QUANTIFYING THE BENEFIT OF VENTING GLAZED SPANDRELS TO REDUCE GLASS BREAKAGE AND CONTROL MOISTURE

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ABSTRACT

While venting glazed spandrels is cited to be a benefit to control heat buildup, several instances of spontaneous glass breakage in spandrel insulated glazing units, attributed to thermal stress, have been reported in vented spandrel cavities used with an opacifier on the inside glass surface. The implication is that if venting is not an effective solution to reduce thermal stress and the associated need for higher strength glass, then it is desirable not to vent to avoid dirt buildup on the inside glass surface as it cannot be cleaned. The benefit of venting or weep holes must also be evaluated in terms of condensation risk and damage.

The objective of this paper is to address questions related to the real need to vent spandrel sections to control heat buildup. This paper covers a field study that includes monitoring spandrel sections with a combination of single- and double-glazing, three different venting scenarios, and both clear- and opacified-glass scenarios. The data collected will be used to calibrate 3-D thermal and CFD simulations. The computer simulations will allow for cross-validation of the field monitoring data and broaden the relevance of the findings through the investigation of other conditions including different spandrel designs, venting scenarios, and climates.

The field monitoring suggests that venting the spandrel cavity has little to no impact on reducing thermal stress in clear-glass double-glazed spandrel sections, and a limited impact in clear-glass single-glazed spandrel sections. With the higher solar absorption associated with an opacifier coating, venting shows even less impact on reducing thermal stress, with some data suggesting an adverse effect. Also, in the temperate climate of this field study, the condensation risk was found to be very low regardless of the venting configuration. Based on these preliminary results, there is reason to question the need to vent double-glazed spandrel sections. The 3-D thermal and CFD model is currently being calibrated and findings will be presented in a subsequent paper. Preliminary simulations results show good agreement with the field monitoring data.

INTRODUCTION

Insulated glazing units are increasingly being used in spandrel assemblies either in shadow box installations or with an opacifier on the 4th surface to provide some depth in appearance. There have been several recent instances of glass breakage in insulated glazing units in spandrel applications in the USA and Canada on the west and east coasts as well as in Russia and Germany (Arztmann 2016). Breakage has been attributed to excessive thermal stress, in both sealed and vented cavities. An example of such glazing failures in spandrel insulated glazing units is shown in Figure 1 below.

Figure 1: Example of Glazing Failures Attributed to Thermal Stress in Spandrels Insulating Glazing Units

Anecdotal information and some research are available to support the theory that the glass is breaking in relation to thermal stress due to strength reduction in the heat-strengthened glass resulting from the application of ceramic frit to opacify the glass (Maniatis and Elstner 2016, Vockler et al. 2017) especially when compared to silicone opacifiers. This raises a question about the effectiveness of venting the spandrel cavity to control heat build-up and control moisture when using an insulated glazing unit in spandrel applications. The benefit of providing venting to control thermal stresses is not easily quantified nor is its viability as a practical solution that does not require higher strength glass for the inner lite for this type of spandrel design.

The implication for shadow-box designs is that if venting does not reduce the risk of glass breakage, then it is desirable not to vent to avoid dirt buildup on the inner surface of the clear glass that cannot be cleaned. Nonetheless, the risk of condensation on the inner surface and possible streaking must also be assessed when evaluating the benefit of venting spandrels.

This paper presents the findings of a field study that explored the impact of venting glazing spandrels sections to control heat build-up and moisture. The field study consists of monitoring spandrel sections exposed to natural conditions that will be used to calibrate 3-D thermal and computational fluid dynamics (CFD) simulations.

The field monitoring includes spandrels with a combination of single- and double-glazing, three different venting scenarios, and both clear- and opacified-glass scenarios. The field monitoring will provide data to calibrate computer simulations that will provide further insight into the impact of discrete parameters that are part of the experimental data. The simulations will be undertaken to broaden the relevance of the findings to other conditions, such as different spandrel designs, venting scenarios, climates, and shadowing of the glass.

Thermal Stress in Spandrel Glass

The main focus of this field study is to validate the benefit of venting the spandrel cavity behind an insulated glazing unit as a way to prevent excessive thermal stress from occurring in the glass. A number of factors

affect thermal stress in spandrel glass including various environmental factors and the quality and properties of the glass (PPG 2008, AGGA Glass and Glazing Association of Australia 2011).

