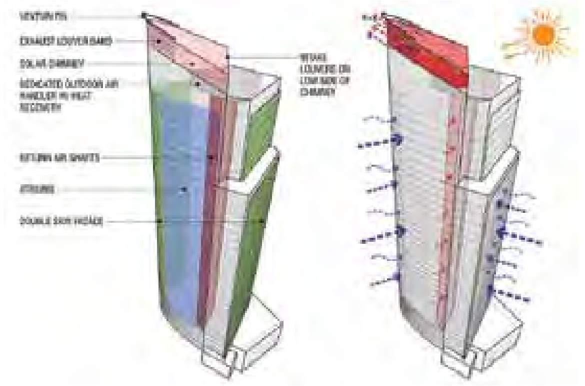

Figure 3. Concept diagram of the tower including double skin façade for natural ventilation, oversized return air shafts linking each floor plate to the air handling units and the Solar Driven Ventilation Cavity on the roof (Source: Buro Happold)
图3. 塔楼的概念图示，包括含自然通风设计的双层皮幕墙、将每一楼层与空调箱和屋顶的太阳能驱动通风腔连接的扩大的回风竖井（来源：Buro Happold）

让使用者判断出多种设计方案和决策的潜在影响。为了探索这种自然通风技术的效果，设计团队采用了一种五步设计方法。

**第一步：通过烟囱效应方程初步计算竖井的尺寸和开口大小**

CIBSE应用手册AM10-非当地建筑的自然通风被用来作为计算依据。尽管手册中没有简化的公式可以用来进行精确的计算，但这个手册仍然很有用处。相关的公式被加入到计算工具中作为初步的尺寸评估和用来判断这种设计概念的效果。这个很有用的手册可以在原理图设计阶段被更广泛的应用。一些关键的计算公式列在下文中作为参考：

下面的公式用来估算建筑烟囱效应不同层的空气温度（Irving & Ford 2005）。

$$T+273=\frac{T_0+273}{\left[1-\left(1-\frac{T_0+273}{T_n+273}\right)\left(\frac{z}{z_n}\right)^N\right]}$$

| | |
|---|---|
| $T_0$ | z=0处的温度 |
| $T_n$ | 中性层高度温度（$Z_n$） |
| z | 高度大于 z=0 |
| $z_n$ | 中性层高度 |
| N | 指数 |

下面的公式用来估算建筑烟囱效应不同层的压差（Irving & Ford 2005）。

$$\Delta p_i=\Delta\rho_0\, g(z_n-z_i)+\frac{\Delta\rho_0\, g z_n}{N+1}\left(\frac{\Delta T_n}{\Delta T_0}-1\right)\left(1-\frac{\Delta T_n}{T_n+273}\right)\left(1-\frac{z_i^{N+1}}{z_n^{N+1}}\right)$$

| | | | |
|---|---|---|---|
| $\Delta P_i$ | 烟囱效应产生的压差 | N | 指数 |
| $\Delta\rho_0$ | 室内外空气密度差 | $T_n$ | 中性层温度（zn） |
| g | 重力加速度 | $\Delta T_n$ | 中性层处室内外压差（zn） |
| $z_n$ | 中性层高度 | $\Delta T_0$ | z=0处室内外温度差 |
| zi | 开口中点与z=0处的距离 | | |

下面的公式用来估算空气流量和在回风竖井内所需的面积（Irving & Ford 2005）。

$$A_i=\frac{q_i}{C_{di}}\sqrt{\frac{\rho_0}{2|\Delta p_i|}}$$

| | |
|---|---|
| $A_i$ | 开口面积 |
| $q_i$ | 开口处的空气流量 |
| $C_{di}$ | 排气系数 |
| $\rho_0$ | 空气密度 |
| $\Delta P_i$ | 烟囱效应产生的压差 |

To estimate the air temperature at various levels in the building stack, the equation below was used (Irving & Ford 2005).

