Cool Skins: Exploring the Cooling Potential of Lightweight, Ventilated Cladding Systems

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ABSTRACT: The heating of the exterior building skin by solar radiation is a significant problem with regards to cooling season thermal performance. Lightweight construction systems are particularly prone to problems under these conditions, yet often rely merely on insulation devised for the winter months to reject the heat of the summer months. In recent decades, ventilated roof systems have demonstrated their effectiveness at reducing cooling season loads by way of solar radiation-induced convection behind the roofing. It is evident from recent research that ventilated cladding systems can have similar benefits; yet the existing research on the subject focuses on massive cladding and does not address the lightweight cladding systems that correspond to lightweight construction methods. Of particular interest in this research is the role of open-joint versus continuous ventilated cladding with respect to solar radiation-induced convection. Physical mockups and computational fluid dynamics computer simulation were used to compare non-ventilated, open-joint ventilated, and continuous ventilated cladding with respect to heat rejection.

KEYWORDS: Rainscreens, cladding, cooling, building skins

INTRODUCTION

The conventional approach to controlling thermal transfer in the building skin focuses merely on insulation (resistance to conduction), largely ignoring the properties of cladding. Yet heat transfer from solar radiation originates on the exterior side of the building envelope, suggesting that cladding material and configuration play a critical role in heat transfer during the hot months. Modern building science has addressed heat gain in roofs by introducing natural ventilation behind roofing; these systems use solar-driven, heat-induced convection between roofing (often metal or tile) and the roof deck, rejecting heat that would otherwise add to the magnitude of heat that the insulation beyond must resist, resulting in substantial, measurable energy savings (Ciampi 2005).

The key concept to ventilated roofs is that the *material layers* in the roof package can be manipulated to reduce heat gain. In their normal configurations, these layers would otherwise remain in contact with one another, transmitting heat by conduction – ventilating the layers interrupts this process, even though from the standpoint of thermal resistance (R-Value or U-Value), the assembly changes very little. This paper looks at a similar concept in light-weight ventilated cladding systems, where ventilation can be used between the cladding and the building envelope to reduce heat transmission driven primarily by solar radiation. Coincidentally, ventilated cladding systems have been common for many decades now and are known more familiarly to architects as 'rainscreen' cladding systems. While rainscreen cladding evolved originally to prevent moisture intrusion into wall cavities, it has the potential to benefit cooling season building performance through similar thermal behaviors as ventilated roofs.

1.0. BACKGROUND

1.1. Challenges of light-weight construction in hot conditions

In the U.S., a significant portion of contemporary building stock is built using light-weight construction – wood or light-gauge steel cavity walls serving either as primary structure or infill, sheathed and clad with similarly light-weight wood, plastic, metal, or cementitious cladding products. Lower building costs, increased material efficiency, and faster erection times were among the improvements realized by modern light-weight systems over their massive stone and masonry predecessors. Along with these improvements also came insulation – the use of low-conductance materials in the building envelope to slow down heat loss during the heating season. Heat loss during the heating season and heat gain during the cooling season are very different, however, as a result of solar radiation. In the winter time, heat loss is largely a steady state process in which conduction of heat through the envelope dominates and heat loss increases as the difference between interior and exterior temperatures increases. In the cooling seasons, conduction works in the opposite direction as heat from the exterior environment makes its way into the building interior. Yet the difference between interior and exterior temperatures is only part of the heat transfer picture; additionally, solar radiation impacts exposed parts of the exterior envelope, adding greatly to the heat gain passing into the interior of the building. In contemporary energy calculations, the effects of radiation and conductive transmission are combined using a value called the ‘sol-air temperature’ which combines radiation and conduction into an equivalent exterior temperature convenient for heat transfer calculations. Coincidentally these heat gain calculations are the same simplified calculations used to assess heat loss in the winter; thus the same measures to combat heat loss are perceived as the best to combat heat gain, even though these thermal processes are very different.