Thermal stress in glass is due to a temperature difference between one part of the glass compared to another part. In the case of spandrel glass as installed in a spandrel section of a building, this temperature difference is caused by solar energy heating the field of the glass, while the glass edges shadowed by the frame remain cooler. The expansion of the heated glass center then results in tensile stress at the edge of the glass, potentially leading to breakage if the thermal stress exceeds the ultimate strength of the glass. These effects are intensified in the closed cavity of spandrel assemblies.

As the speed and magnitude of the temperature increase in the glass are directly related to the solar radiation absorption properties of the glass, coating types, such as low-e and reflective, coating location, as well as glass tint, will contribute to increasing thermal stress whenever their application result in a glass unit that is more absorbing to solar radiation.

Different glass types can accommodate different maximum temperature differences and, depending on the calculation method and source (Haldimann et al. 2008, European Window Film Association 2012, Saint-Gobain 2013), values can be found ranging from 28°C up to 40°C for annealed glass, from 56°C up to 100°C for heat strengthened glass, and from 111°C up to 250°C for tempered glass.

FIELD MONITORING

In order to test the effectiveness of venting spandrel sections to control heat build-up, an experimental setup was designed such that three different spandrel installation configurations corresponding to three different venting strategies are exposed to natural conditions in the temperate marine climate of Burnaby, BC. The three venting strategies considered are as follows:

1) "Sealed" or unvented configuration
2) "Drained" configuration corresponding to drainage weep holes at the bottom of the spandrel cavity
3) "Vented" configuration corresponding to top and bottom venting of the spandrel cavity

The hypothesis is that if venting is an effective approach to reducing thermal stress in spandrel sections, then the magnitude of glass temperature differences observed for the vented configuration would be expected to be significantly less than that of the sealed configuration, with the drained configuration falling somewhat in between as less airflow in the cavity is expected when compared to the vented configuration.

The experimental setup consists of two modules positioned side-by-side, one module being equipped with single glazing while the other module is with double-glazed insulated units, each module comprising three spandrel sections corresponding to the three venting strategies previously mentioned. Two smaller, standard opacified spandrel sections were added on each side of the two modules, as well as a small roof, to shield the tested sections from possible edge effects.

For each single and double glazing unit installed, two types of glass were considered and tested sequentially: clear glass, and an opacified glass with a dark-blue Opaci-coat-300 on the inner pane. The opacified glass having a higher solar absorptivity as compared to the clear glass, it is expected that larger glass temperature

differences would be observed. All glass panes are 778 millimeter tall by 540 millimeter wide, 6 millimeter thick, and heat-strengthened, with a 13.4 millimeter air space for the double-glazed insulated units. A dry glazed captured system was used, except for the single-glazed sections that relied on a wet seal on the inside.

The spandrel mockup was installed facing 16° west of south. It was instrumented and monitoring started on April 2016 and is ongoing as of September 2017. Readings have been recorded every 20 minutes for each sensor. The following measurements have been made:

1) Inner glass surface temperature at several locations inside each spandrel cavity including at the center of glass, top and bottom edges, side edges, and bottom corner edge
2) Glass surface temperature on the outside at the center of glass
3) Backpan temperature
4) Air temperature inside each spandrel cavity including at the top, bottom, and center of glass
5) Relative humidity inside each double glazed spandrel cavity at the center of glass
6) Outdoor air temperature and relative humidity
7) Outdoor solar irradiance

Figure 2 below shows the experimental setup with the sensors locations for the double glazed module as well as the curtain wall profile used in all spandrel sections.