$$T+273=\frac{T_0+273}{\left[1-\left(1-\frac{T_0+273}{T_n+273}\right)\left(\frac{z}{z_n}\right)\right]^N}$$

| | |
|---|---|
| $T_0$ | Temperature at z=0 |
| $T_n$ | Temperature at the neutral height ($z_n$) |
| z | Height above z=0 |
| $z_n$ | Neutral pressure plane level |
| N | Numerical index |

To estimate the pressure difference at various levels in the building due to the stack effect, the equation below was used (Irving & Ford 2005).

$$\Delta p_i=\Delta\rho_0\, g(z_n-z_i)+\frac{\Delta\rho_0\, g z_n}{N+1}\left(\frac{\Delta T_n}{\Delta T_0}-1\right)\left(1-\frac{\Delta T_n}{T_n+273}\right)\left(1-\frac{z_i^{N+1}}{z_n^{N+1}}\right)$$

| | |
|---|---|
| $\Delta p_i$ | Pressure Difference caused by stack effect |
| $\Delta\rho_0$ | Difference of external and internal air densities |
| g | Gravity |
| $z_n$ | Neutral pressure plane level |
| zi | Distance of midpoint of the opening from z=0 |
| N | Numerical index |
| $T_n$ | Temperature at the neutral pressure plane level ($z_n$) |
| $\Delta T_n$ | Temperature difference between inside and outside at neutral pressure plane level ($z_n$) |
| $\Delta T_0$ | Temperature difference between inside and outside at z=0 |

To estimate the volumetric air flow and required area in the return air shaft, the equation below was used (Irving & Ford 2005).

$$A_i=\frac{q_i}{C_{di}}\sqrt{\frac{\rho_0}{2|\Delta p_i|}}$$

| | |
|---|---|
| $A_i$ | Area of the opening |
| $q_i$ | Volumetric airflow at the opening |
| $C_{di}$ | Discharge coefficient |
| $\rho_0$ | Density of air |
| $\Delta p_i$ | Pressure Difference caused by stack effect |

These and other useful calculations allowed preliminary concepts to be tested including areas, influence of discharge coefficient, impact of building height and air exchanges. These preliminary calculations were done ahead of more extensive environmental simulations using thermal and air flow modeling, wind tunnel testing, and computational fluid dynamic models.

**Step 2: Sizing the operable surfaces of the double-skin façade**

Based on past experience with naturally ventilated office buildings and preliminary calculations, it was understood that floor plates would require a range of air exchange rates to maintain comfort conditions. To initiate the analysis process, a design goal of four Air Changes per Hour (ACH) was used to balance heat gains and carbon dioxide levels at each floor plate during periods of natural ventilation. While the variable nature of natural ventilation cannot be fully accounted for in mathematical models, this target was sufficient for estimating the velocity, pressure drop, and volume flow rate at the inner openings in the double-skin façade. These estimates were then further studied and tested using more advanced computational models.

这些和其他有用的公式检验了初步的设计方案包括面积、排气系数的影响、建筑高度和换气的影响。这些初步计算是在更深入的环境模拟之前就完成了的，在这之后才使用热模型、空气流动模型、风洞实验和计算流体力学模型进行模拟计算。

**第二步：计算双层皮幕墙可开启面积**

根据过去自然通风办公建筑的经验和之前的初步计算结果，办公层需要一定的换气次数来保证室内舒适条件。在分析过程的最开始，使用4次换气次数(ACH)作为设计目标来平衡自然通风季节室内的得热和二氧化碳浓度。尽管在数学模型中很多自然通风的性质不能被完全考虑进去，这个设计目标已足以估计双层皮幕墙的内层开口处的空气速度、压降和空气流量。这些估算在之后更深入的计算模型中将被进一步研究和测试。

