Pressure Equalized Insulated Glass Units in Exterior Building Envelopes

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ABSTRACT

This paper challenges the common thinking within the window industry by discussing the practical application of a pressure equalized insulated glass unit (IGU) within exterior building envelopes and introduces the dynamic computer simulation model that was created to model the expected performance. The pressure equalization technology is currently envisioned as being retrofit into in-situ IGUs that exhibit visible signs of failure. Pressure equalized IGUs utilize a special device that equalizes the insulated glass cavity pressure with the exterior of the IGU under specific pressure differentials. These pressure differentials are caused by external environmental factors. By equalizing the pressure, the stresses impacting the IGU sealant material that are typically encountered within the current IGU designs are reduced, resulting in an IGU that is significantly more resistant to seal failures. Due to the exchange of air between the interior and the exterior of the IGU, the pressure equalization technology is not currently compatible with IGUs that use fill gases other than air. This consideration is less important when the technology is applied to existing failed IGUs in the field as the fill gases will have previously dissipated as the interior humidity level of the unit has increased to the point of failure of the unit.

To better understand the complex physical, thermal and moisture dynamics in failed IG systems, a software tool (WinSim, which was developed for EnviroClear Technologies by The Moisture Group Incorporated and is the proprietary property of EnviroClear Technologies) was developed. The physics behind the complex interactions taking place within insulated glass units are well known and documented, however there did not exist a simulation model that incorporated the scientific and climatic data to dynamically model the moisture conditions within these systems. In addition to the International Organization for Standardization (ISO) 15099 calculations, the model also includes dynamic interior and exterior moisture loads, a micro-climate subsystem at the sealant failure location, the effect of convection within the IGU and the impact of the desiccant. WinSim takes hourly climatic data from approximately 50 cities in the United States and Canada and allows the user to "build" the IGU to be modeled from a database containing hundreds of standard glazing components (or custom entered characteristics). WinSim produces raw data, charts and animated movies that dynamically model the thermal and moisture transport in clear glass regions on an hourly basis for both system incorporating the pressure equalization technology and standard failed IGU's.

Variations of the pressure equalization technology have also been deployed in field trials to determine their performance within a real-world setting. The field trials have performed as predicted by WinSim, however a more detailed and rigorous instrumentation of the test IGUs will be required in order to fully validate and calibrate the WinSim outputs.

The results have shown that incorporation of the pressure equalization technology has increased the moisture tolerance of IGU units, reducing and most of the times eliminating the occurrence of condensation on the IGU glass surfaces. It is expected that subsequent generations of the technology can be climatically tuned to further improve the performance of a Pressure Equalize IGU within specific climatic zones. Of particular interest is that WinSim also demonstrates that a Pressure Equalized IGU does not require the presence of a desiccant to manage the appearance of condensation within the interior cavity and indicates that it may be possible to manufacture Pressure Equalized Insulated Glass Units that do not incorporate desiccant within the spacer system.

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INTRODUCTION

An Insulated Glass Unit (IGU) consists of two or more pieces of glass separated by a spacer bar to form one or more sealed air spaces (see Figure 1). The spacer bars are attached to the glass panes using a moisture vapor transmission retardant sealant to prevent air infiltration and a structural sealant to provide flexure resistance. A desiccant material in the spacer bar is used to absorb any residual moisture in the unit during the fabrication process and for future small amounts of moisture that could migrate into the unit. The air space is generally 3/16 in. to 0.5 in. thick and is filled with dried air, argon or krypton and is kept as atmospheric pressure.

Two types of condensation may occur in an IGU that is exposed to various interior and exterior environmental loadings. These are interior/exterior surface condensation and interior seal failure condensation. Below each of these processes are described and briefly discussed.

Interior/Exterior Surface Condensation

It is well understood that occasionally a small amount of condensation on the inner or outer panes of insulated glass units is sometimes accepted, as long as the condensation does not seriously obstruct the view through the window for long periods of time. Damage and mold growth may occur due to interior or exterior glass pane condensation if this occurs more often. A considerable amount of effort in research has already been invested by Lawrence Berkley National Laboratory (LBNL) in understanding these processes and developing a moisture index rating for windows experiencing this type of moisture condensation. Literature suggests that American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and other establishments have reported a large volume of research work. The work reported here is not primarily concerned with this type of exterior and interior window surface condensation, even though the WinSim tool captures these physical phenomena.

Interior IGU Cavity Condensation/Fogging

Interior window cavity condensation resulting from a failed window seal occurs when the amount of moisture entering into the glazing unit through a seal integrity failure exceeds the ability of the desiccant to absorb it. This process can occur slowly over time as moisture diffuses through the sealant material or can occur over a relatively short period of time as a result of a seal integrity failure. A seal integrity failure, while often referred to as a "crack" in the seal, does not actually represent a catastrophic failure of the IGU. For the purposes of this paper, a seal failure is said to exist when the sealants used in the manufacture of the IGU do not maintain a hermetic seal that prevents moisture in any quantity from entering the interior cavity. This is most likely in the form of a microscopic fissure that provides a path for moisture to enter the interior cavity. There are many situations that can cause the seal integrity failure to occur, including manufacturing defects (the presence of contaminants on the glass, improper application of the sealants), chemical incompatibility among components of the IGU elements, improper transportation, handling and installation and the mechanical/environmental stresses placed on the IGU after it has been installed. Such a failure can be visually seen as a fog, a haze, or beads of water running down the interior facing surfaces of the glass panes. There are many factors contributing to the deterioration and ultimate failure of the seal, such as the presence of water, ice and sunlight. Condensation between the glass layers may also be present when glazing use non-approved glazing compounds and when ultraviolet light exposes and deteriorates the glass sealant.

Moisture can migrate into the space between the panes of glass and condense on the colder surface of the exterior pane (Cold Climates) and the interior pane for (Hot Climates). The presence of condensation is annoying not only because it clouds the view but in almost all cases this means that the sealed insulating units must be replaced. Moisture in the glazing unit is also likely to reduce the effectiveness of low-E coatings. It also increases the thermal conductivity of the air slightly, which also contributes to a reduced U-value of the overall IGU. Both degrade the thermal performance of the IGU systems.

If condensation from the seal failure is present on the interior facing surfaces of the glass panes for an extended period of time, the condensate will leach the constituent components from the glass and deposit them on the surface as mineral deposits, resulting in a cloudy appearance even when there is no visible condensation present.

A third type of IGU failure can be found in the chemical fogging (or organic solvent outgassing) of sealed insulated glass units. A chemically fogged IGU has a similar appearance to an IGU that has accumulated mineral deposits due to condensation, however the chemical fogging has little if anything to do with the integrity of the seal. Outgassing occurs as the organic solvents within the sealant, desiccant or other elements of the IGU cure, age or are affected by sunlight. The chemicals released form a cloudy film on the interior facing surfaces of the glass panes.

