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PNNL-33380

Evaluation of the Thermal and Moisture Performance of Insulating Shades

September 2022

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

Heat transfer through windows accounts for a significant percentage of a building's energy use and adds substantially to the peak heating and cooling loads of a home. Insulating cellular shade interior window attachments have the ability to improve window thermal resistance to heat transferring to the outdoors during the winter heating season as well as resistance to heat transferring in through the window during the summer cooling season. During the winter when the window is fully covered, however, the added insulation reduces the amount of warm indoor air that reaches the window surface, thereby lowering the temperature of the window glass and frame and increasing the potential for condensation to collect on the interior surface of the window. To examine the degree to which insulating shades affect the condensation buildup on the interior surface of the window, as well as the conditions under which this occurs, the U.S. Department of Energy (DOE) sponsored research carried out by Pacific Northwest National Laboratory (PNNL) and Hunter Douglas involving a series of experimental condensation tests conducted in a controlled environmental test chamber at the Hunter Douglas facility in Broomfield, Colorado.

Condensation occurs when the surface temperature of a window component drops below either the dew point or frost point of the air adjacent to the surface. In cold climates, single-glazed windows and many double-pane lower-performing windows will characteristically suffer from water condensation and the formation of frost on the inside surface of the glass in winter, especially when humidity levels in the home are relatively high. The testing results presented in this report demonstrated that although the application of insulating coverings, such as cellular shades, can increase the potential for moisture to condense on the surface of the glass, several mitigation strategies demonstrated that this potential drawback could be effectively addressed without significantly reducing the thermal efficiency and comfort benefits drawn from the application of thermally insulating shades. Based on the results of the field testing presented in this report, the following recommendations were made regarding the use and operation of insulating shades:

1. **Open shades during the daytime during the heating season.**

   If possible, do not keep cellular shades closed during all hours, especially during the heating season. Open cellular shades during the daytime to allow condensation to dry and allow in beneficial heat gains through the window. This not only reduces the potential for condensation buildup but is consistent with the recommended operation of shades for efficiency based on guidance from the window Attachments Energy Rating Council. Any condensation that collects on the sill that does not evaporate should be wiped from the window's surface at least every few days.

2. **If shades are required to stay closed throughout the day, raise the shade's bottom rail a 0.5 inch from the windowsill.**

   Raising the shade from the bottom rail windowsill by a 0.5 inch should effectively reduce the amount of condensation that builds up on the surface of the window and sill, while maintaining a majority of the shade's insulating value and preserving privacy.

3. **Install better windows or attach insulating secondary window panels.**

   The results of this study suggest that when condensation collects on the interior surface of windows and sills, multiple factors are likely contributing to this problem, including the overall performance of the window and the humidity level of the home. When condensation occurs with the application of shades, the problem is not exclusive to the shades, but could be more

pronounced with cellular shades due to the highly insulating nature of this window attachment. With code-minimum windows installed in cold climates, condensation formation can occur with any window attachment that blocks a window's radiative transfer within the indoor environment. With windows that are below code, this problem is even worse. On the coldest days, this condensation buildup can even occur without the application of shades or blinds, especially with poor-performance windows and high humidity in the home. This problem can be solved in two ways: (1) by reducing indoor humidity levels, or (2) by installing better windows or adding an energy-efficient secondary window panel (i.e., storm window or interior panel insert). Because of the complexities involved with local climatic conditions; HVAC system type, sizing, and venting; and human health impacts, the authors of this study do not advocate for lowering indoor relative humidity levels as a condensation mitigation strategy, except in situations in which indoor humidity levels are extremely high due to improper airtightness levels or improper HVAC operation. The most logical means of addressing condensation formation in cold and very cold climates is to improve the performance of the window by either installing above-code (e.g., triple-pane) fenestration products or by applying thermally efficient secondary glazings over the primary windows in cold and mixed-cold climates.

The testing also demonstrated that condensation is only seen when environmental conditions allow, so when these conditions are not met insulating shades are able to provide their full benefit with no negative impacts. The number of nights a year when cellular shades will provide their full savings is likely much more than the number of nights some savings will need to be sacrificed to mitigate for condensation

Acknowledgments

The project team gratefully acknowledges Hunter Douglas for providing the use of its environmental test chambers for the experiments and the U.S. Department of Energy (DOE) Building Technologies Office for funding this research. The authors also thank Marc LaFrance, DOE project manager, for his technical guidance.

In addition, the authors thank Mahabir Bhandari of Oak Ridge National Laboratory (ORNL) for providing technical guidance related to the experimental design and test plan. Finally, the authors thank Stacy Lambright from Hunter Douglas, Charlie Curcija from Lawrence Berkeley National Laboratory (LBNL), and Patrick Huelman from the University of Minnesota for their review of the experimental plan and analysis.

Acronyms and Abbreviations

AERC	Attachments Energy Rating Council
Btu	British thermal unit(s)
CU	condensing unit
d	day(s)
DOE	U.S. Department of Energy
°F	degrees Fahrenheit
ft	foot (feet)
hr	hour(s)
HVAC	heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
LBNL	Lawrence Berkeley National Laboratory
NFRC	National Fenestration Rating Council
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RH	relative humidity
yr	year(s)

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1.0 Introduction

Residential buildings in the United States currently require 8 quads of energy per year for heating and cooling. That accounts for more than 40 percent of primary residential energy use (DOE 2018). Heat transfer through windows accounts for a significant percentage of a building's energy use and adds substantially to the peak heating and cooling loads of a home. Over the past 20 years, residential window attachment retrofit technologies have been developed that significantly increase the number of options available to home builders, homeowners, and utilities when considering upgrades of overall window performance. In the U.S. market, interior products are often referred to as window coverings, treatments, or attachments; they can include blinds, shades, drapes, shutters, panels, and films. Within the interior window coverings category, honeycomb cellular shades (see Figure 1) typically have the highest R-values because of their layered or concentric designs.

From an energy efficiency and comfort perspective, the added insulation makes cellular shades an ideal year-round window covering, because these coverings provide thermal resistance to heat transferring to the outdoors through the window during the winter heating season as well as resistance to heat transferring in through the window during the summer cooling season. During the winter when the window is fully covered, however, the added insulation reduces the amount of warm indoor air that reaches the window surface, thereby lowering the temperature of the window glass and frame and increasing the potential for condensation to collect on the interior surface of the window. The degree to which this potential is realized depends on the indoor and outdoor conditions as well as the overall thermal resistance of the window and the shades. To examine the degree to which insulating shades affect the condensation buildup on the interior surface of the window, as well as the conditions under which this occurs, this report describes experimental research conducted in a controlled environmental test chamber at the Hunter Douglas facility in Broomfield, Colorado.

This research was conducted for the U.S. Department of Energy (DOE) Building Technologies Office and the Attachments Energy Rating Council (AERC) in collaboration with Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and Hunter Douglas. AERC is an independent, nonprofit, rating council that has developed a comprehensive energy-rating, labeling, and certification program for window attachments, including cellular shades and other shading products. AERC strives to provide accurate and credible information about the energy performance of rated products.[1]

[1] More information about the range of window attachments available and slated for energy ratings can be found at the AERC website: https://aercenergyrating.org/.