**第三步：建立结合了空气流动网络的动态热模型**

结合了空气流动网络的完整的建筑动态热模型在之后被建立起来。这个动态热模型模拟了全年的建筑物理工况和建筑能耗，模拟中使用典型气象年(TMY3)的气象参数来建立室外边界条件。模拟结果与空气流动模型相结合，计算出模型中每个热区域之间由浮力和压力驱使的空气交换。这种热区域之间热交换和由浮力/压力驱使的空气交换的结合考虑了双层皮幕墙和由太阳能驱动使用了烟囱效应的通风技术的相互作用（见图4）。

除了计算烟囱效应的影响之外，环境模拟还可以通过设置幕墙各开口处的压力系数估算出室外风的影响。通过使用TMY3气象参数，这些压力系数表示出迎风面的正压和背风面的负压，用来决定相对于模型外表面的逐时风速和风向。这个阶段的分析对于估计每一层前后对流通风的影响是十分有用处的。但是由于采用的是通用的风压系数表格，这种分析还不能完全把握住室外风紊流的全部影响。然而对于一些重要的设计概念如舒适性、湿度控制、节能量和二氧化碳浓度，这些经验数据仍然是非常有价值的。为了进一步明确烟囱效应的问题以及引起压差的风的影响，结合了风洞压力数据的计算流体力学模型被建立起来。

**第四步：计算流体力学模型（CFD）**

通过第三步中得到的数据，使用CFD模型对动态热模型全年数据中一系列自然通风的测试日进行了进一步分析。在最初的模型中，外界风的影响被忽略，模拟了一种静态风的情况。CFD模型中包含了足够的细节，包括双层皮幕墙可操作表面和在烟囱效应中建立的由太阳能驱使的通风夹层的影响。很多测试用的室外空气温度参数作为边界条件被赋予给CFD模型。尽管已经有了初步的CFD模型，我们仍然进行了风洞实验，将围护结构表面的压力系数记录下来作为幕墙设计的参考。

CFD模拟的结果被用来测试楼层的热舒适情况，用来明确中性压力层的位置和整个烟囱竖井的压力梯度的影响。此外，CFD模拟结果还指出了一个设计问题，是在一个回风竖井中由于一个平面的移动造成了轻微干扰。这使得压力升高，增加了回风竖井中的排风摩擦力。根据这个分析的结果，中心区域被重新设置来平缓这个轻微的干扰，减小回风竖井中的摩擦，改进受影响楼层的舒适性。

**第五步：将风洞实验的压力数据整合到CFD模型中**

风洞实验完成之后，压力表格中的数据被用来仔细研究，更细致地分析在不同的来风情况下通过围护结构表面压力差的影响。通过围护结构表面所产生的压力是很不同的。在选择双层皮幕墙时，这些波动性也是需要考虑的因素。使用从通用数据表格中得到的压力系数的动态热模型的结果表明，在一些来风情况下楼层可能会有部分是通过前后对流的形式进行通风的，而不仅仅是通过回风竖井的烟囱效应。如果围护结构的背风面的压力差大于回风竖井的烟囱效应，则回风竖井中的排气会进入到楼层中而影响空气质量。为了测试这个问题，从风洞模型中得到的可以表示最不利工况的压力系数被应用到CFD模型幕墙的开口处（见图10）。尽管在模型的背风面会看到在部分开口处有渗风的现象，但是

**Step 3: Constructing a dynamic thermal model with integrated air flow network**

A full building dynamic thermal model was constructed and integrated with an air flow network model. The dynamic thermal model simulated the building physics and energy consumption for the duration of one year using Typical Meteorological Year (TMY3) weather data to establish external boundary conditions. The results were integrated with an air flow network model to calculate buoyancy and pressure-driven air transfer between each thermal zone in the model. The combination of heat transfer and buoyancy/pressure-driven air transfer between thermal zones accounted for the interactions between the double-skin façade and the solar driven ventilation strategy using the stack effect (see Figure 4).