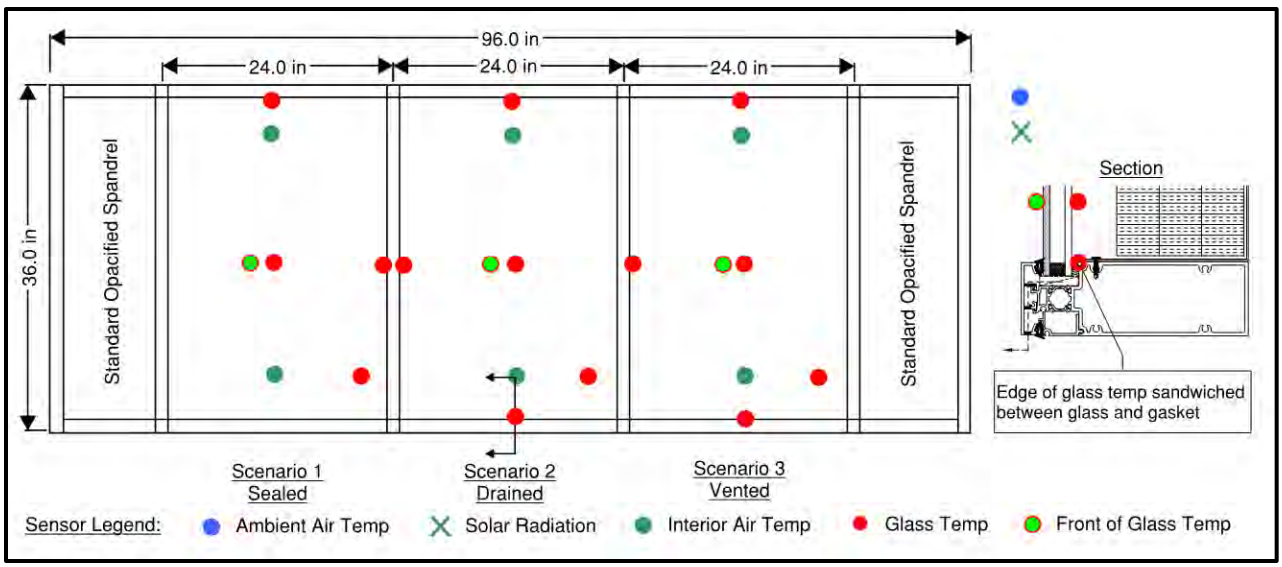

Figure 2: Experimental Setup Showing Sensors Locations

Figure 3 below shows the installed mockup with southern exposure. The 4.5 inches of mineral wool backpan insulation can be seen along with the various sensors, including the solar sensor that was installed vertically with the intent of directly capturing the magnitude of the solar fluxes that hit the spandrel sections.

Figure 3: Installed Mockup with Southern Exposure

In Figure 4 below, the spandrel mockup is shown with the dark-blue Opaci-coat-300 installed on the inner pane of glass.

Figure 4: Installed Mockup with Opacified Glass Installed

With the pressure plates removed in order to display the gaskets, the air pathways through the 1-inch gaps in the gaskets can be seen in Figure 5 below: no gaps for the sealed configuration as shown in Figure 5a, two gaps at the bottom for the drained configuration as shown in Figure 5b, and two gaps at the top and two gaps at the bottom for the vented configuration as shown in Figure 5c.

(a) **(b)** **(c)**

Figure 5: Air Pathways for the Three Tested Configurations (a) Sealed, (b) Drained, and (c) Vented

RESULTS

This section describes the results, analysis, and discussion of the monitoring data gathered between April 17, 2016 and June 15, 2017. Monitoring of the spandrel mockup started on April 17, 2016 with clear glass installed. On September 24, 2016 both the single- and double-glazed modules were re-glazed with opacified glass with a dark-blue Opaci-coat-300 on the inner pane. Monitoring is ongoing as of September 2017.

Glass Temperature Difference, Magnitude and Frequency of Occurrence

To assess the impact of venting strategies on glass thermal stress and therefore on glass temperature difference, the recorded data was processed such that the differences between the temperature at the center of glass and the temperature at each monitored location on the edge of glass were computed for all points in time over the total monitoring period, for all three venting configurations, for both single- and double-glazed modules, and for both clear and opacified glass scenarios.

Table 1 below presents the largest glass temperature differences found from the aforementioned calculation and their corresponding locations.

Table 1: Location and Magnitude of Maximum Glass Temperature Difference with respect to Center of Glass

Glass Type	Venting Strategy	Maximum Glass Temperature Difference, Centre of Glass – Specified Location			
		Double-Glazed Module		Single-Glazed Module	
		Max ΔT	Location	Max ΔT	Location
Clear	Sealed	34.3	Top Edge	24.7	Top Edge
	Drained	38.5	Bottom Edge	22.5	Top Edge
	Vented	30.4	Top Edge	21	Bottom Edge
Opacified	Sealed	42.6	Top Edge	34.5	Top Edge
	Drained	46.9	Top Edge	35.3	Bottom Edge
	Vented	53.3	Bottom Edge	39.5	Bottom Edge

For both the clear- and opacified-glass scenarios, the maximum glass temperature difference was significantly higher in double-glazed configurations confirming that these applications can be expected to result in higher thermal stress than in the traditional single glazed spandrels.