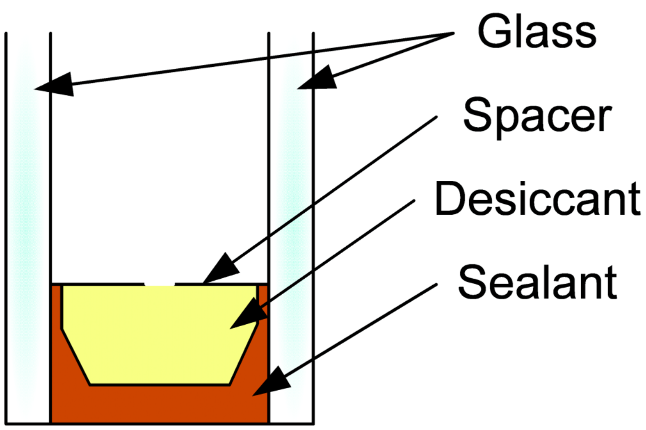

Figure 1 *Cross section of a typical IGU.*

It is difficult to obtain failure statistics for IGUs deployed in the field as the window industry does not currently capture or share this information. While not acknowledged as a problem in the industry, practical experience in the field indicates that failure of installed IGUs is a real concern facing building owners. Most property management firms that we contacted maintain a reserve fund specifically for the replacement of failed IGUs. In addition, a prior generation of pressure equalization technology currently in limited commercial use in the US and Canada has been used to remediate in excess of 250,000 failed IGUs over the past 4 ½ years. While the window industry has made great strides in improving the seal integrity in the new IGUs that have been manufactured in the past few years, there still remains a very significant install base of IGUs that were based on previous generations of sealants and manufacturing standards where the potential for seal integrity failures remains high.

Pressure Equalization—A New Approach

Insulated Glass manufacturers have focused considerable effort on ways to increase the durability of the seal within the IGU. Our practical experience in the field indicates that failure of sealed insulated glass units is still a widespread problem plaguing building owners today. Rather than focus on how to further increase the integrity of the seal, our approach was to examine the forces acting on the IGU and determine how to harness those forces to manage the conditions within the interior cavity of the IGU such that dew point was never reached and visible condensation could not form.

The concept behind pressure equalized insulated glass units is quite simple. The pressure within the interior cavity of an insulated glass unit is never allowed to exceed a certain differential with the exterior of the IGU, thereby greatly minimizing the over/under pressure within the IGU. When the predetermined pressure differential is reached, a pressure equalization device becomes operational and equalizes the pressure. The pressure differential at which the device becomes active can be varied based on the characteristics of the material used in the manufacturing of the device and can be determined through the WinSim computer simulation model. This allows pressure equalization devices to be "tuned" for specific climatic regions. With currently available manufacturing techniques and materials, it is anticipated that the pressure equalization devices will have a life-term in excess of 20 years.

Through trial and error, a process has been developed whereby a failed IGU can be retrofit with the pressure equalization technology in situ and be re-engineered into a pressure equalized insulated glass unit. The process involves creating a precision hole in the failed IGU through which a series of cleaning and rinsing agents are introduced. This is followed by a thorough drying process and the installation of the pressure equalization device. As the resulting pressure equalized IGU undergoes the pressure equalization cycles, residual moisture is expelled from the unit until no visible moisture can be seen on either of the interior facing glass surfaces.

Through the process of pressure equalization, a number of important benefits are realized. First, the IGU seal experiences significantly reduced stress and subsequently has a practically non-existence chance of failure due to stress from pressure differentials. Secondly, the pressure equalized IGU does not experience the bowing and flexing of a typical sealed IGU, resulting in a non-distorted reflection. This has proved to be of particular interest to building architects as they design the optical characteristics of their buildings. This effect is shown in Figure 2.

A further benefit was observed during field testing, and also exhibited during the modeling of the performance of failed vs pressure equalized insulated glass units. When a failed IGU was re-engineered in the field as a pressure equalized IGU, the appearance of visible condensation was eliminated as the pressure equalization cycles allowed the interior cavity to dry out. It was assumed that the desiccant material was completely saturated, losing its ability to absorb moisture and resulting in the appearance of visible condensation within the IGU. It is common practice for IGU manufacturers to utilize a molecular sieve desiccant within their insulated glass units. Once moisture is captured within the molecular sieve material, it can only be extracted through the application of heat at temperatures which the field windows never came close to experiencing. This indicated that the desiccant within the IGU did not appear to be having any impact on the performance of the newly re-engineered unit. Modelling of a pressure equalized IGU without the presence of a desiccant indicates that pressure equalized IGU do not require the incorporation of a desiccant in order to remain failure-free.

An anticipated benefit of pressure equalized IGUs is related to the chemical fogging of units due to organic solvent outgassing. Since there is an active exchange of air between the interior cavity and the exterior of the window, the concen-

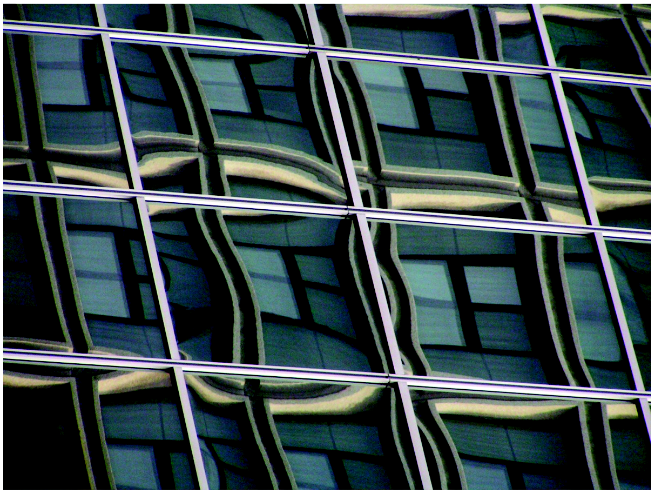

Figure 2 *Reflection distortion in IGUs.*

tration of these organic chemicals will be reduced. Further research and experimentation is required to accurately determine the level of outgassing that can be withstood by a pressure equalized IGU.

The in-situ re-engineering of existing IGUs into Pressure Equalized IGUs provides a significant environmental benefit as the lifetime of the processed unit is extended and the embodied energy within the window components that would ordinarily have to be replaced is preserved. From a practical standpoint, the in-situ remediation versus removal and replacement of a failed IGU is also much less intrusive to the area surrounding the failed IGU.

WINSIM—UNDERSTANDING THE COMPLEX PHYSICAL, THERMAL AND MOISTURE DYNAMICS

When the dynamic pressure equalization concept was first being explored, existing testing laboratories were approached as a means to test the hypotheses that had been developed and also to provide a means to better understand the dynamics of the various physical, thermal and moisture factors impacting the insulated glass units. It quickly became apparent that the existing test apparatus were not sufficient for the task we required and a new approach would have to be undertaken. The project team began to explore the use of computer simulation models. The physics behind the complex interactions taking place within insulated glass units are well known and documented (ISO/DIS 15099 Thermal Performance of Windows, Doors and Shading Devices – Detailed Calculations), however there did not exist a simulation model that incorporated the scientific and climatic data to dynamically model the moisture conditions in insulated glass units. The decision was made to construct a proprietary modeling program specifically to model the moisture conditions within sealed and pressure equalized insulated glass units – WinSim.

The WinSim tool can be used to investigate the heat and mass transfer (vapor transport) that occurs in and through an insulated glass unit (clear glass region) for a selected number of climatic locations in the U.S and Canada. WinSim also allows the prediction of the thermal and moisture transport that occurs across an IGU as a function of interior and exterior climatic conditions. The software architecture allows for the simultaneous prediction of the condensation potential of an IGU with and without the presence of the pressure equalization devices.

