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Sealed Cavity Walls

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DOUBLE-SKIN FACADE SYSTEMS

The advent of the double-skin facade (DSF) has provided several advantages over conventional single-skin designs. The second facade layer and intermediate space created by its introduction provide additional possibilities for the control of physical interactions that occur between the maintained conditions of the building interior and the uncontrolled external environment. By increasing reflection and dampening of external noise, double-facade configurations provide greater sound attenuation of problematic urban sources. Configurations can also be implemented for cooling climates, where the intermediate space serves as a conduit by delivering natural ventilation to cool upper building levels at which high wind prevents effective implementation of operable venting. In heating climates temperature driven heat-loss is reduced by the insulating action of the intermediate space. Heating climate systems can be further enhanced by integration with mechanical systems to achieve heat recovery of HVAC system exhaust air. In addition, shading systems that would typically be vulnerable to external conditions can be housed in the intermediate space.

In order to achieve the aforementioned benefits in cold weather climates, the management of humidity becomes a paramount design consideration due to the fact that the temperature of air contained within or flowing through the intermediate space can deviate appreciably from the controlled set point of the building interior. For each application the unique combination of fluid dynamics, heat-transfer and water vapor transport (mass-transfer) must be appropriately assessed, typically involving more rigorous analysis and testing for validation of performance than conventional single wall systems.

Figure 1: Testing for a compartmentalized wall system.

COMPARTMENTALIZED DESIGN

The focus of this article is to discuss systems which may be implemented to mitigate the potential for condensation in a specific, "compartmentalized," or *box-window*, double-skin facade application. Compartmentalized systems are easily realized as unitized systems where single framed vision areas contain both inboard and outboard glazing, as seen in figure 1. In this configuration there is no uncontrolled communication of the intermediate space between framed units.

CONDENSATION OF WATER AND DEPOSITION OF FROST FROM HUMID AIR

At a surface of liquid water, the rates of evaporation and condensation have a net effect of producing a vapor pressure over the surface. Similarly, ice also exerts a vapor pressure owing to the rates of sublimation and deposition. With sufficient time, and under conditions of uniform temperature, equilibrium of these rates is achieved and the vapor immediately above the surface is said to be "saturated". The thermodynamic quantity prescribed to represent this condition is the saturation pressure of water vapor (p_{ws}) (Eqs.1 & 2) and any subsequent increase or decrease in temperature will respectively result in net evaporation or net condensation until a new saturated pressure is obtained. Equations 1 & 2 (Hyland & Wexler 1983b) provide a correlation for determining the saturation pressure as a function of temperature over a surface of water or ice.

Air removed from a source of water also commonly includes a component of water vapor proportional to its fraction in mass of the total gas constituents which comprise air. Such air is said to be humid with a partial pressure of water vapor (p_w) that varies proportionally with the temperature and pressure of air. Condensation of dew or deposition of frost will occur on a surface under the condition that air immediately exposed to that surface achieves a partial pressure equal to the saturation pressure at that location, and subsequently, it is convenient to express the quotient of the partial and saturation pressure of water vapor as the relative humidity φ (Eq. 3).

In observation of these quantities, as they apply to the design of exterior wall systems, several simplifications become apparent. The range of air pressures encountered as internal and external environmental conditions are of the range of temperature and pressure that the ideal gas relation (Eq. 4) provides a suitable equation of state to determine partial pressures. Furthermore, fluctuations in pressure are sufficiently small to have an unsubstantial effect on partial pressures. Over the range of temperatures observed the saturation pressure exhibits a much stronger dependence on temperature than the partial pressure such that decreasing temperature acts to increase the relative humidity of an air mass from its initial state towards unity at which point a change of phase is initiated. In light of this observation, the goal of analysis is typically to determine the lower temperature that this condition is achieved. The dew point t_{dp} (Eq. 5) and frost point t_{fp} (Eq. 6) correspond to the respective temperatures of condensation and deposition. Equations 4 and 5 (Peppers 1988) may be employed to determine the quantities for a range of temperatures typical to architectural design.

Inspection of equation 3 provides two independent variables that can be utilized to condition the relative humidity of air within a building. The mass fraction air attributed to water vapor is proportional to p_w implying that the concentration of water vapor is one such variable. A second variable is provided by the dependency of the water-vapor partial pressure on temperature.