Traditional massive construction tempers heat transfer by way of its mass: heavier construction takes much longer to lose and gain heat to the external environment, and as a result, its performance during hot and cold periods is similar. Heat travels more quickly in light-weight envelopes, on the other hand, and the layers in these light weight envelopes respond differently in the heating and cooling months. In particular, the exterior cladding of light weight buildings lacks the thermal mass behind it to slow down heat gain from the sun – solar radiation can thus produce tremendous surface temperatures in the cladding itself. This “hot skin” condition subsequently passes heat back to the interior of buildings by combined effects of radiation, conduction, and convection, posing issues to thermal comfort and additional cooling loads; in Figure 2 it is the cladding’s soaring temperature (71°C/160°F+) and not the exterior air temperature that impacts the interior wall beyond. Heat gain originating from solar radiation is a major factor for cooling loads even for relatively temperate locations. Often designers stop merely at protecting glazing; yet for many buildings opaque walls are subjected to a larger amount of solar radiation than windows and as buildings get taller, the radiation affecting walls approaches that affecting roofs. When windows are logically located, sol-air gains (radiation plus conduction) through the opaque envelope can markedly surpass direct solar gains occurring through windows. Thus solar radiation’s effect on the opaque building envelope during the cooling season presents a significant challenge for energy efficiency in lightweight construction.

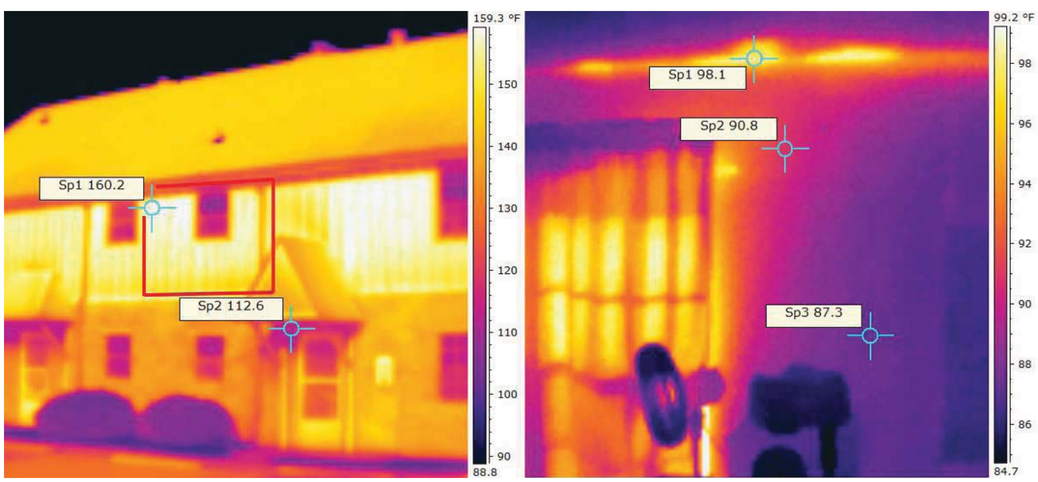

Figure 2: Thermal imagery[2] of a “stick frame” apartment building where solar heat gain impacting the wood exterior cladding is transmitted to the interior walls (and ultimately the interior space); re-radiation, conduction, and internal convection are at work simultaneously and the presence of hot spots suggest gaps in the insulation. Note the interior images were taken in a conditioned space with an ambient temperature of approximately 27°C (80°F) – because of the effects of MRT, the much warmer interior walls would produce an apparent temperature that could be several degrees higher, depending on the point of observation. Source: Author

1.2. Inquiry: ventilated cladding and cooling

Typical rainscreen systems have evolved to provide the following functions via their air cavities: prevent water intrusion by capillary break, provide a drainage space for moisture, allow air circulation to remove moisture, and most critically, to allow for pressure equalization of the cavity and the exterior air to prevent water infiltration by pressure (Salonvarra 2007). The function of pressure equalization is key here: with equalization of pressure, a combination of gravity and ventilation allows moisture to escape the backup cavity rather than be transmitted into the dry envelope assemblies beyond. One design factor that is somewhat ambiguous about ventilated rainscreens, however, is the degree of continuity in the outer cladding; manufacturers of panelized rainscreens often offer open joint and closed joint variations of their products, while the larger array of options for rainscreens include nearly continuous masonry veneers (very few joints) to wood screens (very large and frequent joints).