The pressure equalization devices were modeled as a dynamic valve that allows pressure equalization at certain pressure bleeding/closing value ranges. Performance characteristics of the devices can be modified by the user.

The model accounts for two methods whereby moisture can enter into the interior cavity of the IGU; diffusion and seal failure. Diffusion occurs as the pressure equalization process exchanges air between the interior cavity and the environment. Seal failure was modelled as a fissure in the seal through which moisture could be draw under specific underpressure conditions. In order to test the pressure equalization hypothesis under a "worst case" scenario, we modelled the performance of an IGU with a significant moisture intrusion potential scenario—"High Intrusion". The moisture source that was chosen was the wind-driven rain that presented itself on the surface of the IGU and it was assumed that a percentage of the wind-driven rain was presented itself on the surface would work its way into the interior cavity through the seal failure.

As the moisture intrusion potential of the seal failure is significantly higher than that of diffusion, we are confident that the pressure equalization technology will function as well of better on an IGU that has accumulated moisture within the interior cavity through simple diffusion alone.

Quantification of the amount of condensation as a function of positioning of the pressure equalization devices (either on the exterior or interior glass panes) was incorporated in the engineering software. The outcome of the proposed research software development allows advancement of the current level of quantitative knowledge in moisture control of failed IGUs for the wide range of climatic conditions in North America, as current knowledge is basically qualitative in content. Furthermore, WinSim has been designed such that climatic data from any geographical environment can easily be incorporated with minimal modifications. In addition to understanding moisture control processes in insulated glass units, the tool can be used to predict the orientation and characteristics of the pressure equalization devices for optimum performance, and to estimate the amount of water condensation on any glazing surface.

The thermal processes such as conduction, radiation exchange (reflection, absorption, transmission, emission) at each glass surface, natural convection in the glazing cavity, and thermal resistances at the surfaces that are dependent on ambient temperature and local wind conditions (exterior surfaces) are included in the software. The latent heat transfer of evaporation and condensation is also incorporated. Influence of both intentional (pressure equalization) and unintentional air leakage is included as a source/sink for both moisture and energy transport. Variable temperature and moisture content dependent air properties are coded into the hygrothermal engineering software. In the moisture transport component, the sorption characteristics of air was included along with the condensation potential of water and if temperatures dwell below zero the formation of frost is included. Moisture storage and release mechanisms due to the presence of desiccants are also included. The ISO/DIS 15099 Thermal Performance of Windows, Doors and Shading Devices — Detailed Calculations was be followed for the governing transport equations.

WinSim allows the user to determine the condensation performance of the insulated glass unit with and without the presence of the pressure equalization devices. Hourly simulations are performed that consider the exterior loads: temperature, relative humidity, wind speed, wind orientation, sky cloud index, and rain precipitation. On the interior surface, the interior RH and temperature is modeled as a function of exterior climate using the proposed ASHRAE SPC 160P[1] standard.

The hygrothermal transport dynamics in envelope systems can be very complex. Depending upon the complexity of the problem under consideration, models can be based on very simple, 1-D steady state methods or on more sophisticated, transient methods. Version 1.0 of WinSim was developed based on a transient 1-D simulation analysis.

The following level of inputs were required for the WinSim modelling tool:

Exterior environmental loads
Interior environmental loads
Surface heat transfer conditions
IGU Surface Characteristics
Desiccant Material Properties

ASSUMPTIONS EMPLOYED

The model assumes the following physical properties for calculations.

The simulated IGU can have two or three sheets of glass with cavities of any given thickness. As a default value, cavities thicknesses are of 12 mm (0.5 inches). The effect of temperature differences are taken into account in the cavities by calculating the corresponding Nusselt (Nu) numbers and the radiation components are calculated separately according to ISO standard 15099 entitled *"Thermal performance of windows, doors and shading devices – detailed calculations"*. Figure 3 shows the inputs required for some of the surface properties. The emissivities of the surfaces are affected by the amount of condensate i.e., the initially given emissivities are for dry surfaces. This is an innovation of this model that has yet to be implemented in other IGU performance simulation software.

The software makes a comparison between a failed IGU with and without the pressure equalization device. The moisture entering into the interior cavities is assumed to originate from wind driven rain (WDR).

The failed insulated glass unit is assumed to behave in the following way:

- The air pressure cannot be released through the seal failure and this allows pressure to build up (negative/positive). The seal failure is assumed to allow some air/water exchange and the assumption involved in these simulations is that ventilation exists in the failed IGU, but only after 100 Pa (or other set point) pressure difference.
- The pressure equalization device is assumed to behave in such a way that when the pressure difference between the cavity and outdoor air exceeds the design characteristics for the device, the pressure differential is equalized. The pressure equalization devices do not allow liquid water leakage (zero water penetration), but we assume that the seal failure still exists.

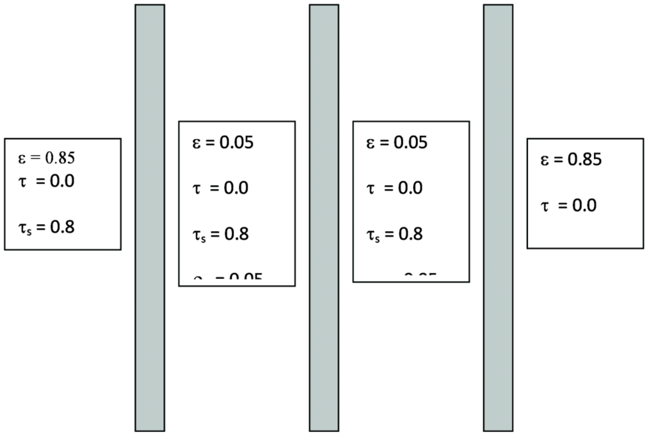

Figure 3 *Schematic of the windows.*

- The air exchange (pressure equalization) occurs once in every hour and the main force is the change in temperature affecting the pressures inside the IGU. The outdoor pressure is read from the weather file and it introduced its corresponding effects. Changes in the pressures shorter than an hour are not currently taken into account due to the limitations of the weather file (1 hourly time step).

Initial conditions are defaulted to dry conditions at an equilibrium moisture of 50%-RH or at any user selected humidity.

DESICCANT

The model allows for the use of desiccant in the glazing cavities. The desiccant sorption curve is given as input. The quantity of the desiccant present is given by multiplying the width of the IGU times the cavity thickness. If the real amount of desiccant is less than that value, then the density provided as an input should be changed proportionally. For instance, setting the desiccant amount to 0 will simulate an IGU constructed without desiccant.

The desiccant sorption curve is given with the equation

$$u = a \cdot RH^b + c \cdot RH^d$$

where u is moisture content (kg-water/kg-dry desiccant) of desiccant and RH is the relative humidity (0-1). Density of the desiccant is also given as input. The default equation currently holds coefficients given the sorption curve as in Figure 4. The coefficients a, b, c and d can define a number of desiccants used in the insulated glass units.

WIND DRIVEN RAIN AND WATER INTRUSION THROUGH THE SEAL FAILURE

The water entering the interior cavity due to wind driven rain is assumed to occur as a function of the underpressure

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[1] As of the authoring date of this paper, 160P has not been accepted as an official standard of ASHRAE.