2.0 Background

In 2013, DOE sponsored a comprehensive energy modeling study led by Lawrence Berkeley National Laboratory that focused on a range of window attachments, including products such as shades, blinds, storm window panels, and surface-applied films simulated in four types of "typical" houses located in 12 characteristic climate zones. The simulations captured the optical and thermal complexities of these products (Curcija et al. 2013) and also considered typical operation and usage patterns based on a separate study that focused on user behavior with respect to how window coverings are operated (Bickel et al. 2013). The studies concluded that with appropriate operation, high-efficiency window coverings such as insulated cellular shades can significantly help minimize heat losses during the winter and heat gains during the summer and can decrease the overall annual home energy use. To help inform consumers of these energy-saving benefits and address the lack of standards and ratings for window coverings, DOE helped launch the AERC in 2014. As of 2020, AERC has energy ratings available for both interior and exterior storm windows (also known as insulated window panels or secondary glazing), cellular shades, roller shades, pleated shades, roman shades, and solar screens, and plans to develop energy ratings for other window attachment categories in the future.

2.1 Insulating Shades

Within the interior window coverings category, honeycomb cellular shades (see Figure 1) typically have the highest R-values because of their layered or concentric designs. Introduced in the 1980s, cellular shades are designed to trap air inside pockets that act as insulators. This design can increase the R-value of the window covering and reduce the conduction of heat through the window that it covers. Insulating shades can also affect solar heat gains if managed properly; the insulating air pockets can also be lined with a metalized layer, which minimizes conductive and radiant heat transfer, similar to the effect that a low-emissivity coating has on windows.

Figure 1. Room-darkening cell-in-cell cellular shade.

The thermal insulating performance of cellular shades has been thoroughly tested under a range of operating scenarios in PNNL's experimental Lab Homes (Petersen et al. 2015; Cort et al. 2018) and ORNL's Single Family Home Testing facility (Bhandari et al. 2021). The testing demonstrates both cooling and heating savings; optimal heating savings occur when the shades are closed during the evenings and opened during the daylight hours (Cort et al. 2017). A PNNL modeling study of three prototype homes in 13 U.S. climate zones (Metzger et al. 2017) demonstrated year-round heating, ventilation, and air-conditioning (HVAC) savings from the application of cellular shades ranging from 10 percent to 34 percent, which included the cold climate zones of Denver, CO, Minneapolis, MN, and Fairbanks, AK. The AERC database of certified products also demonstrates a positive "Cool Climate" energy performance rating for all cellular shade products included in the database.[1]

2.2 Psychometrics

Condensation formation on windows is a complex problem that can be caused by a variety of environmental factors. Most of these factors are directly related to temperature and humidity in the gaseous mixture that is air. The study of the thermophysical properties of air is called psychometrics, which is a field pioneered by Willis Carrier with his invention of the first air conditioner in 1904 (Simha 2012). For this application, three relevant terms from the field of psychometrics can be used to evaluate condensation formation: (1) dry-bulb temperature, which is the absolute temperature of air independent of moisture; (2) relative humidity (RH), which is a ratio of the amount of water in the air compared to the total water carrying capacity of air at that given dry-bulb temperature; and (3) dew point temperature, or saturation temperature, which is the temperature at which air of a certain temperature and RH must be cooled for condensation to form. Each of these terms can be visualized via the psychometric chart in Figure 2.

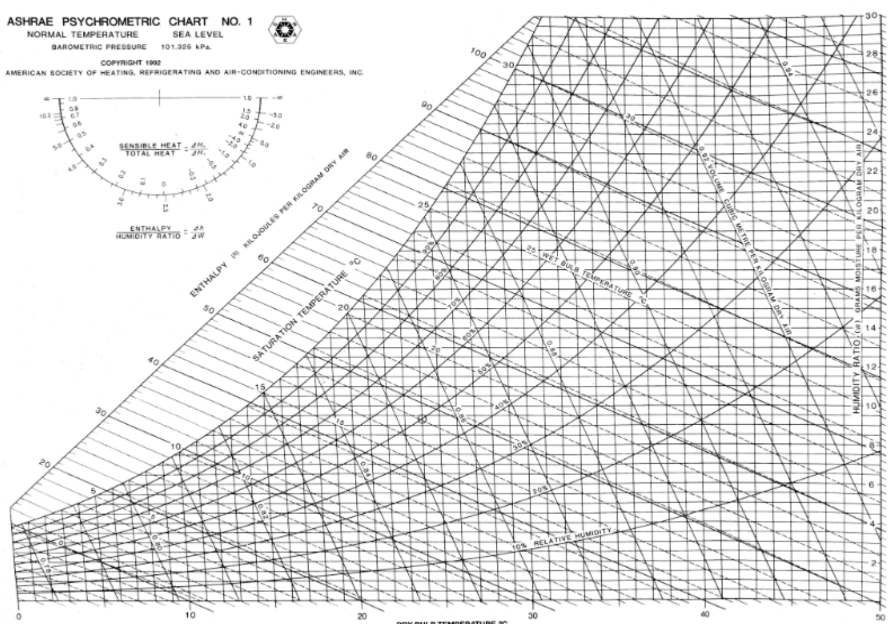


Figure 2. The Carrier psychometric chart (ASHRAE 2003).

[1] See website https://aercenergyrating.org/product-search/residential-product-search/ for product specifications. It is also noted that forthcoming AERC shade automation ratings (expected early 2023), which consider improved performance with automated operation schedules, would increase shade energy performance ratings reported in the database, which are based on manual operation assumptions.

The concepts of dewpoint, dry-bulb, and RH are displayed in Figure 2. Dew point temperatures can be determined graphically by finding the intersection of the dry-bulb temperatures with the RH curve and drawing horizontal lines to find the intersection with the saturation curve. For most practical uses, ASHRAE Fundamentals also provides equations to compute dew point temperatures from a given dry-bulb temperature and RH combination (ASHRAE 2003).

2.3 Why Condensation Forms on Windows

Because of the year-round insulating thermal performance of cellular shades, demonstrated in both field validation studies and AERC's rating specifications (see Section 2.1 above), cellular shades would presumably be a strong candidate for energy efficiency measures for utilities and other efficiency programs in all climate zones. As of 2020, however, only Xcel Energy in Colorado has consumer incentives for an insulating shade measure[1] focused on AERC energy-rated cellular shades. Although several other utilities have expressed interest in the product, some utility program managers in cold climate zones have expressed concern that these thermally insulating shades may increase the condensation buildup potential on the surface of the window, which could result in unintended negative consequences, such as window frame degradation and mold.

Taking the summary introduction to psychometrics from Section 2.2 into account, condensation occurs when the surface temperature of a window component drops below either the dew point or frost point of the air adjacent to the surface. In cold climates, single-glazed windows and many lower-performing double-glazed windows will characteristically suffer from water condensation and the formation of frost on the inside surface of the glass in winter. Because excessive condensation can contribute to the growth of mold or mildew, solving this condensation problem on windows was a major motivation for the development of thermal breaks in aluminum-framed windows (Hart et al. 2015).

With interior window attachments, the condensation potential may increase with the insulating value of the product because the temperature of the glass becomes colder. Condensation potential increases as the outdoor temperatures lower and the indoor RH increases.

