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Performance of Shadow Boxes in Curtain Wall Assemblies

幕墙安装中阴影框的性能

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Abstract

As increased urban density needs influence the verticality of our built environment, scales of economy and practical efficiency of curtain wall design and construction constitute a larger proportion of the building envelope systems used on these buildings. Aesthetically, glass and aluminum curtain wall systems have become ubiquitous and have become a catalyst for discussion surrounding transparent architecture and thermal performance – particularly in colder climates. The notion of conserving energy to maximize benefits of generating and storing it gives rise to the exploration of managing what we use today as a material and design pallet. Whilst improvement in glass performance has been incremental, there belies an opportunity to influence a step-change in overall thermal performance by addressing non-vision areas, specifically, shadow box applications in the enclosure. The balance between thermal performance of the vision and non-vision areas have provided an opportunity for closer examination of how thermal performance can be improved in shadow box areas with the implementation of a holistic approach to building design.

Keywords: Spandrel, Shadow Box, Thermal Performance, Condensation Resistance

摘要

城市密度增加的需求对我们的建筑环境的垂直度产生了一定影响，经济性、幕墙设计与施工的实际效率占建筑围护系统的重要部分。从美观的角度看，玻璃和铝幕墙系统已经无处不在，并促发了尤其是在寒冷气候条件下围绕透明体系结构和热性能的讨论。节约能源、最大化发电和存储效益的概念促使我们探索管理之道——当今用什么作为材料和设计的载体。玻璃性能的持续改善提供一种在热性能而非视觉领域改变和革新的可能。具体而言，可以在建筑外围护结构中应用阴影框以逐步改变整体散热性能。非视觉领域和热性能之间的平衡提供了一个仔细研究如何在整体建筑设计视角下，通过阴影框提高建筑散热性能的可能。

关键词: 拱肩，阴影框，散热性能，抗结露

Introduction

Curtain walls on today's iconic buildings are a true architectural statement that represents the building, owner, occupants, and location. Through the years, the curtain wall has improved its performance characteristics for air infiltration resistance, water infiltration resistance, and structural performance while maintaining its aesthetic qualities. The glass façade still remains popular throughout the city centers of the world. During the past decade, continued effort has been extended to improve the energy performance of curtain walls. The energy performance aspect has required curtain walls to use more durable materials to resist air and water infiltration. Natural disasters such as hurricanes, typhoons and earthquakes have required curtain walls to be subjected to, and required to pass performance-based mock ups with increased windloads and seismic drift requirements. Specifications for impact resistant glazing and glazing technique are implemented in hurricane susceptible areas of the US coastline areas. Critical fire-stopping assemblies at the floor slabs are required to meet performance

引言

当今标志性建筑幕墙是一种真正的建筑表达，代表了建筑物，业主，住户和位置的信息。近些年来，该幕墙已同时具有美学品质、改善其空气渗透性能、良好渗水性、结构性能等特点。在世界各地城市中心区玻璃幕墙仍然流行。过去的十年里，业界一直致力于提高幕墙的节能性能。节能性能方面已要求幕墙采用更耐用的材料，以抵抗空气和水的渗透。自然灾害，如飓风，台风和地震需要幕墙要进行实体模型的性能模拟，以抵御更大的风荷载和地震漂移要求。耐冲击装配玻璃和装配玻璃技术规格参数在美国沿海的飓风灾地区实施。关键阻火组件的楼板必须符合法规和规范所决定的性能要求。建筑所有性能测试通过的同时，还应保持其美感。

通过光谱选择高性能涂料的使用，装配玻璃已使可见光透射率最大化，并使太阳能热增益最小化。这样可以在寒冷的季节降低能源使用，同时兼有透明度和大视野的立面以符合建筑审美。大景观视窗不仅得到建筑物内居住者的青睐，同时也配合建筑物整体外观的需要。

requirements dictated by codes and specifications. All of this performance testing has to be validated while still maintaining its aesthetic appeal.