For the clear double-glazed module, the maximum glass temperature difference for the vented configuration was found to be about 11% less than for the sealed configuration, while for the drained configuration the maximum glass temperature difference was found to be about 12% more than for the sealed configuration. For the clear single-glazed module, the maximum glass temperature difference for both drained and vented configurations were found to be less than for the sealed configuration, at about 9% and 15%, respectively.

For the opacified-glass scenario, as expected from switching from clear glass to one with a dark blue opacifier, larger glass temperature differences were recorded, for both double- and single-glazed modules. However, contrary to what was found for the clear glass scenario, both double- and single-glazed modules exhibited larger glass temperature differences for the drained and vented configuration than for the sealed configuration. Specifically, for the opacified double-glazed module, the maximum glass temperature difference for the drained and vented configurations were found to be more than for the sealed configuration by about 10% and 25%, respectively, while for the opacified single-glazed module, the maximum glass temperature difference for the drained and vented configurations were found to be more than for the sealed configuration by about 2% and 14%, respectively.

Moreover, some of these maximum temperature differences between center and edge of glass, in particular what was observed for the opacified double-glazed vented configuration, approach the low end of the range of temperature differences where the risk of glass breakage can occur.

Next, glass temperature differences between the center of glass and top edge of glass were plotted for one sunny day and one day with a mix of sun and clouds for all three venting strategies for both the single- and double-glazed modules, as shown in Figure 6 below. The selected days are representative of the patterns generally observed and were chosen so that data was available for both the clear and opacified-glass scenarios, and exterior ambient conditions were comparable in terms of solar irradiance and air temperature.