[1] https://co.my.xcelenergy.com/s/residential/home-rebates/cellular-shades

3.0 Experimental Design

Condensation testing occurred over an 8-week period at the Hunter Douglas environmental test chamber (see Figure 3). The testing was designed to address the following key experimental questions:

1. Under what combination of conditions (i.e., indoor conditions, outdoor conditions, and thermal insulating conditions of chamber window) does condensation collect on the interior surface of a window?
2. How does the application of insulating shades change the condensation formation on the interior surface of the window?
3. When/if the condensation potential increases with the application of shades, what mitigation strategies (if any) can effectively reduce the amount of condensation buildup on the interior surface of the window?
4. When mitigation strategies are applied, how much do they affect the thermal performance of the window assembly?

The following sections describe the testing platform, testing conditions, and phases of testing.

3.1 Environmental Chamber

Testing occurred at the Hunter Douglas environmental chamber, which is a two-room modular environmental chamber from Bally Refrigerated Boxes, Inc. A photo of the environmental chamber is provided in Figure 3. Environmental chambers are enclosures designed to test the effects of specified environmental conditions. In order to replicate the conditions where condensation on interior surfaces would be most problematic, the “warm-side” of the test chamber was specified to replicate indoor conditions in an occupied heated home, while the “cold-side” was specified to replicate outdoor temperatures in a cold climate.

Figure 3. The two-room environmental chamber used in this study.

Figure 3 shows the two-room environmental chamber, which is a two-room chamber that allows for independent temperature control of each room, allowing for a simulation of in-service environmental conditions. Both rooms can reach temperatures as low as 0°F and as high as 100°F. These chambers were designed for thermal testing of windows, and the window attachments are calibrated for R-value testing. Figure 4 displays two sample windows located within the environmental chamber.

Figure 4. Sample windows installed within the environmental chambers.

One limitation of this environmental chamber is that it was designed specifically for thermal testing. Due to this focus, the chambers are able to maintain temperature independently but do not have the capability to maintain moisture or RH levels. To introduce humidity into the chamber and maintain humidity levels, an Essick Air 7D6-100 evaporative humidifier was installed in the warm-side chamber to maintain RH levels typically associated with indoor conditions.

3.2 Testing Conditions

Because window condensation is known to be a problem that affects homes in cold and very cold climates, testing conditions were designed to replicate the indoor and outdoor conditions of these climates. Representative temperatures, RH levels, and windows were selected accordingly for this study.

3.2.1 Temperatures

Warm-side temperatures were maintained at 70°F to represent a typical winter heating season temperature setting. Cold-side temperatures were selected to be representative of extremes in cold and very cold climates. For this study, the cold-side temperature was conditioned down to 5°F for testing. Comparing this to representative cities in the cold and very cold International Energy Conservation Code (IECC) climate zones, it is suggested that, on average, days that have temperatures below 5°F tend to drop below 5°F for approximately 12.3 hours. These periods with outdoor temperatures below 5°F most likely represent nighttime hours, and warmer temperatures likely occur during daylight hours. Outdoor temperature data for representative cities are presented in Table 1.

Table 1. Representative climatic conditions for cold and very cold climates. Data extracted from TMY3[1] data (DOE 2021).

Representative City	Climate Zone	Climate Zone Designation	Number of Days with Temperatures Below 5°F	Number of Hours with Temperatures Below 5°F
Minneapolis, MN	6a	Cold	28.0	387
Helena, MT	6b	Cold	18.0	188
Duluth, MN	7	Very Cold	54.0	676

3.2.2 Humidity Levels

Indoor RH is a metric that is influenced by a variety of factors. Indoor humidity levels vary drastically based upon climatic conditions but also vary within climate zones based upon factors such as airtightness levels, HVAC system types, HVAC system sizing, ventilation levels, and occupancy levels.

For cold and very cold climates, it is recommended to keep indoor RH levels near 25 percent during the winter to balance comfort and health (Corrin et al. 2018). This humidity level was selected to be representative of indoor conditions within cold and very cold climates within a typical construction.

[1] Where TMY3 = Typical Meteorological Year, version 3.

3.2.3 Window Selection

For testing, an IECC 2021 code-minimum window was selected. The selected window was a double-paned, wood-framed fixed window with a low-emissivity coating, which is representative of a typical new construction window in cold and very cold climates. The U-factor of the installed window was 0.30 BTU/hr-ft^2-°F.

3.2.4 Shade Selection

For testing, the Hunter Douglas Duette Architella Elan Room-Darkening shade with ¾-inch pleats was selected as a representative cellular shade. This shade was selected for its cell-in-cell construction and room-darkening capabilities, representative of a typical cellular shade that would be found in a residential home. The shade used for testing had a “Top-Down, Bottom-Up” feature, which allows the shade to be both raised from the sill as well as lowered from the header. A photograph of an Elan shade is displayed below in Figure 5.

Figure 5. “Top-Down, Bottom-Up” cellular shade fully closed (left), with “Top-Down” (center), and cell detail for a room-darkening shade (right) (Images Courtesy of Hunter Douglas).

Other shades were selected and tested to identify whether or not the problem of condensation formation is unique to cellular shades. To better understand this problem, a venetian blind and a sheer shade were selected and tested (see Figures 6 and 7). A generic venetian blind was selected because venetian blinds make up 44 percent of residential window covering installations (Bickel et al. 2013). Sheer shades were selected, because they may be installed by homeowners to provide privacy while providing minimal energy impact. For this study, a generic venetian blind was sourced for testing, and the Hunter Douglas Whisper Sheer shade was used to represent the sheer category.

Figure 6. Typical horizontal (venetian) blind. Slats are shown in both the horizontal (left), 45° (center), and closed (right) positions.

Figure 7. Sheer shading with a high view-through.

3.3 Testing Phases

Three phases of testing were performed in order to understand condensation mitigation strategies, condensation buildup with a variety of environmental conditions, and condensation buildup with other typical window coverings. The phases of testing are described in Table 2 and presented in more detail in Appendix A of this report.

Table 2. Testing conditions and objectives.

Phase	Cold-Side Temperature	Warm-Side Relative Humidity (RH) and Temperature	Shade Position	Objective
1	5°F	RH = 25%; Temp = 70°F	Varied from fully raised and lowered and raised and raised/lowered by .5-, 1-, and 2-inch increments (from both top and bottom rails using cellular shade)	Establish baseline conditions (e.g., fully raised/lowered shade) and the effectiveness of mitigation strategies in reducing condensation buildup.
2	Varied from 5°F - 50°F (in 5-degree increments)	RH = 25%; Temp = 70°F	Fully lowered cellular shade	Evaluate condensation conditions with a fully lowered shade under varying outdoor temperatures.
3	5°F	RH = 25%; Temp = 70°F	Fully lowered sheer shade and horizontal slatted shades with slats at different angles	Examine the thermal and moisture (i.e., condensation) performance of sheer shades and blinds for comparison with cellular shades.

3.3.1 Phase 1: Condensation Mitigation

For the first phase of testing, the first step was to understand baseline condensation levels with no window covering and with the Hunter Douglas Duette Architella Elan shade fully closed. Selecting a cold-side temperature so that the glass approaches the dew point along the sill allowing for the full effects of the mitigation strategies to be observed. Each of the baseline conditions is run for 12 hours to allow for steady state conditions to be reached.

After understanding baseline conditions, a number of mitigation strategies were investigated. The first round was focused on moving the bottom rail of the shade to allow the air between the window and shade to be vented. Three tests were conducted with bottom rail mitigation: 0.5-inch, 1.0-inch, and 2.0-inch venting.