Glazing has improved with spectrally selective high performance coatings that typically maximize visible light transmittance and minimize solar heat gain. This keeps energy use lower during the predominantly cooling seasons while maintaining the aesthetic desire for transparency and large vision areas. Not only must the large vision areas appeal to the occupants inside the building, but they are typically desired to match and blend with the overall exterior appearance of the building.

The glass clad building that has the architectural feature of glass in spandrel areas will many times use a shadow box design. The shadow box will typically use the same type of glass used in the vision area, and there will be an architecturally finished panel behind the glass that creates the visual depth. Figure 1 depicts the typical cross section of a shadow box in the spandrel area hiding the floor lines. Due to the amount of Low E glass used on curtain wall façades, shadow boxes will use the same type of glass as is used in the vision to maximize aesthetics. This type of glass an aesthetic is not practical to obtain without and IG unit in the spandrel.

The Building Envelope Design Guide – Curtain walls (Vigner et al 2012) provides a brief note about the issues and challenges with shadow boxes. There are various opinions on the actual mechanics of how the shadow box needs to function with regards to the non aesthetic performance; however the key driver to keep shadow boxes at the spandrel area is for aesthetics. The designer will want the spandrel area to appear as similar as possible to the vision areas. Therefore the spandrel glazing type is typically the same as the vision glazing. The aesthetic desire for depth is then maximized until there is insufficient space to maintain thermal insulation and fire insulation performance characteristics. The depth is typically seldom sufficient and the economics will come into play as increasing deeper curtain wall mullions (and their associated costs) begin to exceed beyond the budgeted scope of the project. This classic "Dance of Compromise" is evident in all aspects of the project. Wausau Window and Wall Systems publish a technical recommendation for shadow box applications (Wausau) and the second point of twelve recommendations is to review the aesthetics before proceeding. As many technical hurdles are present in shadow box performance and durability, aesthetics seem to be the driver.

Curtain wall spandrel options – other than shadow boxes – are typically opacified glass, metal panels, stone panels, or other opaque materials. Each of these options comes with their own challenges, and adds unique aesthetic character to the building. Each of these options may come with performance advantages over shadow boxes, but they do not create the illusion of depth and appearance of a visually continuous façade.

Current Practices For Shadow Boxes

Shadow boxes are the non vision area of the curtain wall, and are typically 1500mm (a module width) by 600-1500mm tall. This dimension depends on the designer's desired window to wall ratio for the building. The shadow box has to perform structurally and resist air and water infiltration to the specified criteria. The shadow box must be installed adjacent to the floor slab and allow a proven fire stopping system to be installed between the backpan and the floor slab. The fire-stopping, typically made of a Mineral Wool for its noncombustible performance is also used as insulation.

Typical glazing on high performance buildings will be specified with a high performance low-emissivity coating. Although the low-e coating will reflect infrared heat back to the exterior, it will also reflect some heat

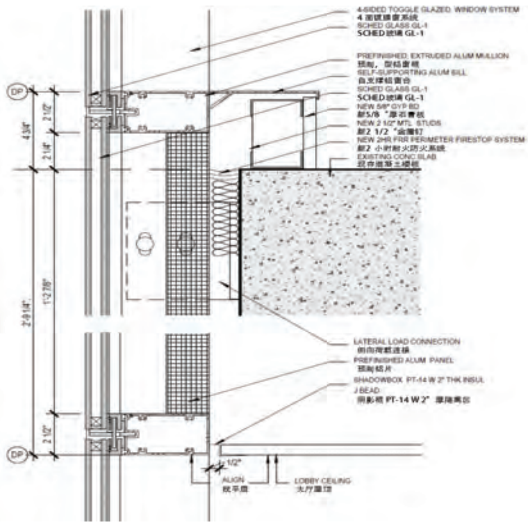

Figure 1. Typical cross section of shadow box design. (Source: Neil McClelland HOK)
图1. 阴影框设计的典型截面。（来源：尼尔•麦克莱兰HOK公司）

覆盖建筑的玻璃将在拱肩区域多次使用阴影框的设计。阴影框通常会在视觉效果相同的玻璃区域中使用，并且通过在玻璃后面安置建筑成品面板达到了增加视觉深度的效果。图1是在拱肩区域隐藏地板线的阴影框典型横截面。由于幕墙外立面低辐射玻璃的使用量，阴影框将使用景观视窗相同类型的玻璃，这种类型的玻璃必须通过单元的拱肩才能达到美观效果。