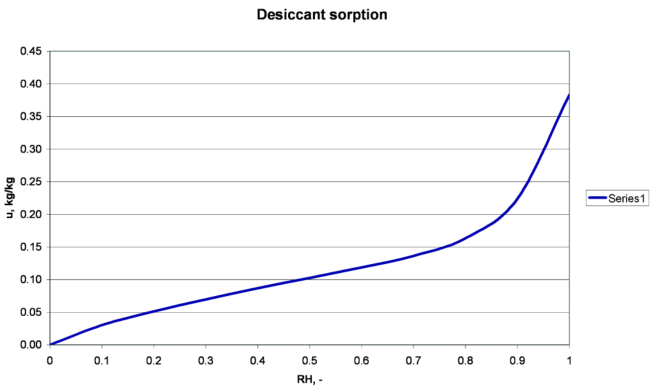


Figure 4 *Default sorption curve of the desiccant.*

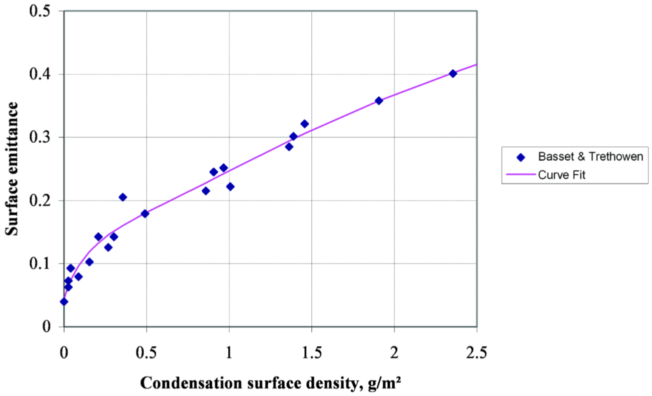


Figure 5 *From Basset and Trethowen (1984).*

inside the IGU. The IGU receives water on its surface and a certain amount of this water can enter into the interior cavity. In these simulations a factor of 0.1% is used. The amount of water entering the interior cavity is linearly dependent on the pressure

$$WaterIntoCavity = min(1, dP/100) \cdot 0.1\% \cdot WDR$$

where WDR is the wind driven rain on the IGU which is a function of wind speed, direction and rain intensity. That means that 0.1% of the wind driven rain gets into the interior cavity through the seal failure once the underpressure between the cavity and outdoors is 100 Pa or more.

CHANGES IN EMISSIVITY OF SURFACES AS A FUNCTION OF CONDENSATION

The emissivity of the low emission coatings on the panes of the IGU increases as the condensation forms on the surface. The emissivity is assumed to behave as in Figure 5 for different initial (dry) emissivities.

The increase in emittance will result in thermal degradation effects and eventually the low U-value may be lost. However, if both surfaces facing the cavity have very low emittance, then the U-value degradation may not be very severe, because water will condense on the colder surface leaving the other low emissivity surface intact.

At fast changes before the balance inside the cavity is reached – both surfaces may condense water. The current assumption in the software however is that the balance in the air cavity is reached within one hour, which is the length of the time step employed in the calculations.

CAVITY RELATIVE HUMIDITY

The relative humidity levels in the air cavities rarely reach saturation because normally one of the surfaces is at lower temperature that (eventually) should control the moisture content of air. The air reaches saturation only if the temperatures of the surfaces are the same, because of the surface condensation occurring at the coldest surface.

CONDENSATE ON THE SURFACES

The condensation occurs mainly in the cavity that has originated from moisture that entered the cavity through the seal failure as determined by the wind driven rain intrusion rate, other sub-system climates can also occur, but this is the most obvious one. The condensate may move between the surfaces to the lower temperature surface. The number of condensation hours per month is calculated by taking the hour as an “hour with condensation” if there is any condensation on any surface including the exterior and interior surfaces of the whole IGU. The exterior surface has typically some condensation but very little in most cases.

MODEL EQUATIONS AND PROCEDURES

The calculations are performed according to the standard ISO/DIS 15099 for heat transfer with some minor modifications (effect of condensate on surface emittance). The material below is replicated from the above standard.

Glazing Layer Energy Balance Calculation

Radiative heat exchange between glazing layers and conductive heat transfer within each glazing layer can be described using fundamental relations. In Figure 6, the energy balance is shown for an insulated glass unit. Calculations dealing with convective heat transfer depend on correlations based on experimental data.

The values of four variables are sought at each glazing. These are the temperatures of the outdoor and indoor facing surfaces, $T_{f,i}$ and $T_{b,i}$, plus the radiant fluxes leaving the front and back facing surfaces (i.e., the radiosities), $J_{f,i}$ and $J_{b,i}$. In terms of these variables q_i, is:

$$q_i = h_{c,i}\lfloor T_{f,i} - T_{b,i-1}\rfloor + J_{f,i} - J_{b,i-1}$$

The solution is generated by applying the following four equations at each glazing:

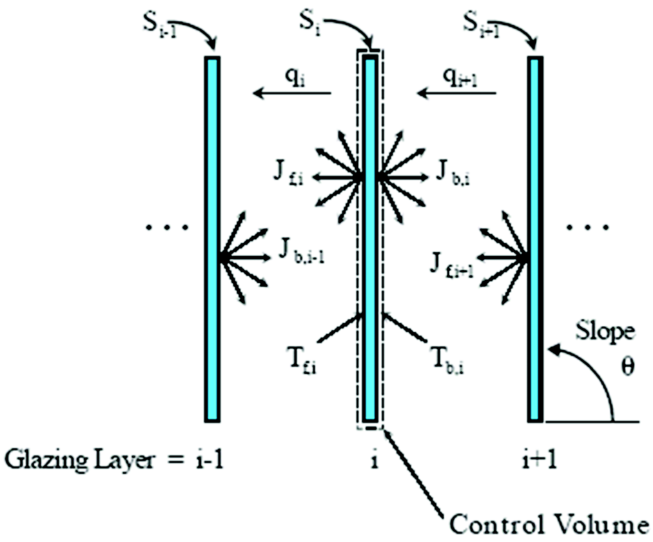


Figure 6 *Energy balance on the* i*th glazing layer.*

$$q_i = S_i + q_{i+1}$$

$$J_{f,i} = \varepsilon_{f,i}\sigma T_{f,i}^4 + \tau_i J_{f,i+1} + \rho_{f,i} J_{b,i-1}$$

$$J_{b,i} = \varepsilon_{b,i}\sigma T_{b,i}^4 + \tau_i J_{b,i-1} - \rho_{b,i} J_{f,i+1}$$

$$T_{b,i} - T_{f,i} = \frac{t_{gl,i}}{2\lambda_{gl,i}}[2q_{i+1} + S_i]$$

Equation for q describes an energy balance imposed at the surfaces of the ith glazing. Equations for $J_{f,i}$ and $J_{b,i}$ define the radiosities at the *i*th glazing. The last equation describes the surface temperatures for the *i*th glazing.