After testing bottom rail venting, mitigation strategies, where both the bottom rail and the top rail were moved an equal distance, were run. Typically, most consumer shades only raise from the bottom rail so these mitigation strategies depend on a consumer having a product that has the ability to be lowered from the top. Three tests were conducted with top rail and bottom rail mitigation: 0.5-inch, 1.0-inch, and 2.0-inch venting.

3.3.2 Phase 2: Condensation Formation at Different Exterior Temperatures

The second phase of testing focused on condensation formation when the Hunter Douglas Duette Architella Elan shade was fully closed and under conditions of varying cold-side temperatures.

For each stage of testing, the warm-side temperature was maintained at 70°F and 25 percent RH. The cold-side temperature started at 50°F and was lowered by 5°F increments every 12 hours. The goal was to understand how condensation develops at different outside temperatures that might reflect more realistic conditions for a variety of climate zones.

3.3.3 Phase 3: Evaluation of Other Common Window Coverings

The final phase of testing was to look at two typical shade products to understand how unique the problem of condensation is to cellular shades. For comparison, chamber testing was conducted on a faux-wood venetian blind and a sheer shade.

These comparison shades and blinds were selected because they represent commonly installed products in homes based on industry sales data. Testing was conducted with the slats in the fully closed position, tilted at 45 degrees, and also in the horizontal position, with the shade fully drawn down and chamber conditions mirroring those of the Phase 1 testing with the cellular shade.

In addition, the sheer shade represented an alternative product relative to the cellular shade that provides home occupants with some privacy but does not provide the thermal insulating efficiency of the cellular shade. The sheer shade was tested in a closed position with chamber conditions mirroring those of the Phase 1 testing.

4.0 Results

The results of the three phases of condensation testing are described in the following sections.

4.1 Condensation Mitigation Strategies

For Phase 1, condensation mitigation testing, the chamber conditions were run with the cold-side of the chamber maintained at 5°F and the warm-side of the chamber maintained at 70°F and 25 percent RH. The chamber was run for 24 hours with no window covering and also with Hunter Douglas Duette Architella Elan Room-Darkening shade with ¾-inch pleats in the fully lowered position. The chamber conditions were set such that with no window covering the bottom edge of the glass was right at the dew point with a small amount of condensation along the sill and in the corners. This would allow for the full impact of mitigation to be seen. The baseline condition with the window covering fully closed showed a large increase in the amount of condensation over a bare window, and ice was formed where the glass temperature was decreased to below the freezing point (see Figure 8).

Figure 8. Baseline condensation conditions on an uncovered (left) and fully covered (right) window with insulating shade.

After understanding baseline condensation levels, the mitigation strategies were employed starting with the bottom rail being raised 0.5-inch, 1.0-inch, and 2.0-inches as seen in Figure 9.

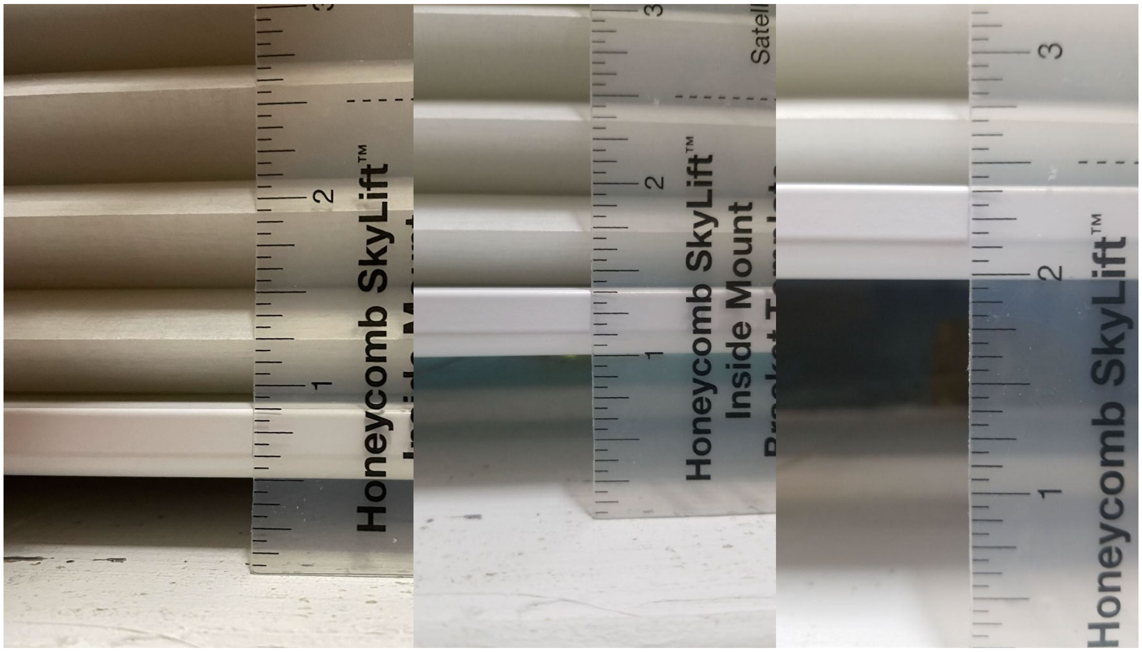


Figure 9. Bottom rail adjustments for condensation mitigation.

During this round of mitigation testing, as the bottom rail was raised the level of condensation was observed to drop. Temperature readings also confirmed increasing glass temperature as the bottom rail was raised, meaning less of the window was below the dew point. Figure 10 shows the condensation levels of these mitigation strategies in green.

Figure 10. Condensation results. Red top and bottom lines represent baseline conditions, green lines represent bottom rail mitigation strategies, and orange lines represent both top and bottom rail mitigation strategies.

The second round of mitigation testing involved the bottom rail being raised 0.5-inch, 1.0-inch, and 2.0-inches while the top rail was simultaneously lowered the same amount (0.5-inch, 1.0-inch, and 2.0-inches), as seen in Figure 11.

Figure 11. Top and bottom rail adjusted for condensation mitigation.

During the second round of mitigation testing, the initial 0.5-inch gaps at the top and bottom resulted in less condensation than a 0.5-inch gap at the bottom alone. The 1.0-inch and 2.0-inches gaps at the top and bottom had similar results with both showing a slight improvement over a 2.0-inches gap at the bottom alone. The results of the second round of mitigation testing can be seen in orange in Figure 10.

In addition to the condensation observations, an estimated R-value[1] was taken at each baseline and mitigation setting. The results of how the estimated R-value changed from the baseline window along with the levels of condensation can be seen in Figure 12. Figure 13 shows the corresponding glass surface temperatures recordings for various mitigation shade settings.

[1] The test conditions for the R-value estimate do not strictly follow the National Fenestration Rating Council standards, because the test conditions were selected to be representative of home and climate conditions in a cold climate to reflect typical conditions.