建筑围护结构设计指南 - 幕墙工程 (Vigner等，2012) 提供了阴影框的问题和挑战的简要说明。许多人对阴影框在非审美表现方应有哪些功能的议题持有不同的观点，有些人认为应该以美观为目标在拱肩区使用阴影框。设计师希望拱肩区域的效果在视觉上与其他部分相似。因此，拱肩玻璃类型通常与景观窗的玻璃类型相同。由于美观的需求，幕墙框的深度被最大化，直到没有足够的空间来维持保温隔热和防火隔热性能。一般情况下深度是不够的，另外由于经济考虑，增加更深的幕墙竖框 (及其相关的成本) 开始超出项目的预算范围。这种典型的"妥协方式"在项目的各个方面都很明显。沃索窗墙系统发布阴影框的应用 (Wausau) 技术建议及十二项建议是，在项目实施之前考虑美观需求。因为许多技术障碍在于阴影框的性能和耐用性，美观性的考虑应该是驱动因素。

相比其他类型，幕墙拱肩的阴影框通常使用不透明玻璃、金属板、石材板或其他不透明的材料。每种材料都有自身的挑战，并增加了建筑物独特的审美个性。所有这些材料可能比阴影框更具性能优势，但他们没有创造深度和外观连续外墙的视觉效果。

当今阴影框的实践应用

阴影框是幕墙的非视区域，并且通常1500毫米宽 (一个模块的尺寸)，600至1500毫米高。该尺寸取决于设计者期望的建筑立面窗墙比对。影子框具有结构作用，抵制空气和水的渗透需达到指定的标准。阴影框必须安装在临近的楼板上，并且为背板和楼板之间火灾制动系统安装留有空间。火灾制动系统通常由矿棉组成，它的不燃性能也被用来作为绝缘层。

高性能建筑的典型转配玻璃应当具有规定的高性能低辐射镀膜。虽然低辐射镀膜将红外热反射到建筑之外，但仍然有一部分热量进入到室内，具有一定程度的热性能。在阴影框区域使用这种玻璃，这些条件可以成为一个合适的热环境，玻璃制造商可以制造指定热强化玻璃，以避免热量对其造成破坏。

增加的风荷载的承载力和防风碎已经促使阴影框的设计包含夹层玻璃的耐冲击系统。夹层玻璃具有较高温度使用范围，在安装时

to the interior, providing a degree of thermal performance. In using this glass in the Shadow Box areas, these conditions can become a heated environment enough that the major glass manufacturers will specify heat strengthened glass to avoid thermal breakage.

Increased windloads and resistance to windborne debris has affected the shadow box design to include laminated glass in impact resistant systems. Laminate glass has upper temperature limitations and must be considered when installed. Glass selection may dictate the upper temperature and the way to regulate that temperature through some sort of controlled venting.

Debates ensue over the practice of venting or not venting shadow boxes. Non-vented shadow boxes may eliminate any accumulation of dust or insects, but they will change in pressure with temperature variation, potentially causing aesthetic changes. Condensation will typically occur within a non-vented shadow box during cold weather; however it should resolve itself via evaporation during the natural reheating process, but may represent a concern for particulate matter accumulation over time.

Vented shadow boxes will resist changes of pressure with temperature, but the condensation of the system during cold weather must be drained out. Accumulation of dust through the vents during pressure cycling when mixed with condensate can render unsightly stains visible from the exterior. Although responsible designers and fabricators will provide baffles at the vents to minimize dirt and insects, it is not uncommon to view field installations that show some ingress of dust after a few years.

This dynamic system will typically have insulation behind the back panel. This thermal layer is no longer in line with the thermal layer of insulating glass in the vision areas. This discontinuity of the thermal control layer exposes the horizontal and vertical frames surrounding the shadow box to temperature extremes that the vision areas are thermally shielded from. The result of this is a potential for unwanted condensation. Vapor retarder barriers must be carefully designed in so that interior building moisture is not leaking into the shadow box during the long winter months causing a constant flow of potentially visible condensate from the exterior. Figure 2 shows a condensing shadow box.