Equation 1

$$LN(p_{ws}) = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}LN(T)$$

Equation 2

$$LN(p_{ws}) = \frac{C_1}{T} + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6T^4 + C_7LN(T)$$

Equation 3

$$\varphi = \left.\frac{p_w}{p_{ws}}\right|_{p,T}$$

Equation 4

$$p = \rho RT$$

Equation 5

$$t_{dp} = C_{14} + C_{15}Ln(p_w) + C_{16}Ln(p_w)^2 + C_{17}Ln(p_w)^3 + C_{18}(p_w)^{0.1984}$$

Equation 6

$$t_{fp} = 90.12 + 26.142Ln(p_w) + 0.8927Ln(p_w)^2$$

Subsequently, systems which mitigate condensation of water or deposition of frost on internal surfaces of building enclosure systems must effectively control the humidity or temperature of air that is exposed to interior surfaces. For the purpose of discussion, these strategies will be addressed broadly as passive or active systems.

When considering the compartmentalized double-facade it becomes apparent that some humidity and temperature control strategies will not be effective. Channeling and delivering air flow from existing HVAC facilities to the cavity of each individual unit for the purpose of maintaining temperature or lowering humidity will likely exceed the acceptable cost to achieve the added benefits of the design versus a conventional single-facade system. Local treatments, such as the use of electric fans or desiccant require periodic maintenance or may be technically difficult to achieve. Historically, the use of pressurization or external ventilation has been successfully implemented. For instance, the enclosure system developed by for the Bibliotheque Nationale de France (Dominique Perrault Architecture, 1994) utilizes a combination of pressurized and passive systems to maintain the multi-story unitized compartmentalized double-facade. High-rise systems feature a distribution network to provide dried air to each cavity from a central pressure source. Ground level systems are passively ventilated to the building exterior, but remain accessible for periodic cleaning of contaminants.

DESIGN OF PASSIVE SYSTEMS

Passive systems operate on the principle that the ambient external temperature is both greater than the ambient dew or frost point temperature and less than that of the cavity. As a consequence, the cavity humidity achieves equilibrium with the external water vapor pressure by either diffusion or convection from the ambient. Since the saturation pressure is greater corresponding to the warmer cavity condition, relative humidity is diminished from the external ambient preventing the formation of water or frost on internal surfaces.

The major benefit of passive systems is cost effective implementation; however, designers should be aware of some inherent limitations to the technique. If rapid fluctuations in external temperature and humidity from proceeding storms or changes in weather occur more quickly than conditions within the cavity can equilibrate, it is possible for the cavity temperature to be lower than that of the ambient – thus presenting a condensation potential. In addition, external pollution or contaminants may be introduced by orifices used for ventilation. Large openings should feature filters to prevent contamination and to provide access to the intermediate space for cleaning. Passive systems should not be applied where periodic cleaning is difficult.

DESIGN OF ACTIVE SYSTEMS

While pressurized active systems differ in operation from passive systems, both are comprised of a common set of components. A source of pressurized air is typically supplied by a pressure vessel, but may also be provided by motorized blowers. Distribution of air flow and communication of the pressurized air source to each double-facade cavity is most commonly achieved with polymer conduit hoses. A controlled orifice for relief prevents the possibility of excessive cavity pressure and establishes the system's operating point with regard to volumetric flow rate and pressure. The assembly of these components is depicted schematically in figure 2.

The primary source of variation that affects operation of the components discussed is the size of the orifice that establishes the operating point of the system. A small orifice will exhibit a large pressure loss coefficient and subsequently will result in a cavity pressure that is close to that of the supply with minimal mass flow through the cavity. A large orifice will inversely result in a cavity pressure that is close to the external surroundings with a high rate of air flow through the cavity. Throughout the remaining discussion the former mode of operation will be referred to as