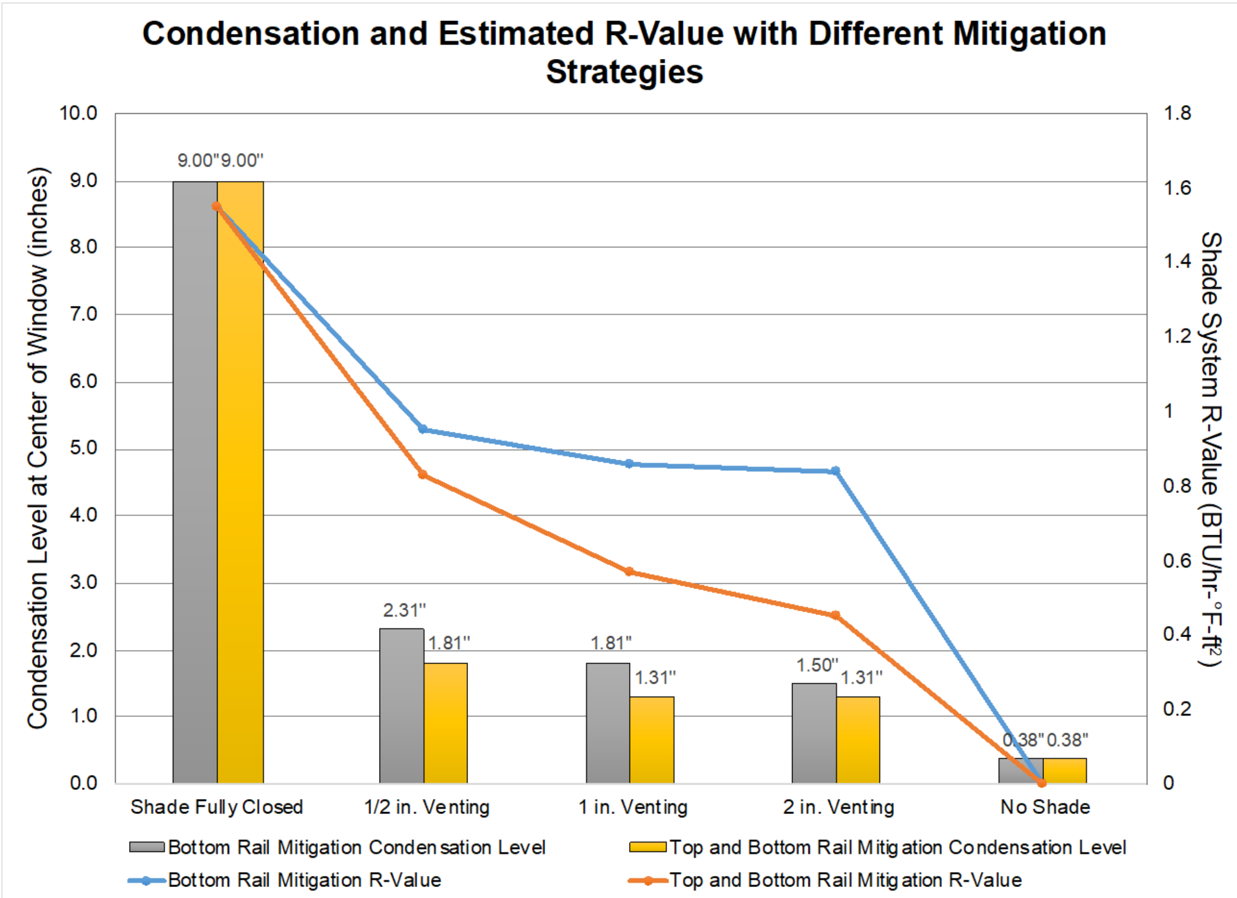
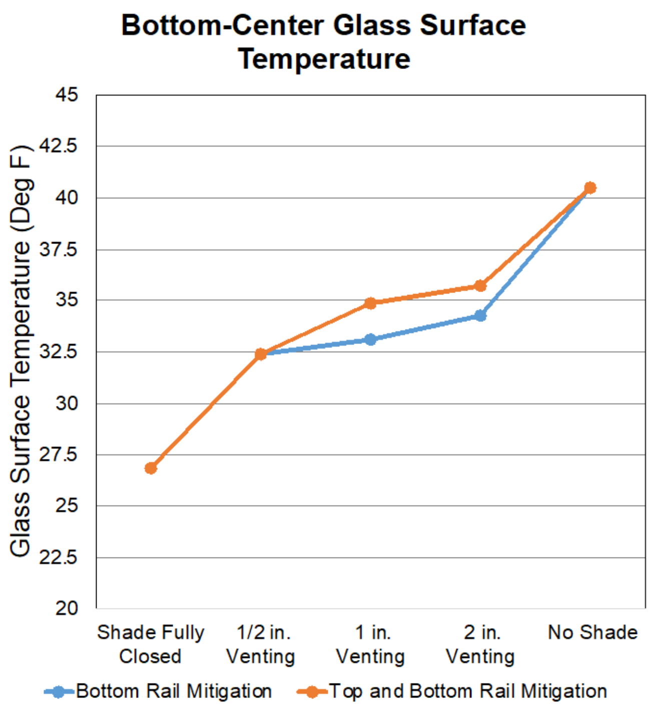
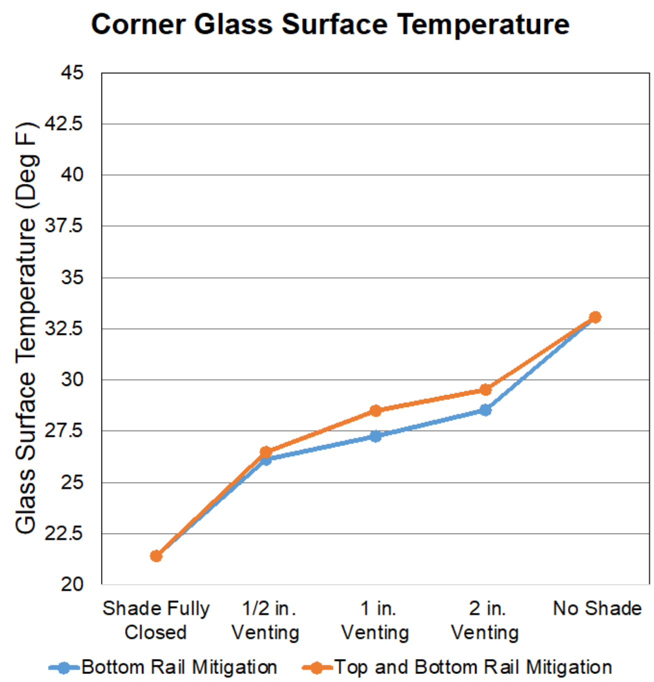


Figure 12. Condensation levels and estimated R-value improvement from baseline for different mitigation settings for insulating shades.



(a) Bottom Center Glass Surface Temperature



(b) Corner of Glass Surface Temperatures

Figure 13. Recorded temperatures from thermocouple placed at (a) bottom center of window glass (seen in the center of the window's bottom edge in Figure 10) and (b) the corner of window glass (seen in the window corner in Figure 10).

All mitigation testing previously described was completed with constant chamber conditions in order to understand the impacts of each mitigation strategy. To understand the potential for condensation under a variety of conditions, Phase 2 of the testing varied the cold-side temperature to see the related impact on condensation with the insulating cellular shade in the fully closed position. Figure 14 shows the condensation formation on the interior surface of the windows, where the colored lines depict the various levels of condensation forming on the window at different temperature settings on the cold-side of the test chamber. Figure 15 shows a graphical depiction of the level of condensation formation at different cold-side temperatures.