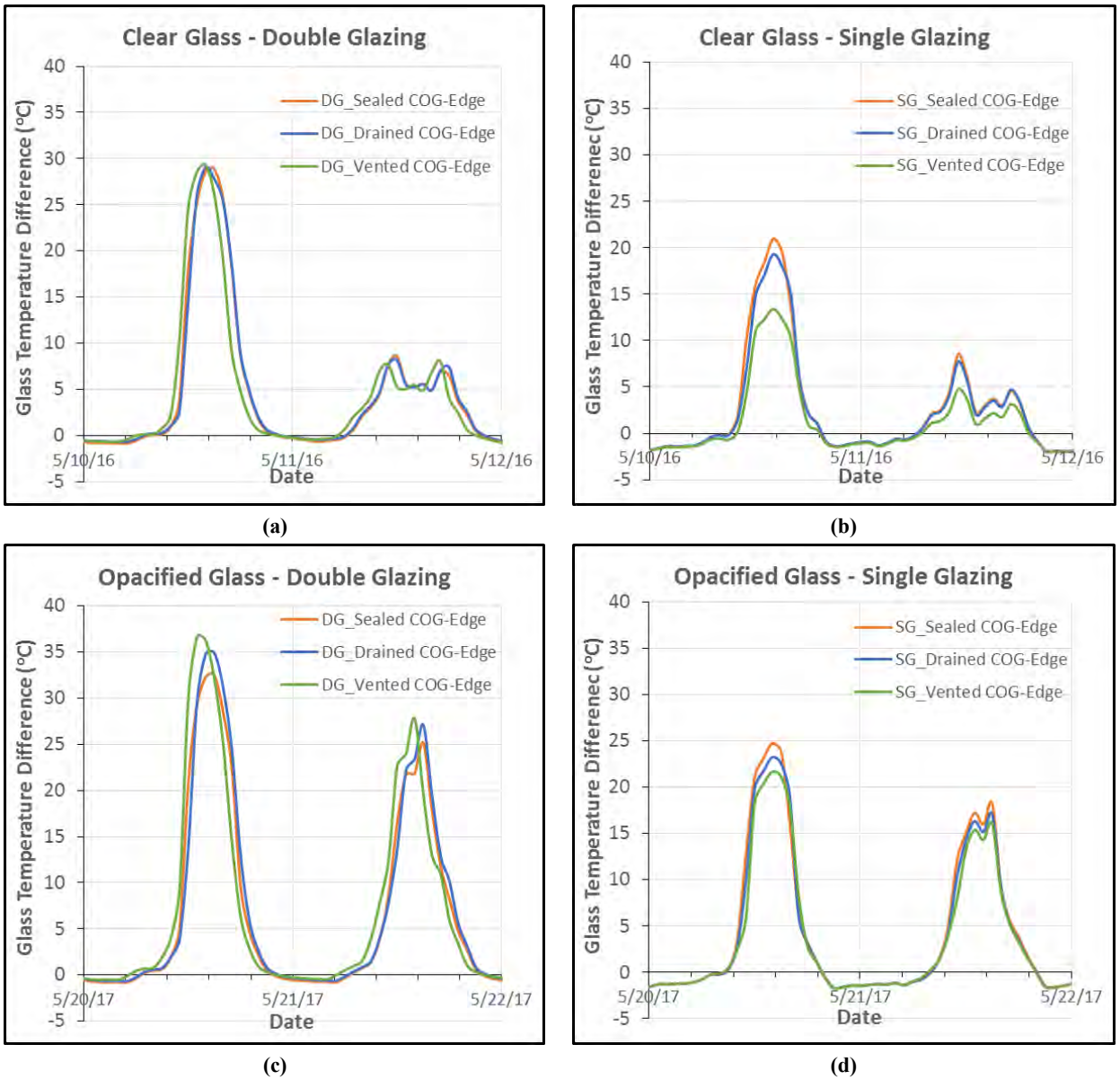

Figure 6: Sample Data Plot Showing Glass Temperature Difference between the Centre of Glass and Edge of Glass for (a) Double Glazed Module with Clear Glass, (b) Single Glazed Module with Clear Glass, (c) Double Glazed Module with Opacified Glass, and (d) Single Glazed Module with Opacified Glass

Again, overall, larger glass temperature differences can be seen for the opacified-glass scenario compared to the clear-glass scenario, as expected.

For the clear-glass double-glazed scenario, contrary to the trend observed when analyzing maximum glass temperature differences, no reduction in amplitude can be seen between the vented, drained, and sealed configurations. For the opacified-glass double-glazed scenario, however, a similar trend to what was observed when analyzing maximum glass temperature differences can be seen, whereby the vented configuration sees a larger amplitude than the drained configuration, and the drained configuration sees a larger amplitude than the sealed configuration.

Now focusing on the clear-glass single-glazed scenario, a similar trend to what was observed when analyzing maximum glass temperature differences can be seen, such that there is a reduction in amplitude between the

drained and sealed configuration, and a further reduction for the vented configuration. For the opacified-glass single-glazed scenario, a similar albeit attenuated behavior can be observed, contrary to the trend observed when analyzing maximum glass temperature differences where the drained and vented configurations maximum glass temperature differences were found to be more than for the sealed configuration.

This would indicate that the typical benefits of venting single-glazed spandrel do not extend to double-glazed spandrel assemblies, which could impact the design of these insulated glazing units.

Next, the temperature differences between the center of glass and top edge of glass were computed for all points in time over the total monitoring period and divided by the total number of days observed, for all venting configurations, for both single- and double-glazed modules, and for both clear and opacified-glass scenarios. Table 2 below presents the aggregated results from the aforementioned calculation such that the frequency at which a given spandrel section experienced a glass temperature difference within a certain range can be evaluated.

Table 2: Glass Temperature Difference between the Center of Glass and Top Edge of Glass and Frequency of Occurrence

Glass Type	Venting Strategy	Glass Temperature Difference, Centre of Glass – Top Edge of Glass, % of Total Observed Time									
		Double-Glazed Module					Single-Glazed Module				
		Above 40°C	Between 30 - 40°C	Between 20 - 30°C	Between 10 - 20°C	Below 10°C	Above 40°C	Between 30 - 40°C	Between 20 - 30°C	Between 10 - 20°C	Below 10°C
Clear	Sealed	0%	0%	44%	27%	29%	0%	0%	32%	45%	24%
	Drained	0%	2%	41%	27%	29%	0%	0%	14%	61%	25%
	Vented	0%	2%	41%	27%	29%	0%	0%	0%	54%	46%
Opacified	Sealed	4%	14%	13%	19%	50%	0%	12%	23%	15%	50%
	Drained	7%	13%	14%	18%	49%	0%	4%	26%	19%	51%
	Vented	6%	14%	13%	18%	49%	0%	0%	28%	18%	54%

Again, overall, larger glass temperature differences can be seen for the opacified-glass scenario compared to the clear-glass scenario, confirming the impact of the more solar-absorbing assembly on thermal stress.

For the clear-glass double-glazed scenario, the data shows that both the drained and vented strategy had little to no impact on reducing either the amplitude or frequency of glass temperature difference compared to the sealed configuration, with some data even suggesting an adverse effect. The data shows that a similar conclusion can be drawn for the opacified-glass double-glazed scenario.