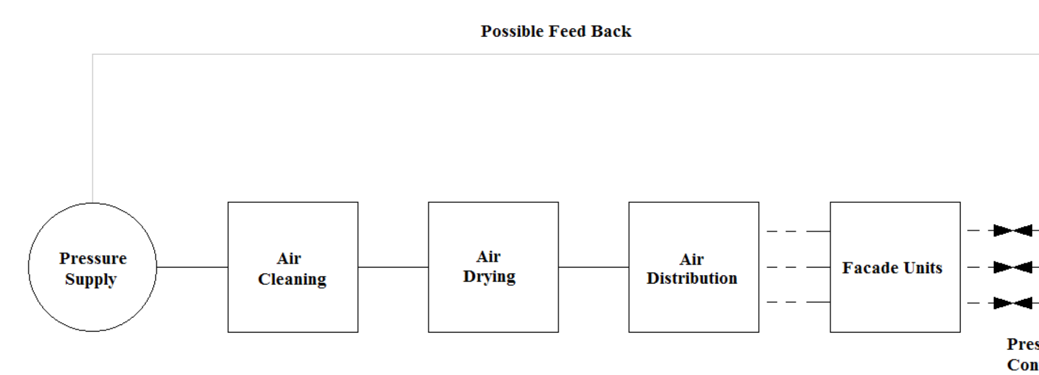


Figure 2: Schematic of Components

TEMPERATURE CONTROL STRATEGIES

Passive:

- Polymeric thermal breaks or discontinuous features in metal framing.
- Integration or replacement of metal components with fiberglass, vinyl, wood or other materials exhibiting low thermal conductivity.
- Placement of loose-fill or rigid thermal insulation.
- Insulated glazing and glass coatings.
- Paints and surface treatments that affect radiation heat transfer.

Active:

- Heating of air or increased convection by mechanical integration of facade elements with HVAC systems or local equipment.

HUMIDITY CONTROL STRATEGIES

Passive:

- Passive ventilation of voids and internal spaces to external ambient humidity.
- Placement of vapor and weather barriers.
- Application of desiccant materials.

Active:

- Maintenance of HVAC system set-points at specified humidity and perimeter zoning.
- Active displacement of humid air with dried air from a controlled source.

(continued)

pressurized and the latter will be referred to as *displacement*. It is important to note that pressurized and air displacement strategies are not distinct modes of operation, and in fact are the extremes of a spectrum of possible operating modes. Figure 3 illustrates these potential modes of operation.

In practice, actual DSF systems have multiple openings introduced by imperfections in manufacture in addition to the control orifice; gaps in gaskets used to seal the glazing, and voids at the interface of framing members. Some common sealants, such as structural silicone, are permeable to water vapor over time. From these avenues water vapor may be introduced to the cavity space by diffusion from the ambient. Unabated, this diffusion would achieve an intermediate cavity humidity that is characteristic of the building exterior and interior, in addition to the openings present.

PRESSURIZED SYSTEMS

The pressurized system relies on the pressure difference of the cavity and ambient to produce an outflow at openings with sufficient flow rate where the advection of dried air from the cavity has a stronger effect on water vapor transport than the opposing action of water vapor diffusion that occurs in accordance with the increasing gradient of vapor pressure in the flow direction. In order to produce a quantitative assessment of this behavior, it is appropriate to observe the Peclet number *Pe* (Eq. 7), the product of the dimensionless Reynolds and Schmidt quantities, that correlates to the ratio of advection to diffusion of water vapor.

Equation 7

$$Pe = Re * Sc = \frac{\rho U D}{\mu}\frac{\mu}{\rho \mathfrak{D}} = \frac{UD}{\mathfrak{D}}$$

With increasing *Pe,* diffusion of water vapor becomes less significant than advection.

While specific knowledge of external humidity, opening geometry, and system operating point are required to correlate internal conditions to *Pe,* it can be stated in general that increasing the opening size at fixed cavity pressure increases *Pe* due to the fact that air flow velocity and opening diameter are proportional to *Pe.* All other quantities, with the exception of the binary diffusion coefficient that exhibits a mild dependency on temperature, are fixed by the properties of air. For the purpose of illustration figure 4 portrays air flow through a circular orifice between two zones of differing water vapor concentration with $Pe = 144$. The color contour diagram indicates the variation of concentration and the overlaid stream lines show the path of fluid motion. In this scenario, which corresponds to a mean air flow velocity across the orifice diameter of X, diffusion is inadequate to produce any upstream presence of humid air within the cavity.

DISPLACEMENT SYSTEMS

The displacement system gains its effectiveness from the process of mixing humid air that enters the cavity with dry air and displacing it. Even in the absence of a positive pressure difference between the facade cavity and ambient, or even with a negative pressure difference, sufficient advection of dry air will mix with potential inflows of humid air to maintain greater than dew point conditions within the cavity. In this mode of operation, the rate with which the concentration of any inflow diminishes is of significant interest. Zones of recirculation or stagnation within the cavity rely greatly or solely upon diffusion to facilitate mixing, and may be susceptible to local condensation near openings. Even in the case where advection is significant it is highly improbable that air flows within the cavity will be uniform. Due to these facts, the variation of water vapor concentration and air flow within the cavity must be determined either experimentally or by computer analysis.