In ventilated roofs, the continuity and smoothness of the ventilation cavity is critical because heat evacuation is driven by thermal buoyancy – the movement of heated air by pressure differential (Salonvarra 2007). Thus a major 'what if' for understanding similar cooling potential in walls is the role continuity plays in the exterior skin. Although different rainscreen cladding materials and configurations may offer marginal performance differences in terms of moisture rejection, when heat rejection is considered certainly cladding material and configuration is critical. The stack effect – a more organized, idealized form of thermal buoyancy – requires that inlets and outlets be limited for a given air volume. Thus it may be inferred that a closed joint cladding system would provide the most organized thermal lift in the air cavity beyond, rejecting the most heat from convection. On the other hand, it may inferred that an open joint system would tend to move air more slowly under conditions that are more equalized with the exterior, rejecting less heat without the benefit of the stack effect.

Early in the research, the author visited a building with a light-weight rainscreen system with 1.3cm (1/2”) joints and high-pressure laminate (HPL) cladding panels during a warm summer to collect data (Figure 4). It was expected that thermal buoyancy and the stack effect would be evident from the vertical temperature profile of the cladding (from heat gain rising to the upper cladding) and from the air velocity and direction within the cavity. The first observations were carried out on a day with light winds; air velocity[1] in the cavity was highly erratic and was attributed to the wind. The next observations were carried out on a day in which winds were calm – yet air velocity and direction in the cavity was still highly erratic. Clearly the open joints in the cladding were defeating the stack effect. During the same observations, thermal imagery[2] revealed very high cladding temperatures (about 11°C or 20°F above ambient) with little differentiation between lower and high panels. Was this rain screen assisting the building at all in terms of heat rejection?

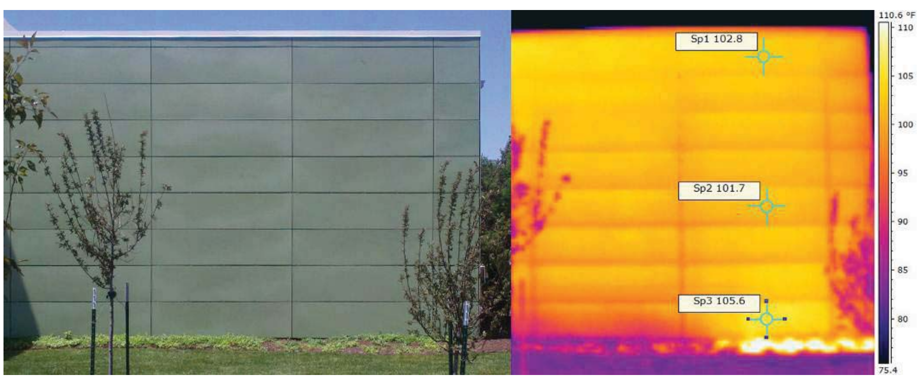

Figure 4: Thermal imagery from a local building that exhibits an HPL rainscreen cladding system. Field observations did not show clear thermal organization on the exterior surface (from cooler to warmer) as was expected from thermal buoyancy. Readings of the air velocity within the cavity did not show stable, upwards ventilation. In sum these initial observations indicated that light, ambient breezes were enough to disturb organized thermal flow and more examination of the benefit or detriment of the open joints was necessary to understand how, if at all, this light weight type of rainscreen could reject heat. Source: Author

1.3. Prior studies in thermal benefits of ventilated facades

The thermal benefits of ventilated cavities are still emerging in the discourse of building science. Enthusiastic interest on this subject has emerged in Mediterranean regions where researches using both experimental observation and numerical models show evidence that significant reductions in cooling loads can be realized by thermally-induced convection in air cavities (Ciampi 2003, Suarez 2011, Marinosci 2011, and Giancolaa 2012). Yet studies exist for less sunny and hot climates (like the German study of E. Jung as cited by Salonvarra 2007) that contradict the Mediterranean research in showing no improvement in thermal performance from ventilated cavities, even in the presence of significant ventilation rates. The cited studies from the Mediterranean are of note because they examine regionally-specific cladding methods using stone and masonry veneer (Marinosci 2011 and Giancolaa 2012) that are heavier and have tighter, less frequent joints than the light-weight systems of interest to this this paper.