For the clear-glass single-glazed scenario, the data shows a significant reduction in both amplitude and frequency for the drained strategy compared to the sealed configuration, with further reduction for the vented strategy. Switching to the opacified-glass single-glazed scenario, similar trends can be seen, although to a lesser extent than the clear-glass scenario. The drained strategy reduced both the amplitude and frequency of glass temperature difference compared to the sealed configuration, with the vented strategy seeing slightly further reduction in both amplitude and frequency.

This would confirm that there is benefit in venting single-glazed spandrel assemblies but that these benefits do not extend to spandrel assemblies with insulated glazing.

Glass Temperature Difference, Solar Irradiance, and Exterior Ambient Temperature

Besides comparing the impact of the three venting strategies, the recorded data also allows for the analysis of the impact of environmental factors on glass temperature difference and therefore thermal stress. Figure 7 shows recorded data of exterior ambient temperature, solar irradiance, and glass temperature difference between the center of glass and top edge of glass for the clear-glass double-glazed sealed configuration, plotted for a period range between August 10 and September 24, 2016.

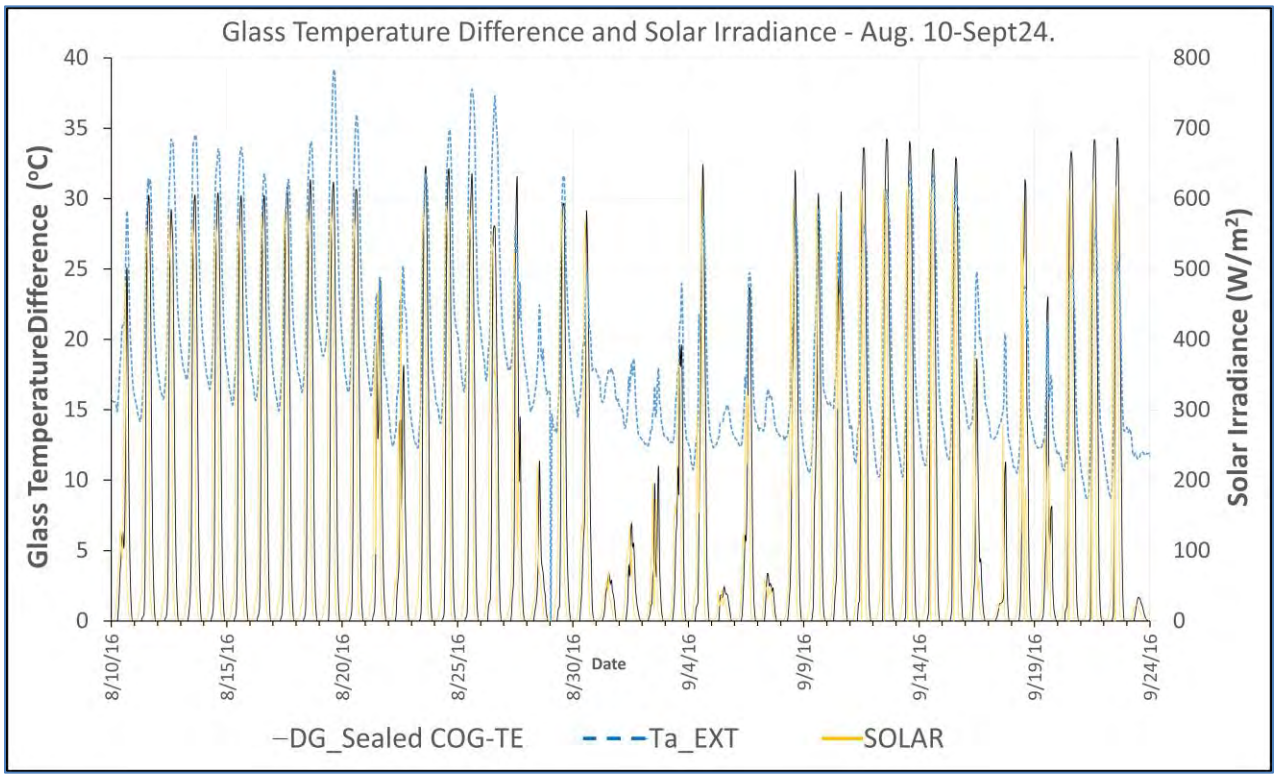

Figure 7: Glass Temperature Difference, Solar Irradiance, and Outdoor Temperature from Aug. 10 to Sept. 24 2016