Cold-side temperatures were started at 50°F and were lowered at 5°F intervals. No condensation was observed on the window until the cold-side temperature reached 25°F. At this point, the cold-side temperature was decreased to 20°F and an increase in condensation was observed. Further reductions in cold-side temperature resulted in growing levels of condensation on the window (see Figures 14 and 15).

Figure 14. Lines represent condensation formation at different temperature settings on the cold-side. Condensation lines colors represented cold-side temperatures of: (From top to bottom) Green: 0°F, Red: 5°F, Blue: 10°F, Purple: 15°F, Green: 20°F, and Red: 25°F.

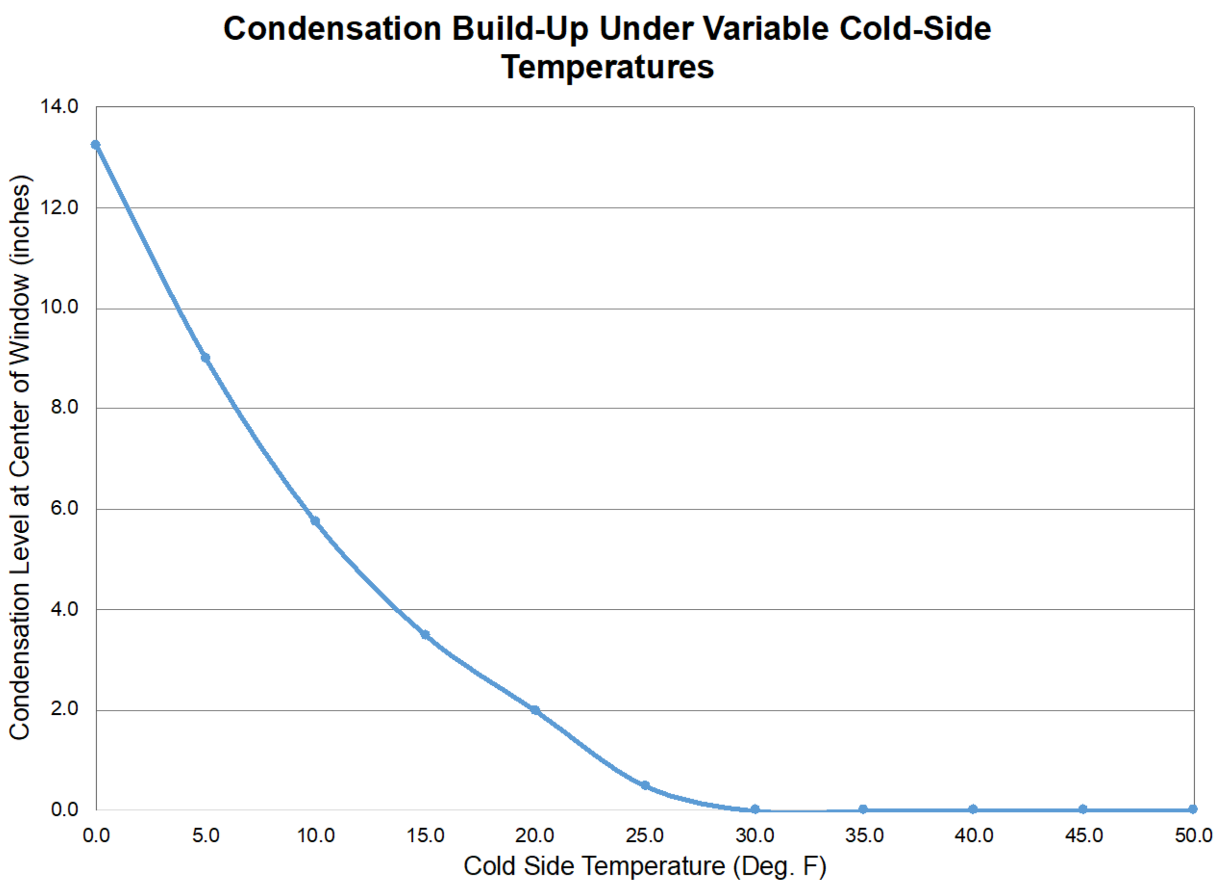


Figure 15. Condensation levels at the center of the sill under differing cold-side conditions with the insulating shade fully closed.

4.2 Evaluation of Other Common Shade Types

Phase 3 of the testing looked at how condensation on insulating shades compares to that seen on other common window covering types. The most common window covering type seen in homes is a horizontal or venetian blind. Testing was done on a typical, faux-wood, horizontal blind that can be purchased from a big box store. Testing was conducted under the same conditions as Phase 1 with the shade in three slat orientations, as shown in Figure 16.

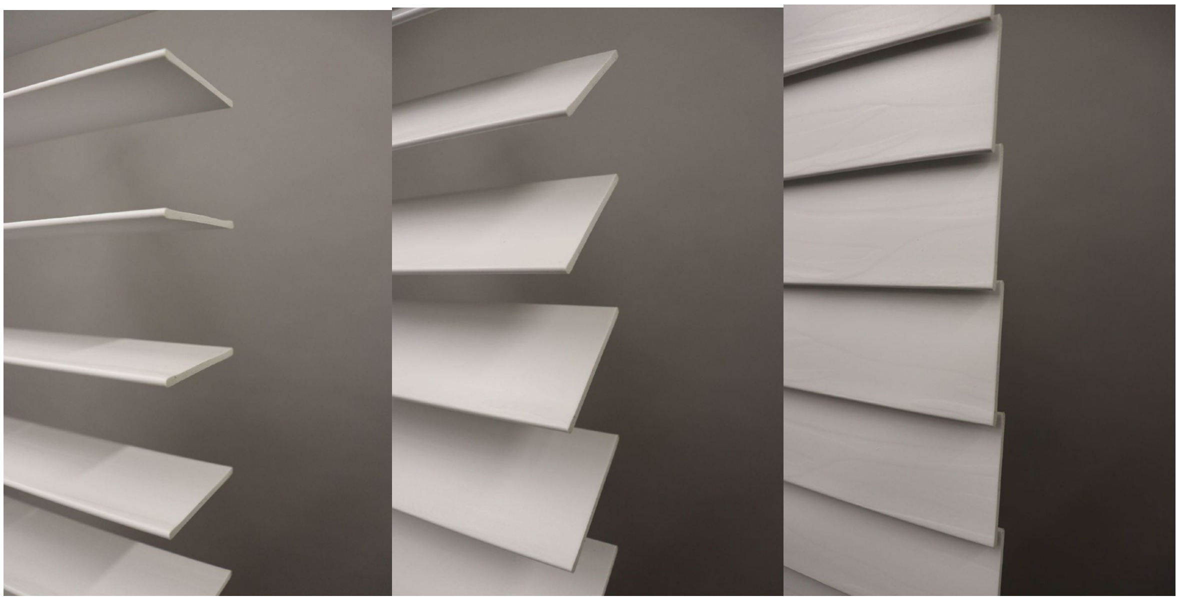


Figure 16. Close-up View of typical horizontal (venetian) blind. Slats shown in the horizontal (left), 45° (center), and closed (right) positions.

Condensation levels observed when the shade was fully closed matched the 2-inch top and bottom rail mitigation strategies seen with the insulating cellular shade, and the condensation levels when the shade had the vanes positioned horizontally were similar to those of the baseline of a bare window. When the vanes were at a 45° angle the results were between those of the closed and horizontal vanes. Figure 17 shows condensation buildup profiles at each position of the venetian blinds.