Despite differences in cladding, a strong body of research exists that suggests the benefits of ventilated facades for hot, sunny climates. Rather than address the quantitative conclusions of each selected source, some key aspects from each source are summarized with their particular relevance to the research questions raised by the author in this paper. In Ciampi et al (2003), a numerical model identifies several factors in the wall assembly with respect to optimizing heat rejection, including the thermal characteristics of the cladding and back up materials as well as the ventilation cavity depth. This study underscores the importance of heat transfer by radiation within the cavity and interestingly, showed that materials like cementitious board can yield energy savings that are very close (within 18%) of heavier masonry claddings although the numerical model assumed the cladding system is continuous (i.e. no joints). A more recent numerical model developed by Suaréz et al (2011) examines heat transfer in the wall cavity more closely, using a more refined numerical model that describes a two-stage process of convection. In the first stage, lower buoyancy results in free convection where surface heat transfer is mostly responsible for convection. The second stage described is one with higher temperatures where laminar flow develops (effectively the stack effect) but where the stable moving air column is responsible for heat extraction much more so than the slower, less organized surface heat transfer that is characteristic of the first stage.

Two recent studies used full scale construction to test the influence of ventilated cladding to reduce the influence of incident solar radiation. In Marinosci et al (2011) a very large full scale mockup was used with fired stone panels (1.0 x 0.5m) with 1cm joints and a 25cm (10”) ventilation cavity. Another source consulted in the research was carried out in Spain by Giancolaa (2012) whose subject was a recently constructed building with a stone rainscreen system, this time with a shallower cavity (about 4cm) and somewhat tighter joints (0.5 cm). Both studies compared data from sensors against computer models; in Marinosci, a more conventional energy modeling software was used (ESP-r) and in Giancolaa a more sophisticated computational fluid dynamics (CFD) simulation was performed which fully simulated convection and air flow in the system. The main difference between these two studies was that in Marinosci, the computer model did not account for the open joints in the system. In that study, correlation between the model and the actual observations was rather wide until the cladding became very hot, suggesting that the joints in the cladding were a critical part of heat exchange at more moderate temperatures. In Giancolaa the CFD simulation integrated the joints and was able to demonstrate better correlation with the real observations, while also demonstrating that air moved in and out of the joints in a sort of gradient from bottom to top rather than in an organized stack.

What is significant in the research discussed above is that the role of joints and the property of cladding has a critical role in heat transfer and the success of the system in rejecting heat from solar radiation, although no research could be found that has tested the specific impact of joints (or lack of joints) on heat rejection. It also remained an open question as to whether generalized stack effect or more varied free convection was more successful in conveying heat out of the cavity.

2.0. INITIAL EXPERIMENT

2.1. Experiment: open or closed joints?

With regard to typical *light-weight construction*, several research questions emerged. How would light-weight facades (as opposed to stone or masonry facades) behave, and is there a measurable difference in performance between non-cavity cladding, open joint cladding, and closed joint cladding systems? Will this difference remain if the effect of wind is eliminated in a controlled experiment? Are there heat transfer behaviors that might suggest an optimal approach to light weight cladding, relative to gapping and/or material and assembly properties? An experiment was subsequently conceived to compare the cooling performance of light-weight, ventilated cladding in open joint or closed joint configurations. Part of the experiment was also design to compare both open joint and closed joint ventilated configurations against a non-ventilated configuration. Early research suggested that the closed joint configuration would yield the best heat rejection results because of the presumed optimization of the stack effect from the continuity of the closed-joint cavity. Certainly, it was expected, the substantial gaps of the open joint prototype would disrupt organization of air flow, limiting convection.

The experiment was designed to use mock ups scaled to reproduce the effects of heat transfer at full scale, yet be relatively portable for use in a test chamber. In order to eliminate interference from the wind, the prototypes were tested in a test chamber at the Institute for Environmental Research at Kansas State University, where a rack of high-powered heat lamps simulated insolation and a dedicated air handling unit maintained a relatively constant temperature. The light rack was constructed identical to the mockup height and width, and outfitted with fifteen 250W heat lamps in a regular pattern that, at the 0.45m (5ft) initial test distance produced a maximum heat flux density[3] of approximately 726W/m^2 (230 Btu/ft^2*h) at the center of the lamp beam, with heat flux density falling off to about 10% of maximum at +/-15° from the center of the beam.