In addition to being able to calculate the influence of the stack effect, the environmental simulations were able to estimate the impact of exterior wind by applying pressure coefficients on the various openings of the façade. These pressure coefficients represent the windward positive pressure and leeward negative pressure using the TMY3 weather data to determine each hour's wind speed and angle of attack relative to exterior surface of the model. This level of resolution is useful for estimating the influence of cross ventilation on each floor plate; however, it does not capture the full influence of the turbulent exterior wind environment due to the generic nature of the wind pressure coefficient data tables referenced. Still, the data contained valuable lessons and indications as to the critical design issues such as comfort, humidity control, energy savings, and carbon dioxide levels. To gain further clarity on issues of the stack effect and the influence of wind induced pressure differentials, a computational fluid dynamics model was linked with wind tunnel pressure tap data.

**Step 4: Computational Fluid Dynamics modeling (CFD)**

Using the data generated during step three, a series of natural ventilation test days were identified within the dynamic thermal model annual data set for further analysis using CFD modeling. For initial models, the influence of the exterior wind was ignored to simulate a still wind condition. The CFD model was built with sufficient detail to capture the size of the double-skin façade operable surfaces and the influence of the solar driven ventilation cavity on the stack effect. Various exterior air temperatures were tested as boundary conditions to the CFD models. While this preliminary CFD modeling was occurring, a wind tunnel test was procured to inform the façade design and provide pressure coefficients on the façade surfaces through pressure taps across the wind tunnel model.

The results of the CFD model were used to test comfort conditions at the floor plates, understand the location of the neutral pressure layer, and determine the impact of the pressure gradient across the entire height of the stack. Additionally, the CFD results indicated a design issue in one of the return air shafts due to a plan shift resulting in a jog. This caused pressure build up and increased friction for the exhaust air contained in the return air shaft. As a result of this study, the core has been reconfigured to smooth out this jog and reduce the friction in the return air shaft; thus, improving comfort conditions on the affected floors.

**Step 5: Incorporating the data from the pressure taps into the CFD model**

Once the wind tunnel tests were completed, the data from the pressure tables were investigated to understand in more detail the impact of the pressure differentials across the façade under different wind conditions. The induced pressures across the façade are highly variable. The selection of the double-skin façade was influenced in part to manage these fluctuations. Data from the dynamic thermal model

主流风的方向是向着进入楼层内部并通过回风竖井向上通过屋顶的太阳能通风腔排出的。

## 从分析中得到的方案设计方面的收获

CFD模拟的结果表明所提出的塔楼构造，包括双层皮幕墙、回风竖井和太阳能驱使的通风腔等，很成功地达到了客户设立的设计目标。在这个过程中得到了一些很重要的收获列举如下：

1. 匹兹堡的原始气象数据表明有很大一部分天数是可以单独用外界环境进行自然通风的。但是在这种情况下，只有当内部得热（包括太阳得热）最小时，才能提供相应楼层所需要的冷量。最终的设计方案中，围护结构受到充分的遮阳，室内的灯光强度为0.7W/sf. 此外，在桌面的LED作

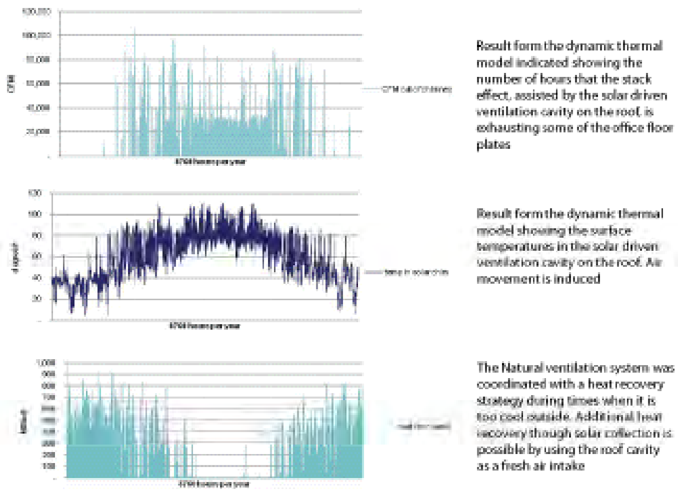


Figure 4. The graphs above indicate the results from test studies done using the dynamic thermal model. This type of hourly dynamic data was critical for establishing the natural ventilation strategy along with HVAC controls, comfort levels, and building energy consumption. (Source: Buro Happold)