One observation from this graph is that there is no heat build-up overnight. Moreover, the glass temperature difference curve and peaks follow closely the solar irradiance, whether on a sunny clear day or on a cloudy or rainy day. Also, higher glass temperature difference can be seen in the month of September compared to August, with slightly higher solar irradiance (around 600 W/m^2 compared to around 580 W/m^2) and lower exterior ambient temperature (between 25°C and 30°C compared to around 35°C). Similar behavior can be observed for the drained and vented configurations, as well as for the single-glazed module. With the more solar-absorbing assembly, this behavior is amplified. It should be noted that the highest glass temperature differences were recorded in late September for the clear-glass scenario – recall that the monitoring period for the clear-glass scenario ran from April to September – and in February and March for the opacified-glass scenario, on clear sunny days with relatively low exterior ambient temperatures. In both cases, the time of the year is when the sun is lower than in summer, so the angle of incidence relative to the spandrel sections is lower and therefore more direct solar radiation reaches the glass.

Condensation Risk

Condensation occurs on a surface when its temperature is lower than the dew-point temperature of the

surrounding air. For the double-glazed module, the relative humidity and air cavity temperature were tracked at the center of glass, therefore the air dew-point temperature can be derived. To assess the risk of condensation, for all points in time over the total monitoring period and for all three venting configurations, the air-cavity dew-point was compared to all inside surface temperature measurements. For all three venting configurations, as the inside surface temperatures remained above the inside dew-point temperatures at all times, it can be inferred that no condensation occurred. The recorded data will be used to calibrate computer simulations that will allow to further explore moisture-related issues, as mentioned in the next section below.

Condensation was observed on several occasions on the exterior glass surfaces, so the condensation potential on the exterior glass surfaces was subsequently checked by following the method described above, by comparing the measured exterior glass surface temperatures to the exterior ambient dew-point temperatures calculated from the exterior ambient temperatures and relative humidity data. The results of this calculation were found to agree with the visual observations.

SIMULATIONS

To test the experimental setup and validate to real world conditions, modeling of the glazed spandrel sections involves capturing the effects of the mockup characteristics:

1) Complex geometry with intricate material connections
2) Complete physics with heat transfer processes including conduction through materials, radiation, and explicit flow and solar
3) Time-varying environmental conditions including air temperature, wind speed and direction, and solar flux intensity and direction

The 3-D thermal and CFD model is currently being calibrated using data from the field monitoring, and the findings from the 3-D finite element analysis will be discussed in a subsequent paper.

The preliminary results presented below relate to cross-validation of the field monitoring and were obtained using a 3-D model of one spandrel section with simplified geometry. As transient 3-D thermal and CFD simulations of one complete spandrel module are computationally very heavy, the intent with using a simplified geometry was to lower computation time while still capturing the physics and time-varying environmental conditions of the spandrel section. Figure 8 below shows recorded temperature data for the center of glass and top edge of glass, as well as temperature difference between the center of glass and edge of glass, for the sealed clear-glass double-glazed scenario on May 10, 2016, plotted versus simulated results obtained from the simplified model.