The first battery of tests were conducted over a period of approximately 70 minutes with the test chamber set to maintain an ambient temperature of 80°F. Mockups with cavities had small test ports (at height = 81", 61", 45", 27", and 9") drilled through the rear of the ventilation cavity to measure cavity ventilation rates and air temperature[1]. Ports were sealed with tape when not in use, and data collected from each port was collected in 2-minute durations and averaged. Ventilation was measured only in a vertical path, directed upwards, with the probe at the center of the cavity. At the end of the test, infrared thermography[2] was used to collect surface temperature data from both the cladding side and sheathing side of the mock ups. A vertical temperature profile was completed by capturing a series of five individual images in sequence and a post-analysis program was used to collect average values from each of the five images in the profile. The averaging of these values was critical to level out the hot spots that were created by the lamps.[4]

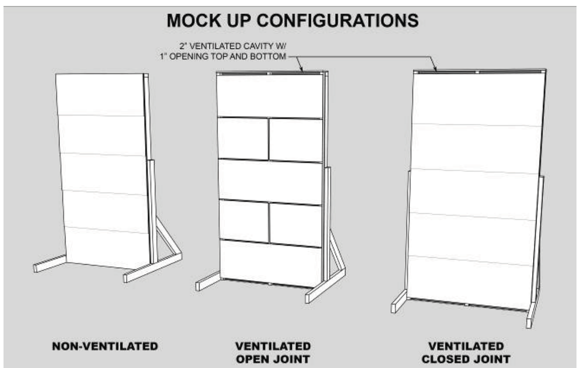

Figure 5: Schematic view of the mockups. Three mock ups were constructed measuring 2.3m high and 1.2m wide (90"H x48"W) using conventional wood framing with 11mm (7/16") wood strand sheathing, covered by roofing paper (similar in properties to building paper). Hardboard (i.e. Masonite) of 5mm (3/16") thickness was used for cladding to approximate HPL rainscreen cladding. One mockup was clad in lapped hardboard in direct contact with the sheathing and wrap (left – "non-ventilated"). Galvanized steel studs of 50.8mm (2") depth were then introduced vertically over the sheathing and wrap of the remaining two mockups (middle and right) to represent the steel offset system used in common rainscreen applications. An EPDM weatherstripping tape was used between the steel studs and the sheathing to prevent thermal bridging from the cladding, as is typically used in rainscreens. One ventilated mockup used individual cladding panels spaced 12.7mm (1/2") apart in an alternating pattern, leaving a larger 25.4mm (1") gap at the top and bottom of the mockup (middle – "ventilated open joint). The final mockup (right – "ventilated closed joint) used a lapped cladding resulting in closed joints except for the top and bottom of the mockup, where a 25.4mm (1") gap was left open for ventilation. Source: Author

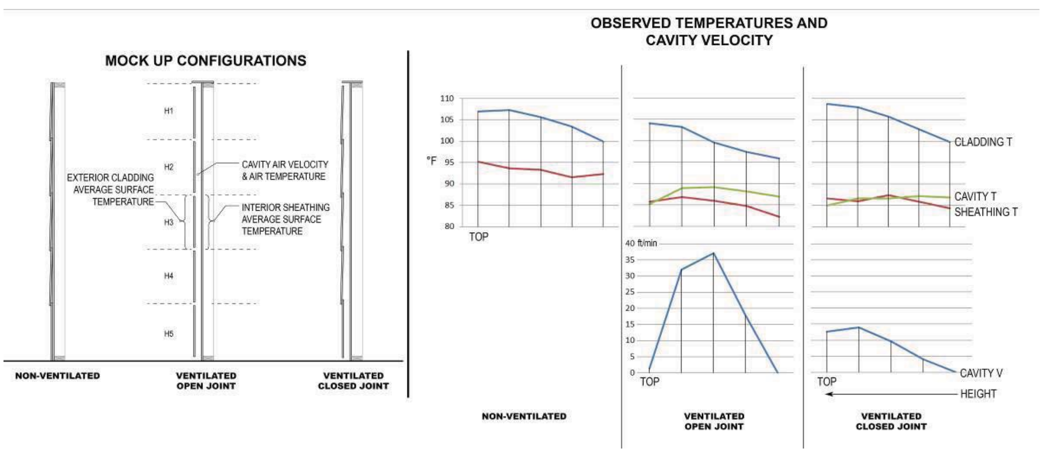

Figure 7: Observations from the initial experiment with the mock ups. Source: Author