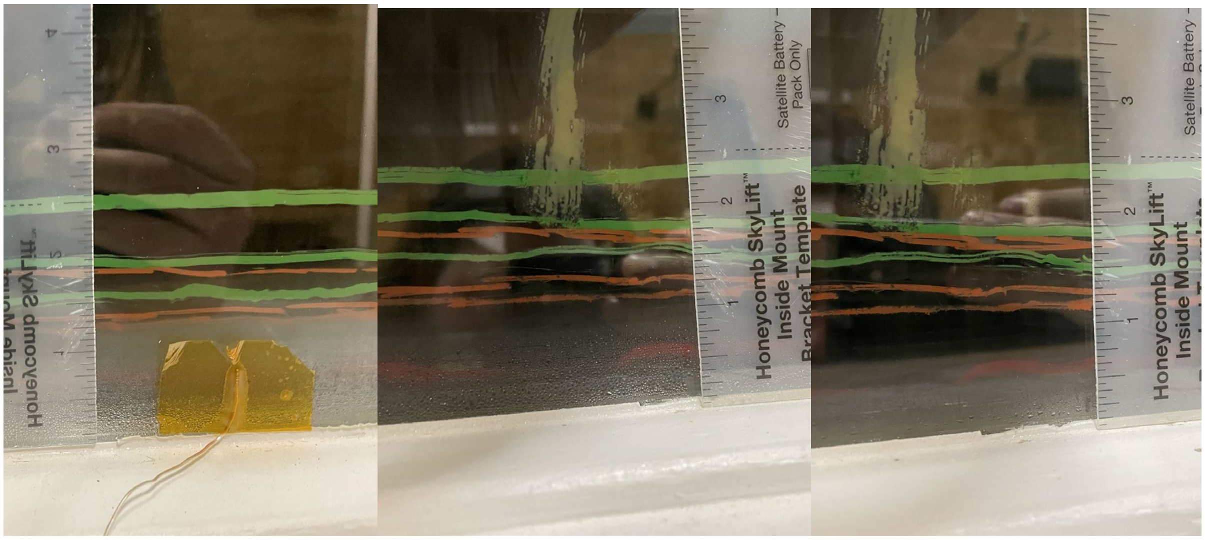


Figure 17. Condensation results from horizontal blind in the closed (left), partially closed (center), and horizontal (right) conditions.

The final shade that was tested was a sheer shade used to represent products with a high view through This sheer shade is displayed in Figure 7. The results of this test, alongside the horizontal blind tests, are displayed in Table 3.

Table 3. Observed condensation levels and R-values for venetian blinds and sheer shades.

Shade Type	Position	Center of Window Condensation Level (inches)	Shade System R-Value (BTU/hr-°F-ft^2)
Faux-wood Venetian	Horizontal Louvers (0°)	0.56”	0.17
	Louvers at 45°	0.94”	0.23
	Closed Louvers (~90°)	1.3”	0.61
Sheer	Shade Closed	1.4”	0.84
None	na	0”	0

When comparing the levels of condensation seen for a cellular shade employing a 2-inch bottom rail mitigation strategy and a fully closed venetian blind the levels of condensation are very similar. The cellular shade, even with this condensation mitigation strategy, still shows superior insulating capabilities and energy-saving potential compared to the venetian blind. In addition, it is important to consider the times when the outside temperature does not drop low enough to cause condensation concerns. On these nights, the benefits of a cellular shade in the fully closed position are even greater. The insulating qualities of a cellular shade make it a superior product in terms of energy efficiency on the majority of days of the year, and with proper mitigation, it can still provide insulation with condensation levels equivalent to other common shading products.

5.0 Discussion and Recommendations

In this study, multiple phases of testing were conducted to understand condensation formation caused by cellular and other types of shades. Testing was conducted on an IECC 2021 cold climate code-minimum window within a two-room environmental chamber. The warm-side of the chamber was conditioned to represent typical indoor conditions, with an air temperature of 70°F and a RH of 25 percent. The chamber cold-side was conditioned down to 5°F with RH levels allowed to freely float.

Based on the testing, the first major observation is that a fully closed cellular shade did cause condensation formation with the tested window setup; however, raising the shade's bottom rail 0.5-inch reduced window condensation levels from 9.00 inch of height up the window to 2.8 inches, with the condensation reduction providing diminishing returns on shade openings greater than a 0.5 inch. While raising the shade bottom rail did reduce window condensation levels, it also had the effect of reducing the cellular shade's insulating value. Raising the cellular shade a 0.5 inch reduced the cellular shade's R-value by 39 percent, with R-value reductions reaching 46 percent for a 2-inch opening on the shade's bottom side. These results suggest that window condensation can be reduced by raising a cellular shade by a 0.5 inch or more to reduce condensation, while still maintaining a majority of the thermal benefit provided by cellular shades.

Secondly, some cellular shades have "Top-Down, Bottom-Up" capabilities that allow for modulation of both the bottom and top rails of a shade. In these cases, adjusting the top and bottom rails yielded slightly more condensation reduction than the bottom rail-only mitigation strategy, but the "Top-Down, Bottom-Up" approaches significantly reduced the insulating value of the cellular shade. It was noted that a cumulative 1-inch opening size for the "Top-Down, Bottom-Up" approach (0.5-inch opening on top and bottom of the shade, respectively) performed similarly to a 1-inch opening on the bottom rail only. However, this phenomenon was not observed with "Top-Down, Bottom-Up" openings of 1-inch or 2-inches (cumulative 2 and 4-inches of opening, respectively). In the latter cases, condensation levels appeared to plateau at 1.3 inches of condensation up the window, but the cellular shade's R-value impacts were reduced by 63 percent and 71 percent, respectively. These large reductions in cellular shade R-value are believed to be a result of a convective loop, which allows for additional air movement which effectively shortcuts the insulating capability of the cellular shade.

Alongside cellular shades, two different types of shades were tested within the environmental chambers—venetian blinds and sheer shades. Based on the testing of both of these shade types, it was discovered that condensation did still form on the window in the presence of these window coverings, indicating that condensation formation is not a problem exclusive to cellular shades. This is a particularly novel effect because venetian blinds were found to have insulating values 67–89 percent less than the tested cellular shade for fully closed and fully open slat orientations, respectively. Condensation levels were also found to be similar between the fully closed sheer shade and fully closed venetian blind, but the sheer shade was found to provide an R-value of R-0.84 compared to the R-0.61 of the venetian blind. From these results, one value occurred across many different trials—the condensation height of 1.3 inches This condensation value, or similar values, occurred in the "Top-Down, Bottom-Up" trials with displacements of 1-inch and 2-inches, in the fully closed venetian blind trials, and the fully closed sheer shade trials. In these trials, it was noted that the shading device was not airtight, allowing for convection to warm the surface of the glass. The shading devices in these trials also impeded thermal radiation between the surface of the glass and the bulk indoor environment, suggesting that, regardless of the airflow, there is a theoretical limit to how warm the glazing surface can be when a shading device blocks thermal radiation. This further suggests that any shading device that inhibits radiative heat transfer between the window and indoor environment will have a risk of condensation formation; condensation is not a problem exclusive to cellular shades. In fact, this logic can be extended to suggest that condensation is not exclusively caused by cellular shades; instead, condensation is caused by any window covering that impedes radiant transfer from the interior surface of the window while not being airtight. In the case of less insulating single-paned windows, condensation may be observed at higher temperatures or with lower-performing window attachments, such as Venetian or sheer shades. This suggests that the best course of action for single-paned windows is to either replace them with higher-performance windows or retrofit with gasketing and storm windows to reduce condensation potential. In the case of double and triple-paned windows, condensation formation may be seen on any interior shading device if exterior conditions reach low enough temperatures. In these cases, extremely low temperatures may only be present for a few hours overnight on only the coldest days of the year.

