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Thermal performance and condensation risk of single-pane glazing with low emissivity coatings

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ABSTRACT

To understand the potential impacts on both thermal performance and condensation risks of using low-e coatings in buildings, especially in the single-pane sector, in this work, parametric numerical analysis in winter is conducted. Three building glazing models, including the single-pane without low-e coatings (SNL), single-pane with exterior low-e coatings (SEL), and single-pane with interior low-e coatings (SIL), are selected and simulated through COMSOL over a range of outdoor temperature and indoor humidity. The temperature of the interior surface of windows, heat flux through windows, winter U-factor of center-of-glass will be obtained and compared. Additionally, a numerical code is developed in R to compute and plot the condensation temperatures of these three models upon the given indoor humidity levels and simulated surface temperatures. The comprehensive analysis of condensation risks on the glazing inner surface of the three models will be conducted.

This parametric simulation effort indicates an interesting feature for a single-pane window: while the SIL gives a substantially lower U than the SNL, it also corresponds to an increased condensation risk under certain limits of external temperature and indoor humidity levels. Upon the resultant condensation temperatures and thermal performance analysis, we can conclude the parameters of the windowpane property, coating emissivity and placement, local climate, and building interior thermal settings must be taken into account collectively when it comes to adding low-e coatings to single-pane windows.

INTRODUCTION

Windows play an important role in forming the façade and the interior of a building. However, windows are normally the weakest elements, in which thermal performance is much lower than other building envelope, i.e. walls, roofs. In general, nearly 40% of the total energy consumption is related to buildings; about 25% of the HVAC (heating, ventilation, and air conditioning) energy is lost through windows [1] . In the United States, 30 ~40% windows are single-pane, especially in older buildings, and they are responsible to over 50% of the total energy lost through windows [2-4]. In order to obtain more energy-efficient buildings, one of the main practical strategies is to add low emissivity (low-e) coating on windowpanes to control the radiative heat transfer. The low-e coating is a micro-thin layer of reflective materials that can be applied to the surface of the glass. Coated by just nanometer-level in thickness of low emissivity materials, such as metallic or metal oxide layers, the resultant low-e windows can block more than 90% of UV and IR radiation in summer while allowing as much visible light in as possible. In winter seasons, as reported, the emissive glass may reflect from 40 to 70% of the heat rays back to room, and further improve the thermal insulation of the units [5].In other words, by using low-e coatings, the reduction in the radiative heat transfer by reflecting solar radiation back to the exterior may lower cooling needs in the summer, and it may also be beneficial to lower heating needs in the winter by keeping the heat from radiating to the outside. Consequently, adding low-e coatings or window films have been commonly recommended to retrofit existing building windows, including single-pane that is estimated to occupy about 35% of windows in the US building stock. On the other side, in actual building applications, the occupied interior has a humidity requirement between 30-60% for occupants' comfort and health [6]. Because of the low absorptance of windowpanes resulted from adding low-e coatings, the inner window surface in winter is theoretically colder than the windowpanes without low-e coatings. It is possible that the existence of the low-e coating may diminish the windows' condensation resistance and consequently decrease the thermal performance by the condensed water or ice. In brief, there is a trade-off between radiative heat transfer reduction and condensation risks: adding low-e coatings to existing windows may potentially save both heating and cooling loads while it may deteriorate the thermal insulating abilities when it comes to low exterior air temperature in winter.

To understand the potential impacts on both thermal performance and condensation risks of using low-e coatings in buildings, especially in the single-pane sector, in this work, parametric numerical analysis in winter is conducted. Three building glazing models, including the single-pane with exterior low-e coatings (SEL), single-pane with interior low-e coatings (SIL), and single-pane without low-e coatings (SNL), are selected and simulated through COMSOL over a range of outdoor temperature and indoor humidity. The temperature of the interior surface of windows, heat flux through windows, winter U-factor of center-of-glass will be obtained and compared. Additionally, a numerical code is developed in R to compute and plot the condensation temperatures of these three models upon the given indoor humidity levels and simulated surface temperatures. The comprehensive analysis of condensation risks on the glazing inner surface of the three models will be conducted.