PRACTICAL CONSIDERATIONS

The primary practical consideration which motivates the use of one mode over the other is the ability to seal the cavity space. If the design is sufficiently simple and manufacturing can minimize uncontrolled openings, the pressurized facade will benefit from the minimal flow rate required to maintain dry conditions within the cavity space, and subsequently both desiccant usage and fluid moving requirements are minimized. For more complicated scenarios, air displacement systems may prove to be more reliable, but at a cost of increased air flow from leakage introduced by manufacturing defects. This will be small in comparison to orifices purposely introduced.

A practical consideration which also warrants attention is the design of open versus closed loop systems. In a closed loop system, the air is returned from the control orifice to a zone of controlled pressure or possibly the pressure supply. In this scenario dry air can be conserved and the inlet and outlet pressures may be controlled independently of local pressure at the control orifice opening. Fluctuations in ambient conditions may also have less effect on operation in this mode. Implementing such a solution requires additional equipment and the cost of that equipment must be considered in design.

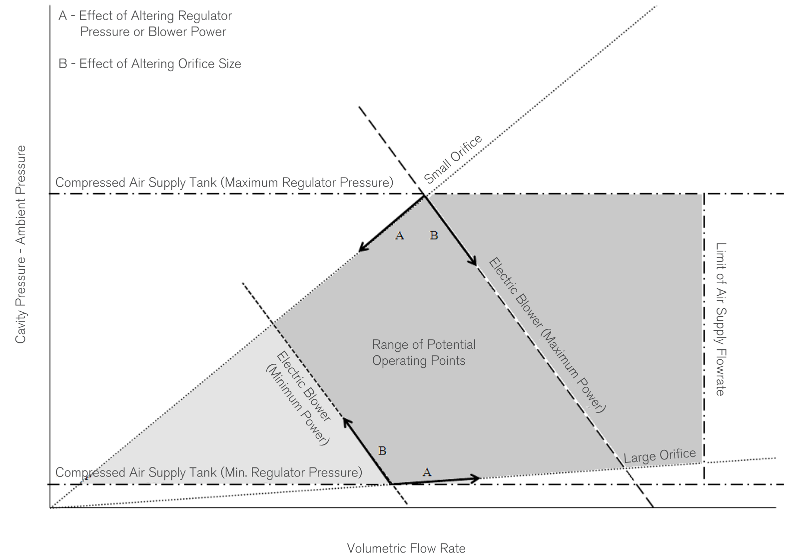


Figure 3: Potential Range of Operation

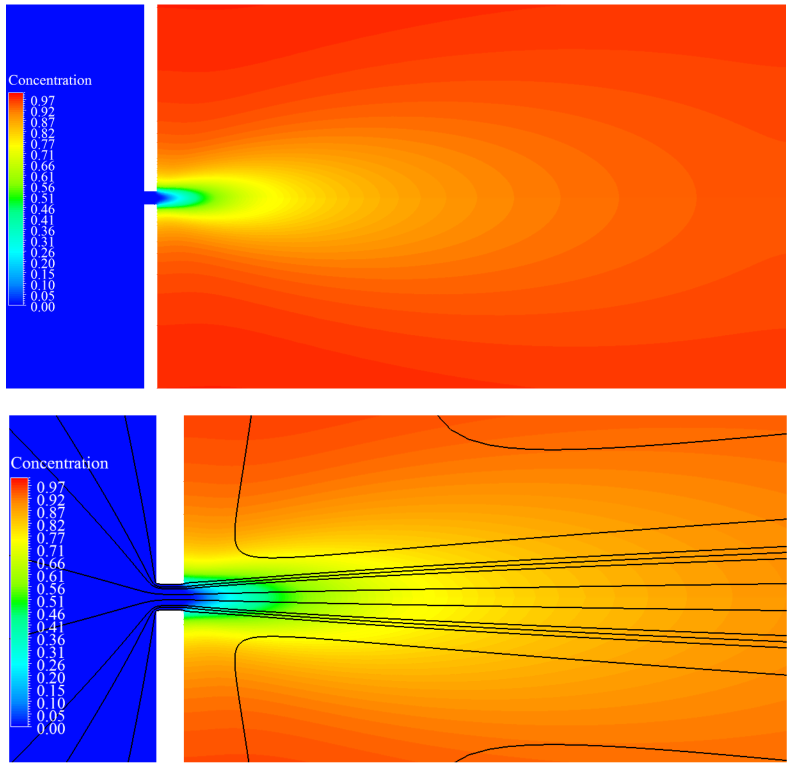


Figure 4: Contour Distribution of Water Vapor Concentration and Air Flow Stream Lines.