2.2. Initial Observations and Interpretation

On one level, the initial experiments comparing the three prototypes confirmed the benefit of ventilation behind the cladding over the non-ventilated configuration. The air cavity clearly mitigates the transmission of radiation as conduction from cladding to sheathing – a characteristic that was seen readily in the thermal imagery. In the non-ventilated mock-up, the hot spots from the lights were transmitted directly to hot spots on the reverse side of the sheathing, producing a nearly identical thermal image; for the ventilated mock ups, the hot spots weren't visible on the sheathing side because this conductive transfer was broken by the cavity. The most telling comparison between ventilated and non-ventilated mock-ups were in the average sheathing surface temperatures, which were significantly lower for the ventilated cladding mockups (29.5°C/85.1°F for the open-joint prototype and 30°C/86.0°F for the closed-joint mock-up) than for the non-ventilated mock-up (34°C/93.2°F) (Figure 7). Lower sheathing temperatures indicate a reduction in heat transfer, confirming the benefit of a ventilated cavity over a non-ventilated cavity for cooling purposes, even with the rather arbitrary materials characteristics of a hardboard skin (i.e. brown, rough surface on the cavity side, etc.).

The comparison between the open-joint and closed-joint mockups yielded results that were unexpected. The first important distinction was from cladding surfaces temperatures, measured on the exterior face of the cladding. The open-joint mock-up ended the test with an average cladding surface temperature of 37.8°C (100°F), while the closed-joint mock-up ended at 40.6°C (105.0°F) – as hot as the cladding on the non-ventilated mock-up. The difference in cladding temperatures is likely associated with the small performance edge for the open-joint mock-up in sheathing heat transfer (29.5°C/85.1°F for open-joint vs. 30°C/86.0°F for closed-joint). Another surprising difference came in the observations of cavity air velocity and temperature. In the open-joint mockup, air velocities were much higher overall (0.19m/s or 37.2 ft/min max, measured at 45" height) than in the closed-joint mock-up (0.07m/s or 14.0 ft/min max, measured at 61" height). Air temperatures in the open-joint cavity were also slightly lower than in the closed-joint mockup.

Based on the experiment, it may be interpreted that both ventilated prototypes outperformed the non-ventilated prototype with regards to heat rejection. The differences between the two ventilated prototypes are more difficult to account for and let to a series of experimental follow-ups that looked at behavior in the air cavity more closely.

3.0. FOLLOW UP EXPERIMENTS

3.1 Observations at varying cavity depth and radiation intensities

After considering the results of the first experiments, the very low air flows and increase in heat transmission for the closed-joint mock-up became an important follow up question. In order to better understand what was happening in the air cavity, a second experiment was run with this mock-up. In this experiment, three velocity and air temperature readings were taken at different horizontal depths (1.5", 1", and 0.5") at each of the five test ports. What was expected from these readings was some picture of the laminar flow that was occurring in the mock-up during the test – would the air flow and temperature be different for these three depths? Preliminary research (Suaréz 2011) suggested that in this configuration, laminar flow would result in higher velocities in the middle of the air cavity, where its flow would tend to convect in a channel rather than from the cavity walls where heat extraction would be most beneficial.

A secondary question involved the intensity of radiation that the cladding was subjected too – would increasing radiation intensities increase or change the air flow in the cavity? To explore this question, the experiment using the closed-joint mockup and multiple depth readings was repeated with the light rack at (1.5m, 0.9m, and 0.45m (5', 3', and 18") distances (yielding approximately 1x, 2.8x, and 11.1x the heat flux in the initial experiments).