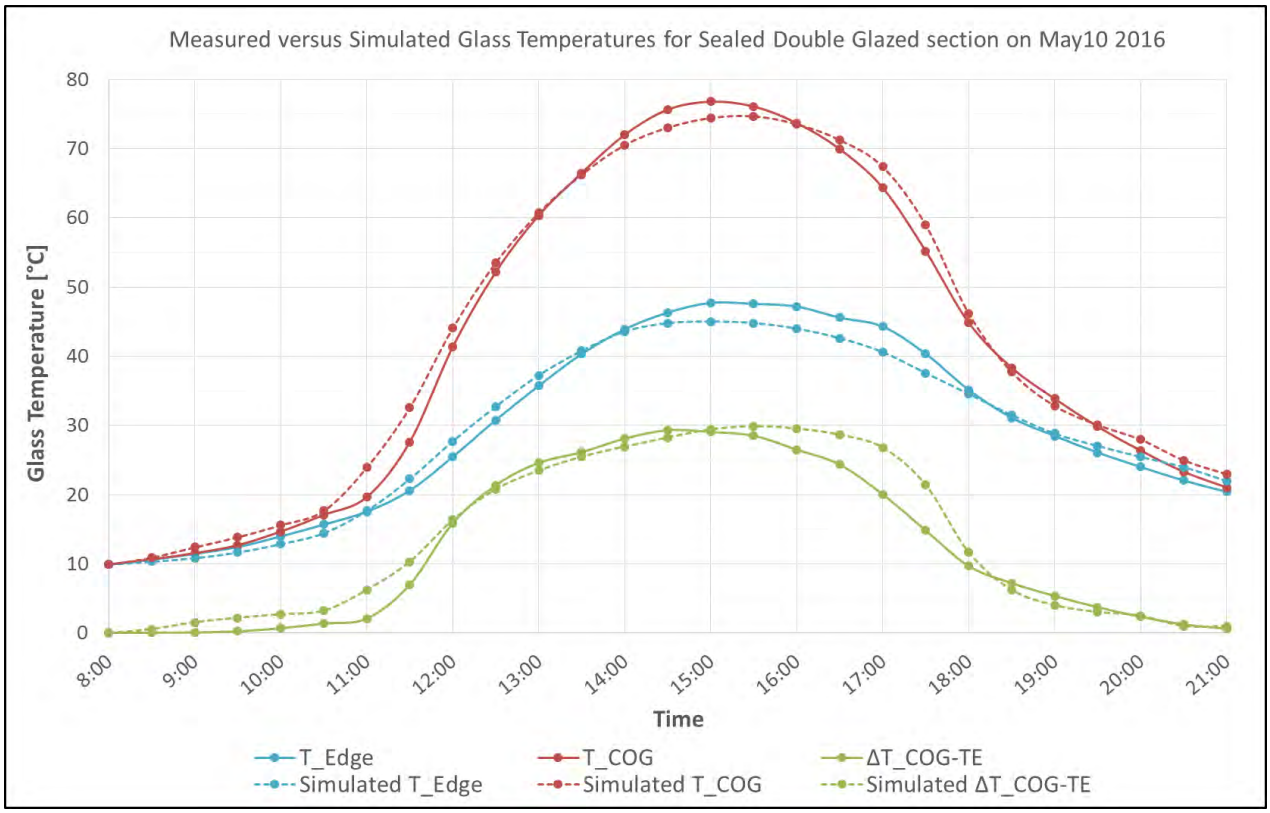

Figure 8: Measured versus Simulated Glass Temperatures for Sealed Clear-Glass Double-Glazed Scenario on May 10 2016

Overall, the simulated results show good agreement with the field monitoring data. Misalignment between the simulated results and the field monitoring data can be mostly attributed to geometry simplification, calculation time step and averaging, and uncertainty with local wind data as the glass convective heat transfer coefficient to the exterior is directly derived from wind speed and direction with respect to the system. For the deviation observed between 11:00am and 12:00pm, for instance, too large of a time step caused a dip in solar flux intensity not to be taken into account in the calculation due to averaging out with the subsequent higher value.

Better correlation is expected to be achieved using more detailed geometry and a complete spandrel module, as well as shorter time steps that more closely follow the fluctuations in environmental boundary conditions of the system. Then, questions related to the impact of different spandrel designs, glass types, venting scenarios, climates, shadowing of the glass, and condensation will be explored.

CONCLUSION

The findings from the field monitoring suggest that, while there is some benefit of venting single-glazed spandrel assemblies, these benefits do not extend to double-glazed spandrels. Venting the spandrel cavity appears to have little to no benefit on reducing thermal stress in clear-glass double-glazed spandrel sections. With more solar-absorbing assemblies, venting shows even less impact on reducing thermal stress, with some data suggesting an adverse effect. Also, the condensation risk for double-glazed spandrel assemblies was assessed and found to be very low regardless of the venting configuration. Moisture-related issues will be further explored using computer simulations.

The initial findings demonstrate that double-glazed spandrel assemblies perform differently from traditional single-glazed spandrels. Double-glazed assemblies can be exposed to significantly higher temperatures that may approach the lower range of temperatures where there is a risk of breakage with heat-strengthened glass.

Limitations of this study include some inconsistency in the measurements due to some sensors malfunctions, the inherent uncertainty linked to the exposure of variable and dynamic outdoor conditions, at grade exposure as opposed to exposure at high elevations on a building, and potential edge effects from the spandrel sections being positioned side-by-side and from having the top and bottom of the frame being exposed to outdoor conditions.

Preliminary results from simulations using simplified geometry show good agreement with the field monitoring data. Next steps consist in 3-D thermal and CFD modeling of the full spandrel mockup to cross-validate the field monitoring data. The simulations will also provide insight into the factors impacting spandrel glass thermal stress, as well as broaden the relevance of the findings through the investigation of other conditions including different spandrel designs, venting scenarios, climates and shadowing of the glass. The findings from the 3-D finite element analysis will be presented in a subsequent paper.

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