5.1 Recommendations

Based on the results of the field testing presented in this report, the following recommendations can be made:

1. **Open shades in the daytime during the heating seasons.**

   If possible, do not keep cellular shades, or any other type of shades, closed during all hours, especially during the heating season. Opening shades during the daytime allows for condensation to dry and allows for beneficial solar heat gain through the window, which not only reduces the potential for condensation buildup but is consistent with the recommended operation of shades for efficiency based on AERC guidance. Any condensation that collects on the sill that does not evaporate should be wiped from the window's surface at least every few days.

2. **When lowering shades, leave the shade's bottom rail 0.5-inch from the windowsill.**

   Raising the shade from the bottom rail windowsill by 0.5-inch should effectively reduce the amount of condensation that builds up on the surface of the window and sill while maintaining most of the shade's insulating value and privacy.

3. **Install better windows or attach insulating secondary glazing panels.**

   The results of this study suggest that when condensation collects on the interior surface of windows and sills, multiple factors are likely contributing to this problem, including the overall performance of the window and the humidity level of the home. When condensation occurs with the application of shades, the problem is not exclusive to the shades but could be more pronounced with cellular shades due to the highly insulating nature of this window attachment. With code-minimum windows installed in cold climates, condensation formation can occur with any window attachment that blocks a window's radiative transfer within the indoor environment. With windows that are below code, this problem is can become even worse. On the coldest days, this condensation buildup can even occur without the application of shades or blinds, especially with poor-performance windows or high humidity conditions in the home. This problem can be solved in two ways: (1) by reducing indoor humidity levels, or (2) by bolstering window performance by installing better windows or adding an energy-rated[1] insulating secondary window panel (i.e., storm window or insulating window panel insert). Due to the complexities involved with local climatic conditions; HVAC system type, sizing, and venting; and human health impacts, the authors of this study would not advocate for lowering indoor RH levels as a condensation mitigation strategy, except in situations in which indoor humidity levels are extremely high due to improper airtightness levels or improper HVAC operation.

In most cases, the logical means of addressing condensation formation for cold and very cold climates is to improve the performance of the window by either installing above-code (e.g., triple-pane) fenestration products or by installing interior or exterior secondary glazing. Secondary glazing can either be exterior, such as air sealing existing windows and applying thermally efficient storm windows on the exterior side of the window; or interior, where an airtight secondary glazing panel is installed on the interior surface of the window.

[1] AERC provides an online database listing of all energy-rated products: https://aercenergyrating.org/product-search/residential-product-search/.

6.0 Conclusion

Condensation has been a persistent and often misunderstood problem associated with windows. It occurs when the surface temperature of a window component drops below either the dew point or frost point of the air adjacent to the surface. In cold climates, single-glazed windows and many double-pane lower-performing windows will characteristically suffer from water condensation and the formation of frost on the inside surface of the glass in winter due to window coverings. Although the application of insulating coverings, such as cellular shades, can increase the potential of moisture condensing on the surface of the glass, the mitigation strategies demonstrated in the field imply that this potential drawback could be effectively addressed with the mitigation strategies tested without significantly reducing the thermal efficiency and comfort benefits drawn from the application of thermally insulating shades.

Additionally, the second phase of testing demonstrated that condensation is only seen when specific environmental conditions are met, such as extremely cold exterior conditions. Outside of these environmental conditions, insulating shades can provide their full benefit with no risk of condensation formation. When condensation conditions do occur, condensation mitigation strategies can be applied. The number of nights a year where cellular shades will provide their full savings is likely much more than the number of nights some savings will be reduced for condensation mitigation.

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Appendix A – Experimental Design Phases

Table A.1. A tabulated summary of experimental testing phases.

Phase	Cold-Side Temp. (°F)	Warm-Side Temp. (°F)	Relative Humidity (%)	Shade Type	Shade Position (Bottom Rail)	Shade Position (Top Rail or Slats)	Objective	Run Time
1	5	70	25%	Cellular	Fully Raised	Fully Raised	Baseline Condition of Shade Fully Raised	12 Hrs
	5	70	25%	Cellular	Fully Lowered	Fully Raised	Baseline Condition of Shade Fully Closed	12 Hrs
	5	70	25%	Cellular	Raised 0.5"	Fully Raised	Bottom Rail Mitigation Strategy 1	12 Hrs
	5	70	25%	Cellular	Raised 1.0"	Fully Raised	Bottom Rail Mitigation Strategy 2	12 Hrs
	5	70	25%	Cellular	Raised 2.0"	Fully Raised	Bottom Rail Mitigation Strategy 3	12 Hrs
	5	70	25%	Cellular	Raised 0.5"	Lowered 0.5"	Top and Bottom Rail Mitigation Strategy 1	12 Hrs
	5	70	25%	Cellular	Raised 1.0"	Lowered 1.0"	Top and Bottom Rail Mitigation Strategy 2	12 Hrs
	5	70	25%	Cellular	Raised 2.0"	Lowered 2.0"	Top and Bottom Rail Mitigation Strategy 3	12 Hrs

Phase	Cold-Side Temp. (°F)	Warm-Side Temp. (°F)	Relative Humidity (%)	Shade Type	Shade Position (Bottom Rail)	Shade Position (Top Rail or Slats)	Objective	Run Time
2	50	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 50 F	12 Hrs
	45	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 45 F	12 Hrs
	40	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 40 F	12 Hrs
	35	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 35 F	12 Hrs
	30	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 30 F	12 Hrs
	25	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 25 F	12 Hrs
	20	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 20 F	12 Hrs
	15	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 15 F	12 Hrs
	10	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 10 F	12 Hrs
	5	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 5 F	12 Hrs
	0	70	25%	Cellular	Fully Lowered	Fully Raised	Condensation Conditions with Fully Closed Shade and Exterior Temperature of 0 F	12 Hrs

Phase	Cold-Side Temp. (°F)	Warm-Side Temp. (°F)	Relative Humidity (%)	Shade Type	Shade Position (Bottom Rail)	Shade Position (Top Rail or Slats)	Objective	Run Time
3	5	70	25%	Sheer	Fully Lowered	NA	Performance of a Sheer Shade at the Condensation Testing Conditions	12 Hrs
	5	70	25%	Cellular	Fully Lowered	Slats Closed	Baseline Condition of Horizontal Shade Fully Closed	12 Hrs
	5	70	25%	Cellular	Fully Lowered	Slats at 45 deg	Baseline Condition of Horizontal Shade with Slats Partially Closed	12 Hrs
	5	70	25%	Cellular	Fully Lowered	Slats Horizontal	Baseline Condition of Horizontal Shade with Slats Open	12 Hrs

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