Results from this experiment (Figure 8) were interesting, in that some explanation for the poorer performance of the closed cell prototype materialized. With the lamps at the original 1.5m (5') distance, air temperatures across the cavity *increased* as the readings moved from the exterior to the interior side of the cavity. This trend intensified as the level of radiation impacting the cladding was increased. Thus while the exterior cladding was getting far hotter than the sheathing, a significantly warmer layer of air was in contact with the sheathing. Observations of air velocity were equally telling. At the original 1.5m (5') distance, air velocity in the cavity was greatest at the cladding surface and decreased almost to zero towards the sheathing. As the radiation level increased, the convection channel moved towards the center of the air cavity while the air closest to the sheathing remained relatively slow-moving. Also interesting was a small increase in general velocity readings when the lamps were moved to 0.9m (3'); yet when the lamps were closest and surface temperatures were soaring, velocity readings *dropped.*

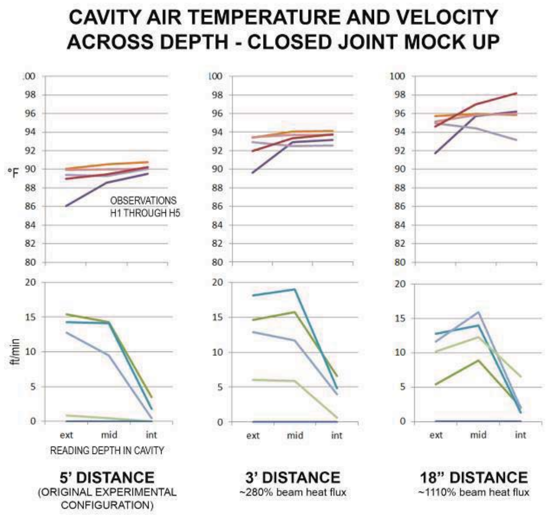

Figure 8: Follow up experiments involving the closed-joint mock up. Source: Author

3.2 Air flow studies using computational fluid dynamics simulation

With a better understanding of air flow across the depth of the air cavity in the closed-joint mock-up, a computational fluid dynamics (CFD) simulation was carried out to examine air velocity in the cavity in greater detail. The simulation was heated by a solar radiation source, configured to represent realistic, full solar intensity for Kansas City on April 1st. The sheathing and cladding were modelled as plywood and fiber hardboard respectively. The simulation was run in steady-state mode (i.e. no transient effects) for 200 iterations, resulting in approximate convergence (i.e. flows in the CFD model stabilized by the final iterations).

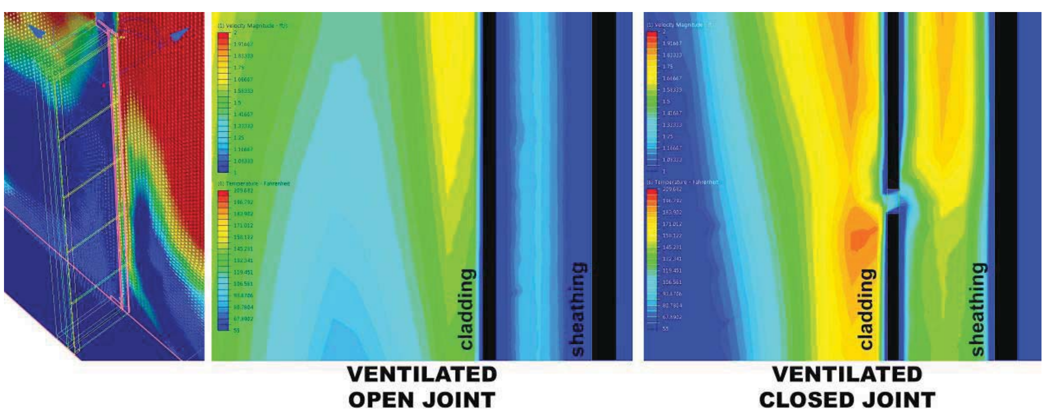

Figure 9: CFD analysis comparing internal air velocities between closed and open joint models. Source: Author

The results of the CFD simulation (Figure 9) reflected what was gleaned from initial research and from the empirical experiments. The closed-joint model exhibited slow, laminar air flow in the cavity and this flow was asymmetrically oriented towards the cladding versus the sheathing side of the cavity. Air flow on the exterior side of the cladding was also relatively slow. What is important is that this behaviour was exhibited from realistic conditions in the model – i.e. realistically hot temperatures from realistic radiant heat flux.