Condensate within a shadow box will cause premature aging of coating, anchors, fasteners and a decrease in thermal performance of typical (contemporary) insulation materials.

Back panels rigidly attached to the framing change dimensions during thermal cycling. Warping or oil canning of the back panel will add unwanted aesthetic changes to the shadow box. Proper fastening of back panels with structural silicone can be done to minimize this aesthetic effect.

Patterns on the #2 surface of the glass can create a shadow within the shadow box and may result in a moiré image that is not within the expected architectural intent. The resulting patterns can be quite unexpected and accentuate and emphasize the need for visual mockups. Figure 3 shows a Moire image.

One of the greatest technical detractors of the current practice of shadow boxes is the thermal inefficiency of the design due to the exposed transoms and mullions. Increasing the insulation between the framing system without changing the frame itself results in a false sense of thermal performance characteristics. Lawton and Roppel (Lawton and Roppel 2011) showed that there is a diminishing rate-of-return by just adding insulation to the back of the spandrel assembly. Many current practices rely on the one dimensional highest thermal resistance rating of the shadow box assembly. The practice of calculating the thermal

必须加以考虑。玻璃类型的选择可能会决定上限温度以及通过控制排气来调节温度的方式。

随之而来的是在通风或不通风的条件下的阴影框做法的争论。通风的阴影框可以消除灰尘或昆虫积累，但是他们会改变与温度变化的压力，可能导致美观的影响。冬季，结露会在不通风的阴影框中出现;但它应该在自然加热过程通过蒸发自行解决，颗粒物的积累随着时间的推移而逐步受到重视。

而非通风的阴影框能够抵御随温度压力变化，但系统会在寒冷天气情况下出现凝结现象，因此必须防止这种现象出现。当混合冷凝的压力循环使通风口积累灰尘，导致了外部可见难看的污渍。虽然相关设计师和制造商将提供挡板的散热孔以减少灰尘积累和昆虫进入，但是通过查看现场调研，几年后灰尘的侵入的情况并不少见。

这样的动态系统通常具有安置在背面绝缘的面板。这种热层在视觉上不再与中空玻璃的热层线对齐。热控制层的这种不连续性暴露在阴影框周围的水平垂直骨架上，将承受环境的极端温度，而景观视窗区域能够避免热辐射的影响。这样做的结果可能导致凝结现场出现。蒸汽缓凝剂障碍必须仔细设计，使建筑物内部的水分在漫长的冬季不渗入阴影框，维持从外部侵入潜在可见冷凝水的恒定流量。图2展示了冷凝阴影框。

阴影框冷凝会引起涂层、锚、紧固件过早老化和常见的绝缘材料热性能下降。

在热循环过程中，刚性地固定在框架的背面板尺寸发生变形。背面板的凹陷和翘曲对阴影框的美观产生影响。可以用硅酮结构紧固背面板，以尽量减少对美观的不良影响。

玻璃表面图案可以在阴影框中创建一个阴影，并可能产生非预期的叠层纹路图像效果。由此产生的图案是出乎意料的，并强调可通过模型预测视觉效果。图3为叠层纹路图像。

Figure 2. Condensation on backside of glass in a shadow box. (Source: Neil McClelland HOK)
图2. 阴影框背面玻璃上的凝结。 (来源: 尼尔•麦克莱兰HOK公司)