This parametric simulation effort indicates an interesting feature for a single-pane window: while the SIL gives a substantially lower U than the SNL, it also corresponds to an increased condensation risk under certain limits of external temperature and indoor humidity levels. Upon the resultant condensation temperatures, we recommend the low-e coating usage on single-pane glazing in different climatic zones and building types. The findings are against the common-sense view of simply adding low-e coatings for energy-efficient building retrofitting. It informs that the parameters of the windowpane property, coating emissivity and placement, local climate, and building interior thermal settings should be taken into account collectively.

INFRARED RADIATION THROUGH SINGLE-PANE WINDOWS

Infrared (IR) light (or heat energy) is transmitted as heat into a building, and begins at wavelengths of 780 nm. Solar infrared is commonly referred to as short-wave infrared energy, while heat radiating off of warm objects has higher wavelengths than the sun and referred to as long-wave infrared. For clear window glass, it is by nature highly thermal emissive and can absorb a ton of IR radiation without reflecting much. This means a single-pane window with clear glass will absorb all of the heat energy from the sun as well as radiant heat from inside, but none of it is being put to use in creating energy-efficient windows. Any heat taken in through the glass during the day is being released right back out through the window at night. This is why in some houses a room can be very hot during the day and freezing when the sun goes down. The net result is that we end up using our heating and cooling appliances more than we need to.

The ability of a material to radiate energy is called its emissivity. Standard clear glass has an emittance of 0.84 over the long-wave portion of the spectrum, meaning that it emits 84% of the energy possible for an object at its temperature. It also means that 84% of the long-wave radiation striking the surface of the glass is absorbed and only 16% is reflected. Reducing the emissivity of a single-pane window improves its insulating properties. This is where low emissivity (or low-e glass) coatings come into play. Low-e glass has a microscopically thin, transparent coating—it is much thinner than a human hair—that reflects long-wave infrared energy (or heat). Low-e glass coatings can have an emittance as low as 0.04 [7]. Such glazing would emit only 4% of the energy possible at its temperature, and thus reflect 96% of the incident long-wave, infrared radiation. Some low-e coatings also reflect significant amounts of short-wave solar infrared energy. When the interior heat energy tries to escape to the colder outside during the winter, the low-e coating reflects the heat back to the inside, reducing the radiant heat loss through the glass. The reverse happens during the summer.

LOW-E COATING WINDOWS

There are a couple of different methods used for coating low-e windows. In general, it can be categorized into hard or soft coats. Pyrolytic coatings are applied at very high temperatures at the plant when the glass is manufactured. Pyrolytic coatings are usually tin dioxide and are also called "hard coating". Hard-coated low-e glass surfaces are considered to be medium-grade energy-efficient windows and perform much better than plain clear glass. Hard coat low-e windows are relatively durable, can be handled easily, and are something most often used in single-pane applications; however, hard coat surfaces have a higher solar gain that soft coat and have the possibility of developing a slight haze over time. The second method is called the "magnetron sputtering". This process takes place when the glass is placed in a vacuum chamber and has several thin layers of silver with antireflective properties applied to it. This is considered "soft coating" and must be enclosed in double-pane window units to protect it. Soft-coated low-e glass is deemed as a more efficient and higher performing of the two energy-efficient window types. Soft-coated low-e windows are normally used in a double-pane unit and are nearly invisible coatings which provide more visible light. Soft coat windows have much better U-value than hard coat surfaces and allow less UV transmittance by almost 75% over clear glass [8].