图4. 上图表示了使用了动态热模型的测试结果。这种逐时的动态数据对于建立自然通风技术与HVAC控制、热舒适程度和建筑能耗之间的关系是非常重要的。（来源：Buro Happold）

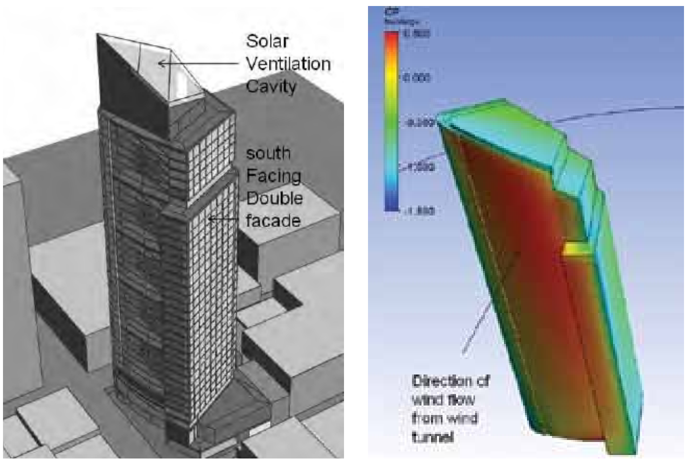


Figure 5. The image on the left is the dynamic thermal model with integrated air flow network model. Generic pressure coefficients were applied to the operable surface based on their height and exposure to the wind. The image on the left is generated from wind tunnel pressure tables for a westerly wind at 20 mph. The variation in color captures positive and negative pressures across the façade induced by the wind. Additionally, the influence of surrounding buildings on wind speeds is captured. (Source: Buro Happold and Boundary Layer)

图5. 左图表示结合了空气流动模型的动态热模型。根据可开启表面高度和面对风向的不同，通用的风压系数被设置在这些表面上。左图是从以西向20英里每小时的风为边界条件的风洞压力表格得到的。颜色的不同表示出由风引起的在通过围护结构时形成的正压和负压。此外，周围建筑对于风速的影响也被表示了出来。（来源：Buro Happold）

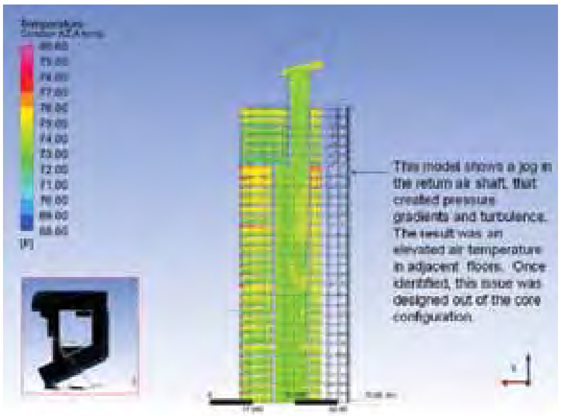


Figure 6. Temperatures on each floor during natural ventilation period. (Source: Buro Happold)
图6. 在自然通风季各层的空气温度（来源：Buro Happold）

using pressure coefficient from generic data tables indicated that there were some wind conditions where floor plates may be partially ventilated through cross ventilation rather than solely through stack effect via the return air shafts. If the pressure differential on the leeward façade opening was greater than the stack effect in the return shaft, then it seems possible that exhaust air from the return air shaft could enter a floor plate and impact air quality. To test this issue, pressure coefficients from the wind tunnel model representing an averaged worse case condition were applied to the outer openings of the façade as represented in the CFD model (see Figure 8). While some exfiltration could be observed at façade opening on the leeward side of the model, the dominant flow path on the floor plates was into and up the return air shaft through the solar ventilation cavity at the roof.