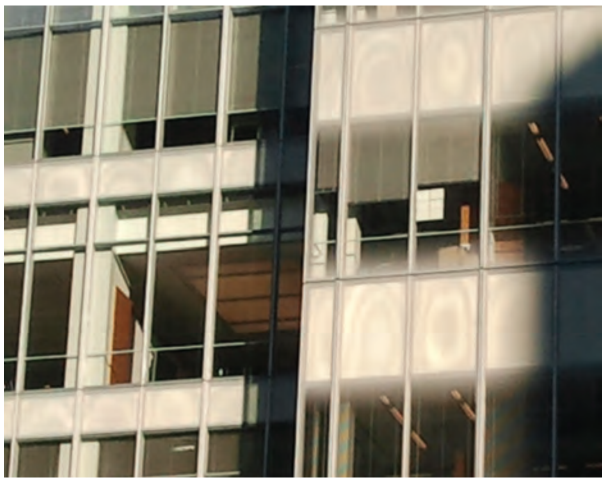

Figure 3. Moire Pattern in Shadow Box (Source: Neil McClelland HOK)
图3. 阴影框的层叠云纹图案 (来源: 尼尔•麦克莱兰HOK公司)

performance of the shadow box by adding the thermal resistances of the exterior glazing, air cavity, and insulation could yield a misleading performance characteristic. A more practical approach is to use the concept of thermal modeling of glazing where one will conducted an area-weighted-average of the center, edge conditions and frame conditions. This method takes some additional work because a simulation model has to be created and summarized.

Next Generation Shadow Boxes

The aesthetics of shadow boxes will continue to be the driver for their use. It is expected that the desire for deeper shadow boxes will drive the fabricators to provide solutions for such assemblies. The primary focus for next generation technology is to keep or enhance aesthetics while increasing thermal performance.

Shadow boxes will continue to be popular amongst the architects of the world on iconic buildings. Windloads will not likely decrease, only increase. Therefore glazing will either become thicker, or it will use laminates. Higher windloads will require deeper mullions which can result in deeper shadow boxes. Laminated glazing will require the consideration of temperature in the shadow box so that the heat gain experienced by the assembly will not render the glazing unfit for purpose.

Fire concerns will still remain. The fire-stopping at the floor slab of a commercial building is a global requirement. The curtain wall system that is anchored to the floor slab must be able to be fire-stopped. Assembly testing to standards such as ASTM E2307 evaluates the safing slot fire-stopping performance. Tested systems do include thermal insulation behind the shadow box and in front of the floor slab. This will not change in the future. What will change is the addition of high performance insulation to augment the insulation characteristics of the required fire-stopping materials.

Condensation and dirt accumulation will not be tolerated in the next generation. Sealed desiccated systems will become a standard, and heat build-up will be moderated.

One enabling item to assist in achieving the goals of the increased performance curtain wall shadow box will be higher performing insulation materials. Insulation today is based on mineral wool due to its fire resistive properties, yet its thermal inefficiency will not allow a deeper shadow box. Vertical mullions are wrapped with mineral wool for fire reason in the spandrel areas and the thermal models show significant improvement. Higher performing silicon based insulation will be able to also perform this task and provide additional insulation.

Higher performance insulations that will be used here are in practice today as Vacuum Insulation Panels (VIP), and Aerogel Blankets. These silicon based insulations have extremely small particle sizes and bring insulation properties that are double that of typical insulation used today. The Vacuum Insulation Panels have nearly an order of magnitude upgrade in insulation characteristics compared to standard materials today. When the silicon based solutions are prepared for VIP's, the fumed-silica core is an ash from a burned silane. The silicon solutions mentioned here are inorganic and have excellent fire resistant properties. The silicon solutions are not susceptible to mold or mildew growth, are extremely hydrophobic, and are incumbent technologies in other industries. These silicon solutions will be able to provide significant upgrades in the thermal performance of shadow boxes, while maintaining aesthetics, and performance to air, water, structural, thermal and fire properties. The thermal conductivity for Vacuum Insulation Panels will have an

其中一种阴影框做法的最大干扰是暴露横梁和竖框导致的热效率低下的设计。不改框架本身而增加框架系统之间的绝缘效果，没有真正作用但会给人一种似乎有效的错觉。劳顿和罗贝尔((Lawton and Roppel 2011) 发现，只是在拱肩背面加上绝缘组件，其回报率随组件数量的增加递减。目前，许多的做法依赖于阴影框组件的单维最高热阻率。通过增加外部玻璃、空气腔、保温层而提高阴影框的散热性能的做法可能会产生对于性能效果的误导。一个更实际的方法是装配玻璃的热模拟概念，其中一个方法是使中心、边界区域和框架区域的重量分布均匀。这种方法需要一些额外的工作，因为必须对仿真模型进行创建和总结。