CONDENSATION OCCURRENCE ON SINGLE-PANE WINDOWS

Condensation on the interior surface of single-pane windows occurs if the interior surface temperature equals or falls below the interior dew point temperature. Condensation can not only reduce visibility or window view but also cause damage to building materials. More importantly, from the energy-efficient perspective, the condensed water will diminish the thermal insulating abilities of the original materials or structures. Several factors affect the formation of condensation on the interior surface of single-pane windows, including the inside surface temperature of the glass, the outdoor temperature, and the relative humidity inside the building [9]. Dew point temperature is defined as the temperature of moist air saturated at the same atmospheric pressure, with the same moisture content as that of the given moist air sample. The relative humidity is defined as the ratio of the water vapor pressure in a given moist air sample to the water vapor pressure in an air sample saturated at the same temperature and atmospheric pressure [10]. The dew point temperature according to relative humidity for the case where the inside air temperature is 21°C is shown in **Table 1**.

Table 1. Dew point temperature according to the relative humidity (temperature 21°C, atmospheric pressure 101.325 kPa)

Relative humidity (%)	20	30	40	50	60	70
Dew point temperature (°C)	-2.47	2.78	6.9	10.19	12.95	15.32

Condensation Resistance (CR) and Condensation Resistance Factor (CRF) are two indices for rating the condensation resistance of fenestration products which have been developed by the National Fenestration Rating Council (NFRC) and the American Architectural Manufacturers Association (AAMA) separately. Both CR and CRF ranges from 0 to 100, the higher the number the better a product resists forming condensation. CR is based on interior surface temperatures at 30%, 50%, and 70% indoor relative humidity for a given outside air temperature of -18°C under 5.5 m/s wind conditions. CR is an optional rating on the NFRC label, and determined based on computer simulations [9], however, different outdoor temperature and relative humidity except for 30%, 50%, and 70% are not accounted for CR value. AAMA provides the Condensation Resistance Factor Tool to calculate the suggested CRF for different cities. It just needs simply enter the project specific environmental information including outdoor air temperature, indoor air temperature, and indoor relative humidity [11]. But it only provides a general reference on suggesting a minimum CRF and is unable to consider the radiation effect on the windows.

A single-pane window with low-e coatings treatments reduces the amount of radiative heat moving through a window system. This reduced heat flow results in colder surfaces on the cold side of the window and warmer surfaces on the warm side of the window. Condensation may occur under high relative humidity at only cold outside temperatures. As the outside temperature drops, the inside surface will also get colder. Therefore, condensation will form at lower relative humidity on cold days. The colder inner window surface in winter due to the existence of the low-e coating may significantly diminish its condensation resistance and consequently decrease the thermal performance by the condensed water or ice. Furthermore, heat flux through windows will increase for the decreasing of the thermal performance of the windows. This is a trade-off between thermal performance and condensation risk of single-pane glazing with low-e coating. To understand the potential impacts on both thermal performance and condensation risks of using low-e coatings in buildings, especially in the single-pane sector, in this work, parametric numerical analysis in winter is conducted.

FINITE ELEMENT SIMULATION

Three building glazing models, including the single-pane without low-e coatings (SNL), single-pane with exterior low-e coatings (SEL), and single-pane with interior low-e coatings (SIL), are selected and simulated through COMSOL Multiphysics 5.4 over a range of outdoor temperature and indoor humidity. The temperature of the interior surface of windows, heat flux through windows, and winter U-factor of center-of-glass will be obtained and compared.
Boundary conditions such as the setpoint temperature, the surface heat transfer coefficient for the inside and outside surfaces of the building, and the material properties are presented in **Tables 2** and **3**. The generic clear glass (ID 103) from the International Glazing Database (IGDB) was adopted for the single-pane window. Its thickness is 5.715mm, conductivity is 0.96 W/m°C, emissivity is 0.84. The low-e coating's emissivity is 0.04. The convection heat transfer coefficients of the inside surface and outside surface are assumed 10 W/m^2°C, and 34 W/m^2°C respectively. The simulated model and meshed finite element model are presented in **Figure 1**.