CASE STUDY

In order to access the performance of a typical compartmentalized DSF to resist condensation, the following discussion of conducted tests will provide some insight to typical sizes and conditions observed in actual systems. The appartus used is explained in figures 5-7.

Figure 5
The specific system evaluated is rectangular prismatic, has an aspect ratio of height versus depth of 7.2 and width versus depth of 9.9. Infiltration of humid air at saturation corresponding to ambient temperature and dry air are introduced by separate fluid flow circuits as indicated above. The inner and outer lights are typical 1" insulated glazing units held by an aluminum frame.

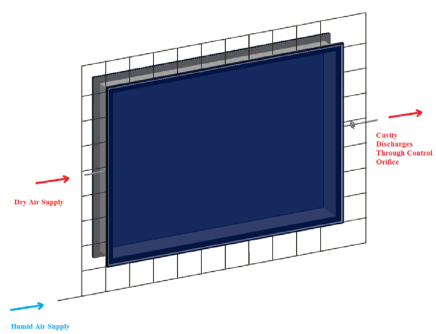
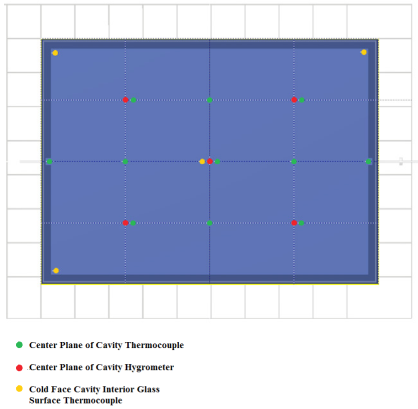


Figure 6
This configuration simulates a worst case scenario for an open system operating in the air displacement mode, with positive external pressure such that the mixing rate of humid air infiltration and dry air controls the cavity condition. Since relative humidity and saturation pressure are strong functions of temperature, the outer surface of the glazing is cooled in some tests to produce a temperature field that corresponds to winter conditions. The actual test piece and cold chamber utilized to produce this effect is depicted to the right.

Figure 7
Cavity conditions are monitored by an array of thermocouple temperature sensors and hygrometers suspended within the cavity by thin nylon wire. Interior surface of glass temperatures were also monitored by thermocouples.



COLD CHAMBER TESTING

The cold chamber test simulates a winter temperature environment and provides the most accurate representation of actual conditions. Gradients in vapor pressure associated with temperature may affect diffusion of water vapor. Natural convection currents will also affect advection and actual condensation or frost deposition that can be observed at the limit of performance.

In order to assure an initially dry state the cavity was purged of humid air by the dry supply at a high flow rate until the hygrometer used indicated a condition of dry air. The cold chamber was allowed to equilibrate for several hours until steady state heat transfer was achieved.

The test is initiated by reducing the dry air flow rate to a value typical of operation and increasing the saturated humid air flow rate to a value characteristic of infiltration that may be expected to occur under worst case conditions. After sufficient time, conditions within the cavity equilibrate and variation in humidity and temperature are observed. The dry air flow rate can then be reduced until a new steady condition is observed and the minimum required flow rate is determined.

WARM CHAMBER TESTING

It is also possible to assess cavity conditions with a warm chamber test. Warm chamber tests neglect the aforementioned effects of temperature on water vapor transport, but may be employed for longer periods than would be practical for cold chamber testing. In this test the reduction in cavity water vapor pressure can be determined for various combinations of saturated infiltration and dry air flow rates.