It is assumed that the solar energy is absorbed uniformly through the thickness of the glazing. The reflectance (ρ), transmittance (τ) and emissivity (ε) follow the equation

$$\rho = 1 - \tau - \varepsilon$$

Convective Heat Transfer Coefficient in Glazing Cavities

Convective heat transfer coefficients for the fill gas layers are determined in terms of the dimensionless Nusselt number, Nu_i;

$$h_{c,i} = \mathrm{Nu}_i\left(\frac{\lambda_{g,i}}{d_{\varepsilon,i}}\right)$$

where $d_{g,i}$ is the thickness of the ith fill gas layer (or pane spacing) and $\lambda_{g,i}$ is the thermal conductivity of the fill gas. Nusselt number Nu_i is calculated using correlations based on experimental measurements of heat transfer across inclined air layers. Nu_i is a function of the Rayleigh number, Ra_i, the cavity aspect ratio, $A_{g,i}$, and the cavity slope, θ.

The Rayleigh number can be expressed as

$$\mathrm{Ra} = \frac{\rho^2 d^3 g\beta C_p \Delta T}{\mu\lambda}$$

Thermal expansion coefficient of the fill gas, β, is (assuming perfect gas law)

$$\beta = \frac{1}{T_m}$$

where T_m is the fill gas mean temperature (K). The aspect ratio of the gas cavity is $A = H/d$, where H is the distance between the top and bottom of the fill gas cavity and d is the cavity thickness.

The assumption is that the cavity is heated from the indoor side. If the window is tilted and the outdoor side temperature is higher than indoor side temperature then the tilt angle used in the equations need to be changed to 180-θ. The equations for the different conditions and tilt angles (θ) are as follows.

Cavities Inclined at $0 \le \theta < 60°$

$$\mathrm{Nu}_i = 1 + 1.44\left[1 - \frac{1708}{\mathrm{Ra}\cos(\theta)}\right]^*\left[1 - \frac{(1708\sin^{1.5}(1.8\theta))}{\mathrm{Ra}\cos(\theta)}\right] + \left[\left[\frac{\mathrm{Ra}\cos(\theta)}{5830}\right]^{1/3} - 1\right]^*$$

$$\mathrm{Ra} < 10^5 \text{ and } A_{g,i} > 20$$

$$\text{where } [x]^* = (x + |x|)/2$$

Cavities Inclined at $\theta = 60°$

$$\mathrm{Nu} = [\mathrm{Nu}_1, \mathrm{Nu}_2]_{max}$$

where

$$\mathrm{Nu}_1 = \left[1 + \left[\frac{0.0936\mathrm{Ra}^{0.314}}{1 + G}\right]^7\right]^{1/2}$$

$$\mathrm{Nu}_2 = \left[0.104 + \frac{0.175}{A_{g,i}}\right]\mathrm{Ra}^{0.283}$$

$$G = \frac{0.5}{\left[1 + \left[\frac{\mathrm{Ra}}{3160}\right]^{20.6}\right]^{0.1}}$$

Cavities Inclined at $60° < \theta < 90°$

For layers inclined at angles between 60° and 90°, a straight line interpolation between the results of equations for θ = 60° and for θ = 90° is used.

Vertical Cavities θ = 90°

$$\mathrm{Nu} = [\mathrm{Nu}_1, \mathrm{Nu}_2]_{max}$$

$$\mathrm{Nu}_1 = 0.0673838\mathrm{Ra}^{1/3} \quad 5 \times 10^4 < \mathrm{Ra} < 10^6$$

$$\mathrm{Nu}_1 = 0.028154\mathrm{Ra}^{0.4134} \quad 10^4 < \mathrm{Ra} \le 5 \times 10^4$$

$$\mathrm{Nu}_1 = 1 + 1.7596678 \times 10^{-10}\mathrm{Ra}^{2.2984755} \qquad \mathrm{Ra} \le 10^4$$

$$\mathrm{Nu}_2 = 0.242\left[\frac{\mathrm{Ra}}{A_{g,\,i}}\right]^{0.272}$$

Cavities Inclined from 90° to 180°

$$\mathrm{Nu} = 1 + [\mathrm{Nu}_v - 1]\sin\theta$$

where Nu_v is the Nusselt number for a vertical cavity.

Fill Gas Properties

The density of fill gases in windows is calculated using the perfect gas law

$$\rho = \frac{PM}{RT_m}$$

where $P = 101300$ Pa and $T_m = 293$ K.

The transport properties and specific heat are evaluated using linear functions of temperature as listed in ISO/DIS 15099. In this software the fill gas is assumed to be air.

Boundary Conditions

The boundary conditions consist of:

- Indoor and outdoor temperature
- Indoor and outdoor convective heat transfer coefficients
- Solar radiation
- Long wave irradiance on the outdoor and indoor glazing surfaces (cloud index included)
- Wind speed and direction
- Precipitation

Convective Heat Transfer Coefficient—Indoor Side

The convective heat transfer on indoor side primarily occurs by natural convection, and rarely by mixed and forced convection. Standard boundary conditions assume natural convection on indoor side. The density of convective heat flow on the indoor boundary is defined as:

$$q_{c,\,in} = h_{c,\,in}(T_{s,\,in} - T_{in})$$

where $T_{s,in}$ is the indoor side glazing surface temperature.

Heat Transfer by Natural Convection

The natural convection heat transfer coefficient for the indoor side, hc,in is determined in terms of the Nusselt number, Nu.

$$h_{c,\,in} = \mathrm{Nu}\left(\frac{\lambda}{H}\right)$$

where λ is the thermal conductivity of air and H the height of the glazing surface. Nu is calculated as a function of the corresponding Rayleigh number, Ra_H, based on the height, H.

$$\mathrm{Ra}_H = \frac{\rho^2 H^3 g C_p |T_{b,\,u} - T_{in}|}{T_{m,f}\,\mu\lambda}$$

where the fluid properties are those of air evaluated at the mean film temperature:

$$T_{m,f} = T_{in} + \frac{1}{4}(T_{b,\,u} - T_{in})$$

Since the temperatures depend on the heat transfer coefficient and vice versa, iterations are needed.

The Nusselt number is calculated for different inclination angles in still air using the following equations.

Inclination Angle 0 ≤ θ < 15°

$$\mathrm{Nu}_{in} = 0.13\mathrm{Ra}_H^{1/3}$$

Inclination Angle 15 ≤ θ ≤ 90°

$$\mathrm{Nu}_{in} = 0.56(\mathrm{Ra}_H \sin\theta)^{1/4} \qquad \mathrm{Ra}_H \le \mathrm{Ra}_c$$

$$\mathrm{Nu}_{in} = 0.13(\mathrm{Ra}_H^{1/3} - \mathrm{Ra}_c^{1/3}) + 0.56\mathrm{Ra}_c \sin\theta \qquad \mathrm{Ra}_H \le \mathrm{Ra}_c$$

$$\mathrm{Ra}_c = 2.5 \times 10^5\left(\frac{e^{0.720}}{\sin\theta}\right)^{1/6} \qquad \theta \text{ in degrees}$$

Inclination Angle 90 < θ ≤ 179°

$$\mathrm{Nu}_{in} = 0.56(\mathrm{Ra}_H \sin\theta)^{1/4} \qquad 10^5 \le \mathrm{Ra}_H \le 10^{11}$$