## Design Lessons Learned through Analysis

The results of the CFD modeling indicated that the proposed configuration of the tower including the double-skin façade, return air shafts, and solar driven ventilation cavity successfully achieved the design goals established with the client. Some important lessons learned through this process included the following:

1. The raw climate data for Pittsburgh suggests a reasonable number of days when external conditions alone seem favorable to natural ventilation; however, these hours can only provide the needed cooling to the floor plate if internal heat gain (including solar gains) is kept to a minimum. As a result, the façade is heavily shaded and the internal lighting power density is at 0.7 W/sf. Additionally, the illuminance levels in the general office space are set to be 15 foot-candles supplement by LED task lights at the desks.
2. Open office floor planning is essential--this includes the careful selection of office furniture to ensure that there is adequate air flow under the desk. Work space partitions had to be selected such that it did not meet the floor except at legs and small pedestals. This promotes air flow from the operable elements of the façade to individuals locate near the core.
3. The location and placement of sensors are critical in maintaining control of the façade and return shaft operable surfaces. This is especially true when radiant surfaces are part of the HVAC system. Internal air temperature, relative humidity and carbon dioxide levels are constantly monitored to provide data for controlling the façade operable surfaces, chilled beams,

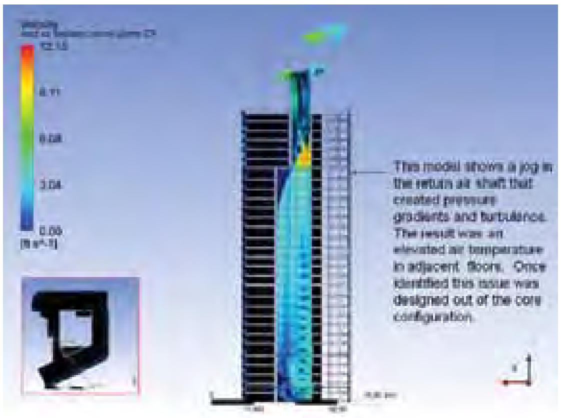


Figure 7. The velocity of the air in the oversized return air shaft is slow until the jog. In general, the oversized shaft reduces the impact of friction and provides a low resistance path for exhaust air to make it to the solar driven exhaust cavity. (Source: Buro Happold)
图7. 在扩大的回风竖井中空气速度很小，直到受到轻微干扰。一般来讲，扩大的竖井可以减小摩擦带来的影响，为排向太阳能驱使的排气腔的空气提供较低的阻力路径。（来源：Buro Happold）

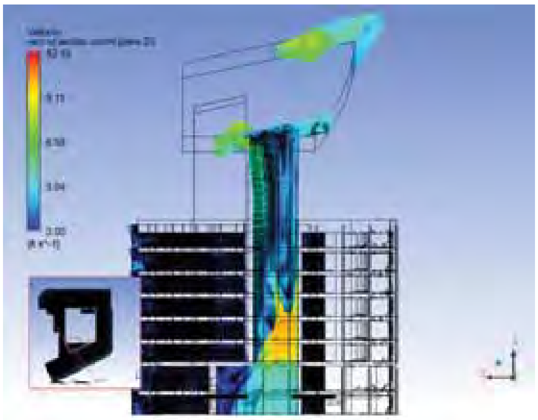

Figure 8. The shape of the solar ventilation cavity places vents on two sides. Even with the positive push of wind on windward side, there is still pressure from the stack effect to promote natural ventilation through this solar-assisted exhaust path. (Source: Buro Happold)
图8. 太阳能通风腔在两边各有出口。即使在迎风面有正压力推使风进入楼中，烟囱效应仍然会产生压力促进空气经过太阳能辅助的排风通道排出。（来源：Buro Happold）