新一代阴影框

阴影框的美学作用将成其继续被应用主要动因。据估计，对更深的阴影框的需求将推动制造商提供这种组件的解决方案。新一代阴影框技术的主要重点是保持或提高美感，同时提高热性能。

阴影框将继续深受世界上标志性建筑的建筑师的欢迎。而风荷载将不可能减少，只会增加。因此，玻璃需要变得更厚，否则将需要使用层压板。更高的风荷载将需要更深的竖框进而出现更深的阴影框。夹层玻璃需要对在阴影框的温度进行考虑，通过组件获得的热增益的方式将不会导致玻璃不适用的情况出现。

消防问题将依然存在。商业建筑的楼板阻火性能是一个全球性的普遍要求。锚定于楼板的幕墙系统必须具有阻火作用。组装测试标准，如ASTM E2307，将评估阻火安全槽的性能。测试系统的对象包括阴影框背面的热阻材料和楼板前的保温层。这种情况在未来也不会改变。而未来的改变包括加高性能的保温，以增加所需的阻火材料的绝缘特性。

新一代阴影框将不允许冷凝和灰尘积累的情况出现。密封式干燥系统将成为一个标准，而热量积聚效应将会放缓。

保温材料将帮助阴影框实现更高的性能目标。如今，绝缘是具有耐火性能矿棉，但其热效率不能满足阴影框更大深度的需求。为了防火作用而包裹矿棉的垂直竖框拱肩区域和热模型技术有了极大提高。基于硅绝缘更高性能将能够同时执行此任务，并提供额外的绝缘作用。

在当今实践中，绝缘性能更高的材料是中真空绝热板 (VIP) 和气凝胶毯子。这些基于硅的绝缘材料有非常小的颗粒尺寸，其保温性能是现今使用的典型绝缘材料的两倍。真空绝热板的保温性能提升幅度与现今标准相比接近达到了数量级的变化。基于硅的解决方案为重要客户准备，熏处理的二氧化硅核心是燃烧过的硅烷灰。这种基于硅的解决方案是无机的，并具有优良的耐火性能。不容易发霉，并具有较强的疏水性，并且这些技术在其他行业也有应用。这些芯片解决方案将能够显著升级阴影盒子的散热性能，同时保持美观和透气性能、防水性、结构性能、热性能和防火性能。真空绝热板导热系数将为7mW/mK，气凝胶隔热层为15mW/mK，矿棉为34mW/mK。基于硅的解决方案性能是近现今绝缘材料的5倍和2倍。图4展示了基于硅的解决方案相与当代绝缘材料的热阻对比。

系统集成

当代保温材料已通过其在阴影框的广泛应用展示了其灵活性和材料特性。然而，随着对建筑物外围结构，特别是幕墙系统的散热要求日益严格，如今，材料本身的限制会导致对其他材料的考虑。需要更好的散热性能的新材料，且不会影响现有的框架特征。在阴影框上装配这些绝缘部件的战略布局可以达到三个目标。阴影框可以变得更深，同时保持相同的绝缘性能，阴影框可

aged thermal conductivity of 7mW/mK, Aerogel Insulation blanket will have a thermal conductivity of 15mW/mK and Mineral Wool will have thermal conductivity of 34mW/mK. The silicon based solutions are nearly 5X and 2X the insulation of contemporary insulation. Figure 4 shows the thermal resistance comparisons of these silicon based solutions compared to contemporary insulation.

System Integration

Contemporary insulation material has demonstrated its flexibility and material properties through its widely accepted use in shadow box applications. However with the increasingly stringent thermal requirements on the building enclosure and in particular curtain wall systems, there comes a point where the material's own limitations will give rise to the consideration of other materials. New higher performing materials that can impart better thermal performance without impacting existing frame dimension characteristics are desired. The strategic placement of these insulation components in the shadow box assembly can perform three tasks. The shadow box can become deeper while keeping the same insulation performance; the shadow box can be thermally improved over contemporary designs, or a combination of the two.