Inclination Angle 179 < θ ≤ 180°

$$\mathrm{Nu}_1 = 0.58\mathrm{Ra}_H^{1/3} \qquad \mathrm{Ra}_H \le 10^{11}$$

In case of forced convection the following correlation is to be used for the convection heat transfer coefficient (ISO 6946)

$$h_{c,\,in} = 4 + 4V \quad \mathrm{W/m^2}k \qquad (V \text{ in m/sec})$$

Convective Heat Transfer Coefficient—Outdoor Side

The convective heat transfer on the outdoor side primarily occurs by forced convection. The density of convective heat flow on the outdoor boundary is defined as:

$$q_{c,\,out} = h_{c,\,out}(T_{s,\,out} - T_{out})$$

The forced convection occurs due to wind washing the window surface. The following parameters are needed as input:

V = wind speed (m/s)

θ = wind direction (from south clockwise)

ε = wall azimuth angle (positive degrees westward from south and negative eastward)

Calculation Proceeds as Follows:

Calculate wind direction relative to the wall surface $\gamma = \varepsilon + 180 - \theta$

if $|\gamma| > 180$ then $\gamma = 360 - |\gamma|$

if $-45 \le |\gamma| \le 45$ the surface is windward;
otherwise the surface is leeward

Calculate the air velocity near the outside surface u:

a. windward $u = 0.25v$ ($V > 2$), $u = 0.5v$ ($V \le 2$)

b. leeward $u = 0.3 + 0.05v$

Calculate the outside convective heat transfer coefficient $h_{c,out} = 4.7 + 7.6u$

Longwave Radiation Heat Transfer

Outdoor irradiance can be defined through the use of outdoor mean radiant temperature, $T_{r,m}$. In the model the mean radiant temperature is calculated assuming that the ground temperature is the same as the outdoor air temperature and the sky temperature is

$$T_{sky} = 0.0552 \cdot T_{OUT}{}^{1.5}$$

where T_{out} is in K.

The view factors and the mean radiant temperature are calculated using equations

$$\mathrm{F2} = cos(\theta/2)^2$$

$$\mathrm{F1} = 1 - \mathrm{F2}$$

$$T_{r,m} = (\mathrm{F1} \cdot T_{out}^4 + \mathrm{F2} \cdot T_{sky}^4)^{1/4}$$

Calculation of Solar Energy Absorbed by the Glazing

Calculations were based on Annex A, ISO/DIS 15099. A window with n glazing together with the outdoor ($i = 0$) and indoor ($i = n + 1$) spaces form an $n + 2$ element array. The glazing system optical analysis can be carried out by considering the spectral fluxes of radiant energy flowing between the $i-1$th and ith glazings, $I_i^+(\lambda)$ and $I_i^-(\lambda)$. The + and – superscripts denote radiation flowing toward the outdoor and indoor side, respectively, as shown in Figure 7.

The following two equations are applied while setting the reflectance and transmittance of the conditioned space to zero $\rho_{f,n+1} = 0$ and $\tau_{n+1} = 0$.

$$I_i^+(\lambda) = \tau_i(\lambda) I_{i+1}^-(\lambda) + \rho_{f,i}(\lambda) I_i^-(\lambda) \qquad i = 1 \text{ to } n+1$$

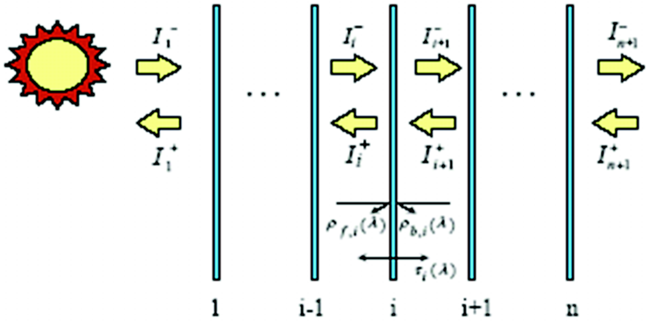


Figure 7 *Analysis of solar flux in multi-layer glazing system.*

$$I_i^-(\lambda) = \tau_{i-1}(\lambda) I_{i-1}^-(\lambda) + \rho_{b,i-1}(\lambda) I_i^+(\lambda) \qquad i = 2 \text{ to } n+1$$

It can be shown that the ratio of $I_i^+(\lambda)$ to $I_i^-(\lambda)$ is given by:

$$\frac{I_i^+(\lambda)}{I_i^-(\lambda)} = r_i(\lambda) = \rho_{f,i}(\lambda) + \frac{\tau_i^2(\lambda) r_{i-1}(\lambda)}{1 - \rho_{b,i}(\lambda) r_{i+1}(\lambda)} \tag{1}$$

and the ratio of $I_{i-1}^-(\lambda)$ to $I_i^-(\lambda)$ is given by:

$$\frac{I_{i+1}^-(\lambda)}{I_i^-(\lambda)} = t_i(\lambda) = \frac{\tau_i(\lambda)}{1 - \rho_{b,i}(\lambda) r_{i+1}(\lambda)} \tag{2}$$

Now all values of $I_i^-(\lambda)$ and $I_i^+(\lambda)$ can be found using the following steps. First, use Equation 1 as a recursion relationship to calculate all values of $r_i(\lambda)$ by working from $r_{n+I}(\lambda) = \rho_{f,n+1}(\lambda) = 0$ to $r_1(\lambda)$. Second, use Equation 2 to obtain $t_i(\lambda)$ from $i = 1$ to $i = n$. The rest of the solution follows by first calculating the flux reflected from the glazing system to the outdoor side $I_i^-(\lambda) = r_1(\lambda) I_i^-(\lambda)$ and then marching toward the indoor side from $i = 2$ to $i = 1$ calculating the remaining fluxes $I_i^-(\lambda) = t_{I-1}(\lambda) I_{i-1}^-(\lambda)$ and $I_i^+(\lambda) = r_i(\lambda) I_i^-(\lambda)$.

Finally, the desired portions of incident radiation at each of the glazing layers are given by:

$$A_i(\lambda) = \frac{I_i^-(\lambda) - I_i^+(\lambda) + I_{i-1}^+(\lambda) - I_{i+1}^-(\lambda)}{I_i^-(\lambda)}$$

and the portion transmitted to the conditioned space is

$$\tau_i(\lambda) = \frac{I_{i+1}^-(\lambda)}{I_i^-(\lambda)}$$

$I_i^-(\lambda)$ is set equal to unity for the purpose of solving these equations.

Moisture Performance and Air Exchange

The IGU cavity can have air exchange between outdoor or indoor air through the seal failure or through pressure equalization devices made for this purpose. The seal failure in the IGU may also permit water to enter into the cavity when the cavity is at lower pressure than the exterior surface. The pressure difference can be caused by the wind pressure acting on the surface, by the temperature changes in the cavity air or by the variations in atmospheric pressure. The air in the interior cavity contains humidity that may condense on the surface(s) in the cavity if the humidity exceeds the dew point. The amount of moisture that the air can contain depends on temperature as well as total pressure.

The altitude affects the air pressure as in Table 1. Water vapor pressure behaves in the similar fashion—the relative humidity stays constant i.e., the saturation pressure at the same temperature but at lower pressure is lower.

The water entering the cavity through the seal failure increases the humidity in the cavity air. Air exchange between the cavity and ambient air creates flow of water vapor into or out of the cavity. The flow of air is caused by the pressure difference between the cavity and exterior and this pressure difference is mainly caused by the temperature changes in the IGU cavity. Increasing temperature will exhaust air from the cavity thus removing moisture from cavity. Higher temperature means higher capacity for air to contain water vapor and therefore exhaust air can have higher moisture content than the replacement air that is cooler (later when the IGU cools down the pressure decreases and causes air inflow).