Table 2. Glazing Summary, Single Pane Center of Glass Values

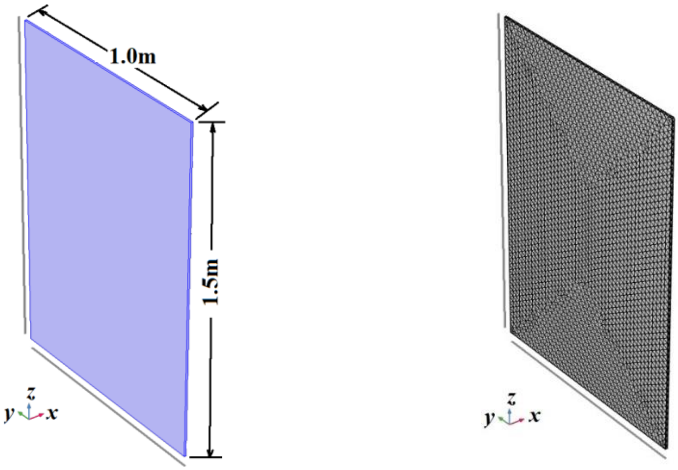
Property	Value	Units
GENERAL PROPERTIES		
Number of Panes	1	
Pane Thickness	5.715	mm
SINGLE PANE OPTICAL PROPERTIES		
Thermal infrared (longwave) emittance	0.84	
Low-e coating emittance	0.04	
THERMAL PROPERTIES		
Conductivity of Glass	0.96	W/m°C

Table 3. Boundary conditions

Part	Air temperature (°C)	Surface heat transfer coefficient (W/m^2°C)
Inside	21	10
Outside	-15~15	34

RESULTS AND DISCUSSION

The setpoint of indoor temperature is 21°C, over a range from -15°C to 15°C of outdoor temperature, the temperature of the interior surface of windows can be obtained through COMSOL Multiphysics 5.4. **Table 4-6** show results of the temperature of the interior surface of windows when condensations have occurred, corresponding outdoor temperature and indoor humidity, and heat flux through windows of SNL, SEL and SIL models, respectively.



(a) Single-pane window model *(b) Single-pane window meshed model*

Figure 1. Finite element models and mesh of the single-pane window

Table 4. single-pane without low-e coatings (SNL)

U-factor = 9.09 W/ m²-K

Relative Humidity (%)	Outdoor Temperature (°C)	Inside Surface Temperature (°C)	Heat Flux (W/m²)
20	-13	-2.87	341.12
30	-6	2.60	265.21
40	0	6.70	207.50
50	5	10.11	158.90
60	9	12.83	119.66
70	12	14.88	90.02

Table 5. single-pane with exterior low-e coatings (SEL)

U-factor = 8.76 W/ m²-K

Relative Humidity (%)	Outdoor Temperature (°C)	Inside Surface Temperature (°C)	Heat Flux (W/m²)
20	-15	-2.95	342.17
30	-7	2.42	267.65
40	-1	6.43	211.20
50	4	9.76	163.79
60	8	12.42	125.62
70	12	15.07	87.218

Table 6. single-pane with interior low-e coatings (SIL)

U-factor = 7.24W/ m^2-K

Relative Humidity (%)	Outdoor Temperature (°C)	Inside Surface Temperature (°C)	Heat Flux (W/m^2)
20	-11	-3.02	245.07
30	-4	2.21	191.80
40	2	6.71	146.00
50	6	9.71	115.39
60	10	12.71	84.72
70	13	14.97	61.66

Based on the results in **Table 4-6**, a numerical code is developed in R to plot the condensation temperatures of these three models upon the given indoor humidity levels and simulated surface temperatures. **Figure 2** and **3** show the outdoor temperature versus inside surface temperature and the heat flux through windows. **Figure 4** shows heat flux through three models upon the given indoor humidity levels. **Figure 5** explains the condensation risk of three models over the different indoor humidity and outdoor temperature.