As important as improved thermal performance characteristics for shadow boxes, a high performance insulation shadow box solution should be one that can be more readily embraced and accepted by the exiting contracting infrastructure. A higher performing solution that has a marginal impact on the design, engineering, assembly and installation of curtain wall systems will meet with wider spread technical acceptance.

Summary

While it is widely recognized that there is a strong aesthetic inclination to incorporate shadow box constructions in largely glazed buildings, it is also noted a higher degree (beyond one-dimensional) thermal analysis of these conditions will be necessary. A more thermally advanced and performing system incorporating silicon-based high performance insulation components (Vacuum Insulation Panels and Aerogel Blankets) that provide a thermal barrier for the spandrel area in an easy to design and install package will be brought forward. The silicon-based components would provide an improvement in the continuity of the thermal control layer by being closer to the plane of the vision glazing while also mitigating the need to ventilate the space behind hence mitigating condensation and dirt pick-up potential.

The simple component approach would minimize the potential to redesign existing curtain wall systems to accommodate it; hence renders itself better poised for existing system designer, and installers to embrace and utilize the component in both the new construction and potentially retrofit markets. Both these applications in sufficient numbers could begin to represent a larger reduction in the energy footprint – particularly in the context of increase urbanization and increases built environment densities that the aforementioned is typically associated with.

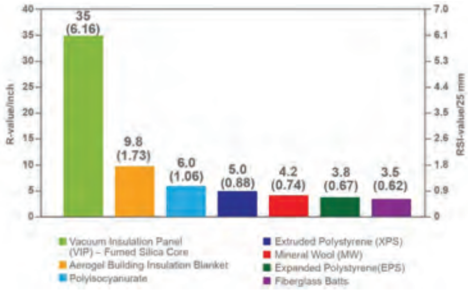

Figure 4. Comparisons of Silicon based and contemporary insulation materials (Source Dow Corning)
图4. 基于硅的解决方案相与当代绝缘材料的热阻对比 (来源: 道康宁公司)

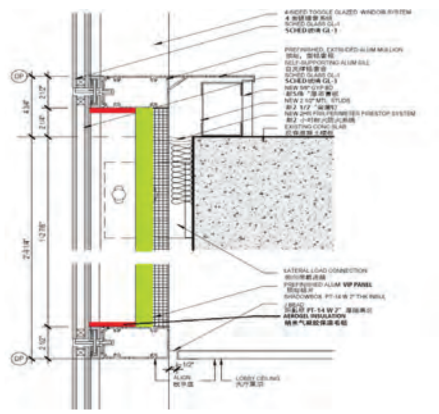

Figure 5. Shadow Box with additional Silicon based solutions of VIP and Aerogel. (Source HOK/Dow Corning)
图5. 特殊硅基VIP阴影框方案和气凝胶。 (来源HOK/道康宁公司)

以通过现代设计进行热处理改善，或者是两者的组合。

提高阴影框散热性能同样重要，高性能绝缘阴影框解决方案应该更容易被基础设施承包方接受。性能更高的解决方案对设计、工程、装配及安装玻璃幕墙系统都将产生广泛的影响，并且能被更广泛的传播技术接受。

总结

虽然人们普遍认识到，把阴影框结构应用在玻璃幕墙建筑物上具有较强的审美倾向，它还应注意这些条件下必要的热分析。更先进的散热和执行系统集成硅基高性能绝缘部件 (真空隔热板和气凝胶毡)，在拱肩区域提供了一个易于设计和安装的隔热层。在基于硅的元件将提供在更靠近景观玻璃窗的平面内的热控制层的连续性改进，同时也减少了背面因减轻冷凝现象和灰尘积累的通风需要。

简单的组件方法将最大限度地减少现有幕墙系统的为了再适应的重新设计; 因为能够使用现有的系统设计，设计者、安装者在新项目或者翻译工程中都会使用这种组件。两种应用被广泛采用，可以大规模的降低能源消耗，特别是在城市化进程的加深和建成环境密度的提高的情况下，上述的方法被更为广泛地应用。

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