COLD CHAMBER RESULTS

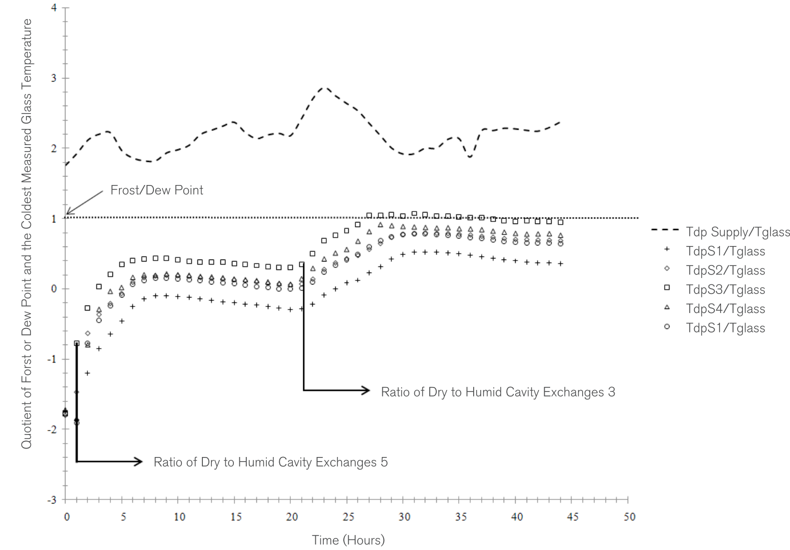
Figure 8 depicts the results of cold chamber testing at two flow rates. At each hygrometer the quotient of the measured frost point temperature and coldest measured cavity-interior glass surface temperature on the cooled glazing are plotted against time. The quotient corresponding to the humid air supply is also measured. Fluctuations are associated with the warm ambient temperature, which varied daily to some extent. Under the conditions in which the glass achieved the frost point, some deposition was observed and is indicated in figure 9.

WARM CHAMBER RESULTS

Warm chamber tests were conducted to evaluate the effect of daily variations in ambient temperature on the performance of the system. Figure 10 displays the balance of flow rates required to maintain a relative humidity and temperature within the cavity at conditions typical of most office buildings and residences. The mode of operation and test facilities are similar to those of the cold chamber tests, but absent of the refrigeration unit.

CONCLUSION

Strategies for condensation management in compartmentalized double-skin facade cavities have been discussed with attention paid to the physics of condensation, both passive and active control strategies, and testing to evaluate the performance of systems. The best application for any specific system ultimately depends upon a multitude of factors, including access to the double facade cavity, the ability to seal the facade space, and the severity of exterior conditions. In any scenario, analysis and testing are appropriate to determine parameters of operation, and facade contractors throughout the United States will increasingly be asked to put forth an effort to adopt the sophisticated analysis and testing capabilities required by this emerging architectural trend. Enclos is committed to addressing the needs of our contractor and architectural clients by developing innovative strategies for condensation management in double-facade systems so that their benefits may be realized independent of winter conditions inherent to the project.



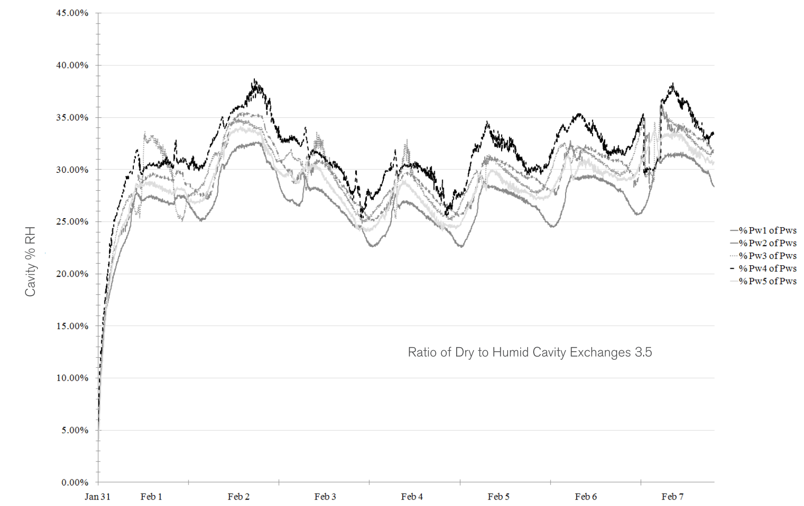


Figure 8 (top): Cold chamber test quotient of dew point and glass temperature at various flow rates of dry and humid air versus time.

Figure 9: Frost on glazing.

Figure 10 (bottom): Warm cavity test humidity versus time.