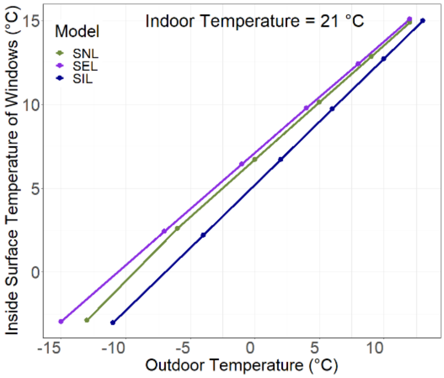


Figure 2. Inside surface temperature vs. Outdoor temperature

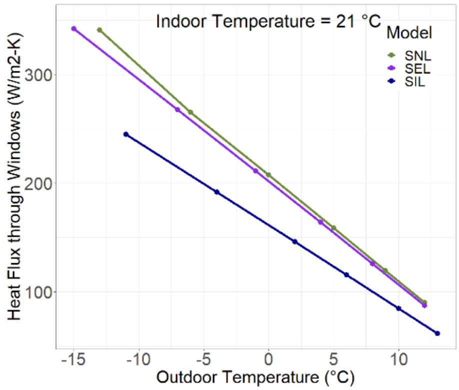


Figure 3. Heat flux through windows vs. Outdoor temperature

From Figure 2 and 3, it can be seen that the inside surface temperature of windows is directly proportional to the outdoor temperature, while the heat flux through windows is inversely proportional to the outdoor temperature. When the outdoor temperature is the same, the order of the inside surface temperature of the window is SEL, SNL, SIL, model SEL is the highest and SIL is the lowest among three models. This means single-pane windows with the interior low-e coating will occur condensation in the first place when the outdoor temperature is the same. When the outdoor temperature is the same, the heat flux through windows is SNL, SEL, SIL, model SNL is the highest and SIL is the lowest among the three models. Therefore, single-pane window with interior low-e coating has the highest thermal insulating ability. It may be also concluded from their U-factor calculations.

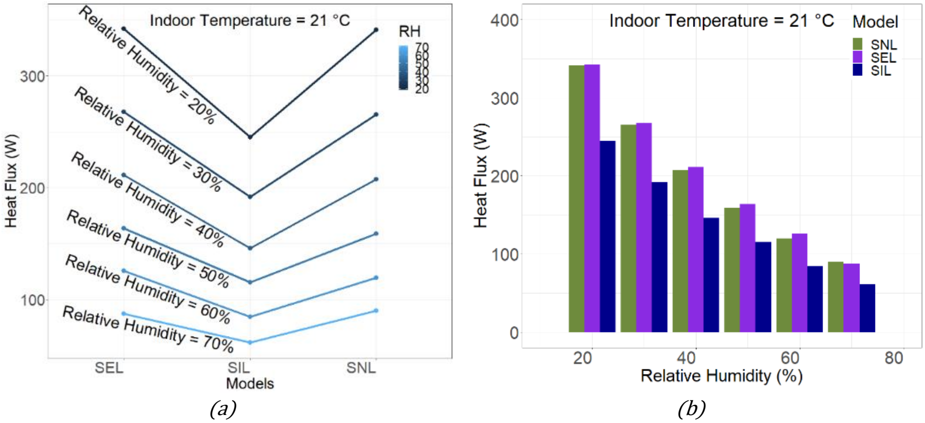


Figure 4. Heat flux through single-pane windows

From **Figure 4**, it can be seen the heat flux through windows of model SNL and SEL is approximately equal over the same indoor humidity. The model SIL transfers the lowest amount of heat through windows at the same indoor condition. The heat loss through windows will decrease following the indoor humidity increases.