The open-joint model demonstrated very different performance in the CFD simulation (Figure 9). Air flow within the cavity was almost 50% higher than in the closed-joint model, and the overall area of convection within the cavity was much greater, showing increased convection at both the cladding and sheathing walls. Furthermore, air flow on the exterior faces of the cla dding was greater for the open-joint model. Flow for the open-joint model was certainly not as uniform as in the closed-joint model, but it was apparent that convection was more affective as a result of the open joints. Another benefit for the open-joint configuration (not shown in the figures) came with the cladding surface temperatures; around the edges of the panels, surface temperatures dropped greatly in response air circulation into and out of the cavity. Thus the interaction of air around the open joints seemed to both increase cavity convection and decrease overall cladding temperature. The sum of these effects, given the configuration of the models tested, seems to indicate that open joints result in greater heat rejection than closed joints.

CONCLUSION

The most direct suggestion from the research is that even when deploying light-weight materials, a ventilated rainscreen will perform better in the cooling season than non-ventilated cladding. A footnote to this conclusion is that conventional thermal resistance values (R-values and U-values) would recognize very little difference among the three configurations examined in this research. This emphasizes the importance of re-examining the thermal behavior of building assemblies in the cooling season versus the heating season, when simple measures against solar radiation, such as ventilated cladding, can be quite effective without changing envelope insulation or thickness. The second conclusion is that the research here suggests that significant (albeit at the time un-quantified) performance difference exists for open-joint rainscreens over those that have closed joints. While this claim is best directed at applications similar to those tested in the experiments (2" cavity, single floor wall height, fiber cladding product) it seems logical that the apparent benefits of open cladding systems may transfer to different configurations.

Returning to the original assumptions in this research, it appears that the stack effect does not occur as originally presumed. In the configuration tested, in a continuous cavity, the stack effect is actually less effective at transporting heat than free convection, because versus free convection, the convective column is slower and more isolated from the cavity walls. In contrast, when a cavity has open joints, free convection occurs with greater velocities and more heat is transported from the cavity walls. Reintroducing the factor of wind, the effectiveness of open-joint cladding seems to increase rather than decrease; on a breezy day, the admission of ambient temperature air directly into the cavity can only lower the cavity temperature in an open-joint rainscreen. While the stack-effect in ventilated cladding may be more useful in some scenarios (tall buildings, extremely hot conditions) it appears that more consistent benefits to cooling can be delivered by open-joint cladding.

Lastly, further research is planned upon the design of the cladding systems themselves. If a minor change such as the opening of joints can impact convection significantly, it is also promising to further optimize beneficial convection through the design of materials, cladding detailing, and cladding geometry. With most rainscreens still highly conventionalized to panels, assembly units, and boards it seems that increasing knowledge of ventilation behavior can inform a rethinking of the skin to improve heat rejection. Certainly this rethinking can integrate the multi-functional imperatives that rainscreens already promise across aesthetic, moisture mitigation, and thermal imperatives. As cooling performance becomes increasingly important for buildings, cool building skins may offer an important solution towards energy efficiency.

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ENDNOTES

[1] Air velocity and temperature measurements were carried out with a CIH20DL General Tools hot wire anemometer with a handheld probe, logged at 5-second intervals and averaged.

[2] Thermal imagery was captured with a Flir i7 infrared camera (thermal sensitivity of 0.1°C) with emissivity set at 0.95. Spot temperatures and area-averaged temperatures were determined using Flir software.

[3] Solar radiation heat flux density was measured using a DBTU1300 General Tools solar power meter with readings averaged over 30-second intervals.

[4] The intensity and lens type of the lamps used created hot spots in the infrared spectrum. Such light racks have a precedent in this type of research although the effect of the hot spots on the results is unknown. Averaging temperatures from thermography made it possible to mediate the hot spots in the observations.