业灯的补充下，一般办公区域的照明强度设置为15英尺烛光。

2. 开放式办公区域的设计是很重要的—这包括要仔细选择办公家具来保证有足够的空气通过桌下。工作隔断也要仔细挑选，使得除了支脚和基座外没有其他地方接触到地板。这会促进从外部幕墙可开启部分流入的空气在内部靠近中心部位的人员处流动通畅。
3. 传感器的位置对于幕墙和回风竖井操作表面的控制很重要，特别是在HVAC系统采用了辐射表面的情况下。室内空气温度、相对湿度和二氧化碳浓度被持续监测着，这些数据用来控制幕墙的可操作表面、冷梁系统、空调箱、自动遮阳设施以及通过太阳能驱动的通风腔的排风。
4. 融合了空气流动模型和HVAC模型的动态热模型表明热回收装置在降低建筑全年能耗时起到了很重要的作用。为了增大这个作用，在室外空气温度低于55华氏度时，通过太阳能通风腔的空气流动方向被逆转。这使得新风在进入处理独立新风的空调箱之前在腔体中被加热了3至8度（取决于空气流量），减少了热盘管的负荷。
5. 动态热模型在决定控制逻辑和操作顺序方面起到了很大作用，可以帮助判断自然通风、热回收、冷梁和新风供应之

air handling units and automated solar shading and exhaust air flow through the solar driven ventilation cavity.

4. The dynamic thermal model linked to and airflow and HVAC network indicated that heat recovery plays an important part of reducing the building annual energy consumption. To augment this, the air flow through the solar ventilation cavity is reversed when the outside air temperature is less than 55°F. This allows incoming fresh air to be passively heated by 3 to 8 degrees, depending on flow rate, in the cavity before entering into the dedicated outdoor air handling unit reducing the load on the heating coils.
5. The dynamic thermal models contributed greatly to informing the control logic and sequence of operations. This helped define the interrelationship between the natural ventilation, heat recovery, chilled beams and fresh air supply. To ensure that this interrelationship is fully captured and implemented it was necessary to engage vendors, manufactures and contractors in a design assist contract.
6. Commissioning is a key component to delivering the energy savings potential from natural ventilation and an automated façade.

The culmination of this design and analysis process was the confidence to build. The analysis process influenced the design of the double-skin façade, solar-driven ventilation cavity, and the return air shafts.

## Conclusion

The analysis process described indicates that the building will have the opportunity to provide thermal comfort to occupant through natural ventilation for approximately 1800 hours per year. This reduces the fan and pump energy while providing occupants with a productive and efficient work environment. The use of the roof to collect solar radiation and heat the exhaust air above the last occupied floor increases the ability of natural ventilation to provide adequate air exchanges on all floors while moving the natural pressure to the upper elevations of the buildings stack. The result achieves the design goals of the client. The lessons learned though the extensive environmental modeling described in step one through five assisted the design team in developing architectural, engineering, and operational control strategies that will deliver flexibility, comfort and energy savings year round.

间的关系。为了确保这种相互之间的联系可以被执行到实际建筑中，很有必要让供应商、制造商和承包商在设计方案的引导下相互配合。

6. 调试是让自然通风和自动控制幕墙实现节能的关键部分。

建造的信心是整个设计和分析过程的最精处。分析过程影响了双层皮幕墙、太阳能驱动的通风腔和回风竖井的设计。

## 结论

以上所描述的分析过程表明了这幢建筑全年可以有大约1800个小时通过自然通风的形式来满足室内人员的舒适性。风机和水泵的能耗减少了，同时也提供给室内人员一个高效的工作环境。屋顶被用来收集太阳辐射，在最后一层有人员的楼层之上加热排气，这使得自然通风可以为所有楼层提供足够的换气，并且将压力中性层移到建筑上层。设计的最终结果满足了客户提出的设计要求。深入的环境模拟已经在步骤一至步骤五中表示出来，模拟中得出的分析结果辅助了设计团队提出建筑、工程和操作控制方面的技术，提供了灵活性、舒适性并且节约了全年能耗。

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