The effects of temperature on the pressure in the cavity is based on ideal gas law which gives for pressure

$$P = \rho RT/M$$

when the volume is constant (which is not exactly true since there can be very minute deflection of the window glazings). The flow continues until the balanced pressure is reached.

SUMMARY AND DISCUSSION

In this section various thermal and moisture performance output from the WinSim model are presented to show the performance of the pressure equalization technology for one city in the USA (Seattle) and one in Canada (Toronto).

The simulation model was run for a representative rectangular IGU with a width of 1.2 m (47.2 in.), a length of 1.2 m (47.2 in.), a spacer thickness of 12 mm (0.5 in.) and both exterior and interior pane thicknesses of 3 mm (0.1 in.). The exterior glass (clear glass) had a solar transmittance of 0.83384, a solar reflectance of 0.074763, a longwave transmittance of 0, and an longwave emittance of 0.84 for both exterior (1) and (2) interior glass surfaces. The interior glass was a gray coated glass, with a solar transmittance of 0.608956, solar reflectance surface (1) of 0.059576, solar reflectance surface (2) of 0.060991, a longwave transmittance of 0, and a longwave emittance of 0.84 for both surfaces (1) and (2). Two orientations were chosen (North and South), with the majority of the simulations performed with the IGU oriented north. All IGUs were positioned vertically, as found in vertical wall systems, and none were inclined. Two desiccant settings were modeled (new desiccant and no desiccant) to examine the performance of the pressures equalization devices in a desiccant free IGU.

Table 1. Effect of Altitude on Air Pressure

Height		Temperature		Pressure
(ft)	(m)	(°F)	(°C)	(hPa)
0	0	59	15	1013
3280.84	1000	47.3	8.5	900
6561.68	2000	35.6	2	800
9842.52	3000	23.9	–4.5	700
13123.36	4000	12.2	–11	620

The pressure equalization devices where only connected to the exterior environment. In all the simulations, a high water intrusion scenario was employed. All windows were located on the first floor of a commercial building.

The simulations were run with time zero equivalent to January 1. Two years of simulations were performed, corresponding to the 10% cold and hot years (ASHRAE SPC 160P). During each simulation, two conditions were simulated; one corresponding to a window that had pressure equalization devices and the other without.

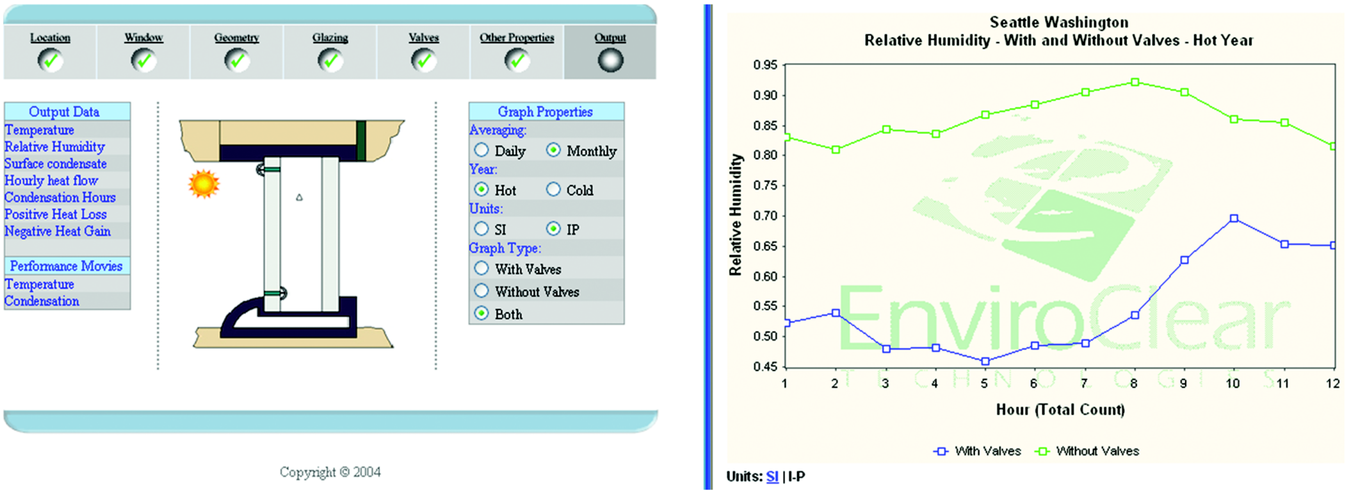
Model Outputs

Figures 8 through 11 depict the thermal and moisture performance of a failed IGU as a function of the pressure equalization devices with and without the IGU containing a desiccant.

There are positive thermal performance gains when employing the pressure equalization devices, in addition to reducing or even eliminating the amount of condensation occurring on the IGU surfaces. In Figures 9 and 10, the benefits of employing the devices is clearly observed for an IGU in the city of Seattle without desiccant. Reduction of the relative humidity of up to 40% (Figure 8) and a significant reduction in the number of hours with even a small amount of condensation (Figure 9) is achieved through the operation of the pressure equalization For the city of Seattle, the IGU condensation numbers are higher during the rainy period of year coinciding with the months of October to February. The WinSim model predicts this behavior very well.

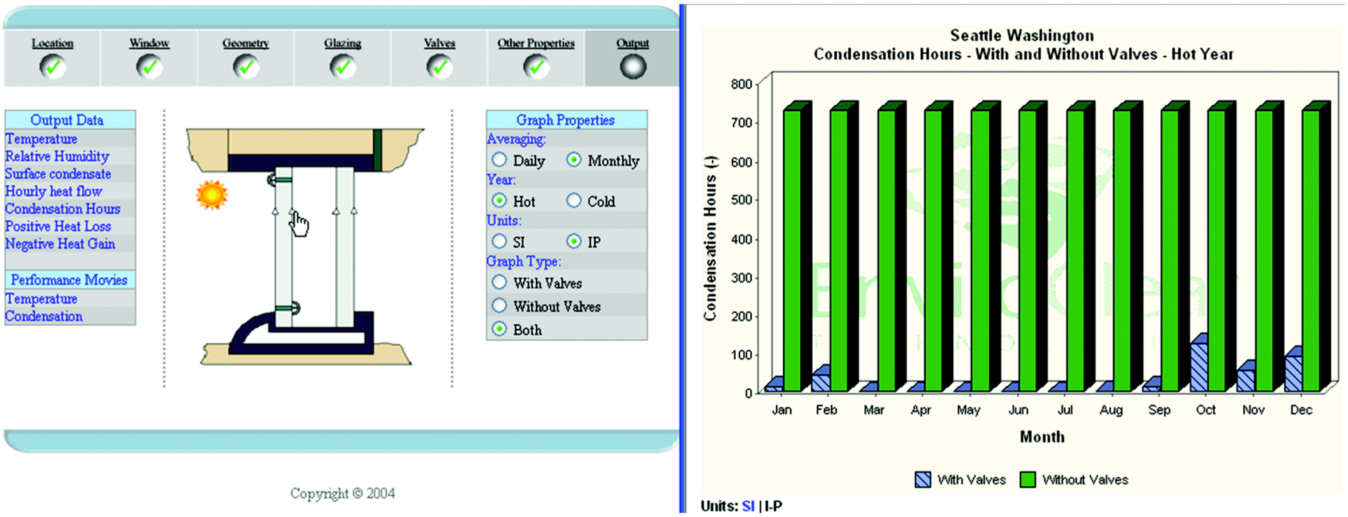
For a colder climate such as the one in Toronto (Figures 10 and 11), a similar behavior is found for the pressure equalization devices.