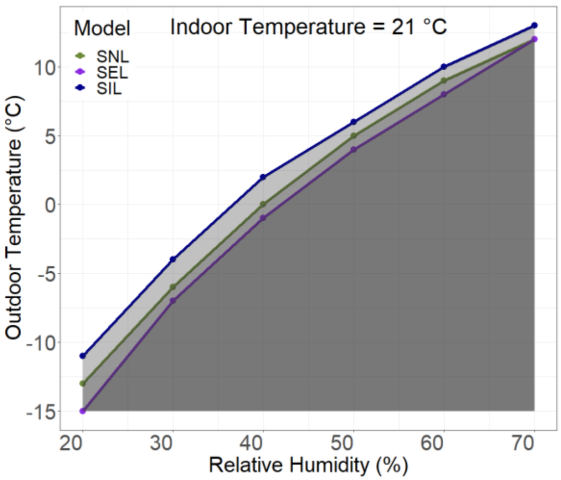


Figure 5. Condensation risk of single-pane windows

Figure 5 shows that the shadow area is the condensation risk region. Under the same environmental condition, the condensation risk of the model SIL is the highest, the condensation risk of the model SEL is the lowest. Therefore, it is a trade-off problem that the low-e coating position due to the model SIL has higher condensation risk and lower heat loss while the model SEL has lower condensation risk and higher heat loss. In particular, if the indoor relative humidity is about 40% and most outside weather conditions are with > -1°C temperatures, the SIL model will still be the best candidate for the building energy efficiency.

An alternative thought is, if the model SIL design cooperates with other applications preventing condensation, the integrated effect may reach to a "perfect" status: low heat loss through the window and low condensation risk. Such condensation control investigations include interior storm window [12], shutters or blinds [13], transparent hydrophobic films [14-15], and super-hydrophobic coating [16-17]. Interior storm windows, shutter and blind are the solutions by mechanically separating the moist inside air from the cold windowpane, while hydrophobic film or coating can decrease dew condensation on windows by modification of glass surface hydrophobicity. Furthermore, in our previous studies, a new transparent spectrally selective photothermal window film has been developed and tested, which can convert the solar infrared to thermal energy which increases the windowpane's temperature. This could be an alternative solution to increase the window condensation resistance if the solar irradiation is available in winter. Also, a According to our earlier investigation, such spectral selective photothermal coating can improve the U-factor of the window as well in winter seasons effect [18-19]. Therefore, a combination of the SIL model and photothermal coating seems to be very promising for most winter situations (under solar radiation conditions), and the continuous works on this design by experiments and simulations will be shown in later reports.

CONCLUSIONS

It is well-known that the low-e coating may increase the thermal performance of window systems by controlling the solar infrared and long-wave infrared. However, it may also have negative effects on the window condensation resistance. The present study was designed to understand the potential impacts on both thermal performance and condensation risks of using low-e coatings in buildings, especially in the single-pane sector. This numerical analysis was conducted to understand the potential impacts on both thermal performance and condensation risks of using low-e coatings in single-pane windows. Three building glazing models, including the single-pane without low-e coatings (SNL), single-pane with exterior low-e coatings (SEL), and single-pane with interior low-e coatings (SIL), were selected and simulated through COMSOL over a range of outdoor temperature and indoor humidity. The findings reported here shed new light on the single-pane window with interior low-e coating has good thermal performance but low condensation resistance, the single-pane window with exterior low-e coating is right opposite. The heat flux through windows of model SNL and SEL is approximately equal over the same indoor humidity. The model SIL transfers the lowest amount of heat through windows at the same indoor condition. However, under the same environmental condition, the condensation risk of the model SIL is the highest, the condensation risk of the model SEL is the lowest. Under different outdoor temperature conditions and indoor relative humidity settings, different recommendations of low-e coating positions should be made towards the building energy efficiency goals. Therefore, this study suggests that the buildings in climate zone 1~3 should be adhesive low-e coating on the exterior surface of the single-pane window due to warm and high humidity; the single-pane window of the buildings in climate zone 4~7 place with interior low-e coating is the better choice. The insights gained from this study may be of assistance to further research into reducing condensation on windows by mechanical and optical measures. A more user-friendly design tool incorporating the weather data analysis and low-e coating recommendations with detailed spectral compositions will be developed in our future work.

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