In conclusion, the results have shown that incorporation of the pressure equalization devices has increased the moisture tolerance of IGU units, reducing and most of the times eliminating the occurrence of condensation on the IGU interior glass surfaces. The results presented here are unique in this regard and have not been presented in the open literature. It is expected that the next generation of pressure equalization devices will be climatically tuned for better performance.



Graph Properties
Averaging:
○ Daily ● Monthly
Year:
● Hot ○ Cold
Units:
○ SI ● IP
Graph Type:
○ With Valves
○ Without Valves
● Both

Figure 8 *Seattle RH within IGU (no desiccant case).*



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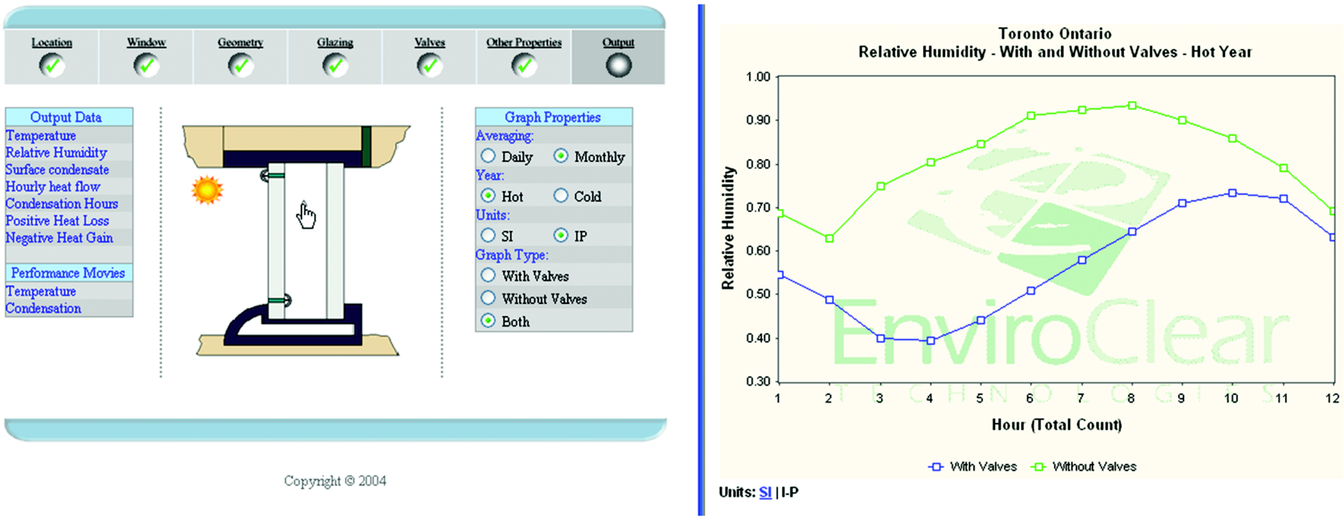
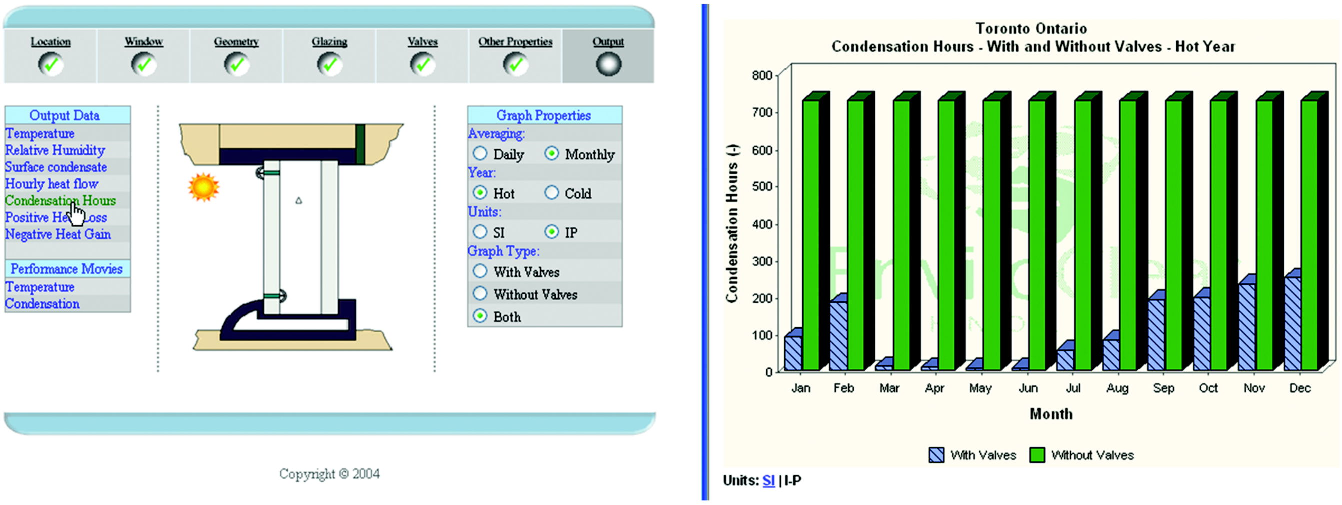
Averaging:
○ Daily ● Monthly
Year:
● Hot ○ Cold
Units:
○ SI ● IP
Graph Type:
○ With Valves
○ Without Valves
● Both

Figure 9 *Seattle number of condensation hours with and without pressure equalization devices (no desiccant case). Note: This chart displays the total number of hours where any condensate is present on the glass surface. Experimentation is required determine the point at which the condensate is visible to calculate the number of visible condensation hours.*



Graph Properties
Averaging:
○ Daily ● Monthly
Year:
● Hot ○ Cold
Units:
○ SI ● IP
Graph Type:
○ With Valves
○ Without Valves
● Both

Figure 10 *Toronto RH within IGU (no desiccant case).*



Averaging: ○ Daily ● Monthly
Year: ● Hot ○ Cold
Units: ○ SI ● IP
Graph Type: ○ With Valves ○ Without Valves ● Both

Figure 11 *Toronto number of condensation hours with and without pressure equalization devices (no desiccant case). Note: This chart displays the total number of hours where any condensate is present on the glass surface. Experimentation is required determine the point at which the condensate is visible to calculate the number of visible condensation hours.*

REFERENCES

ASHRAE. 1999. ASHRAE Standard 160P (proposed), Prevention of Moisture Damage.

Basset M.R. and H.A. Trethowen. 1984. Effect of Condensation on Emittance of Reflective Insulation. Journal of Thermal Insulation. Vol. 8. October. pp. 127-135.

ISO. 2000. ISO/DIS 15099—Thermal Performance of Windows, Doors and Shading Devices—Detailed Calculations.

Karagiozis, A. 2005. WinSim 1.0—A Dynamic Moisture Simulation Model for Thermal Windows.

Karrer, R., and Henkel. 2005. How compatibility tests lead to the introduction of compatible adhesives and sealant systems.