Spring 2021

# Evaluating the Thermoresponsive Properties of Hydroxypropyl Cellulose Solutions for Smart Window Applications

Adam Reed
acr97@zips.uakron.edu

# Honors Project Final Report

# 4200 497 001

# Evaluating the Thermoresponsive Properties of Hydroxypropyl Cellulose for Smart Window Applications

I affirm that this report represents work performed by me and I assume full responsibility for originality, comprehension, and accuracy of all aspects of the report.

**Name**: Adam Reed
**Signature:**_ACReed_
**Date: 5/5/2021**

# Contents

# Executive Summary

As global emissions continue to rise, there has been a strong push to reduce energy consumption. HVAC systems used to heat/cool buildings account for 20% of total energy use in the U.S.[2] With HVAC usage expected to increase, there is a strong need for autonomous thermal management solutions. A smart window is a form of autonomous thermal management that reduces energy costs by blocking solar transmission from entering a building at high temperatures and by allowing the solar transmission to enter at low temperatures. Smart windows can be activated by many different stimuli[3] including heat, electricity, light, and humidity. There has been a growing interest in thermoresponsive (TR) smart windows that are activated by ambient temperature changes. These windows are typically made from temperature-responsive polymers. As the temperature increases, the TR polymer phase separates from the solution. This leads to scattering – which blocks heat from passing through the solution.[4] The point at which the scattering begins is referred to as the cloud point.

Most TR smart windows have been developed using a liquid solution. A liquid solution poses some design challenges because the TR solution could spill out if broken. Depending on the solution, this could be a safety concern. TR solutions typically have poor freeze resistance. If frozen, TR solutions decrease in transmittance, preventing heat from entering a building. In the winter, this solar transmission helps to heat up the building. This main goal of this project is to develop a self-supporting smart window that transitions at environmentally relevant conditions for a building. A self-supporting system that retains its TR properties is more advantageous than a liquid solution because the window will have a greater ease of handling and the highly viscous gel will not spill in the case of breakage.

TR solutions were prepared by adding the TR polymer hydroxypropyl cellulose (HPC) in

solution with water and glycerol. The concentration of glycerol and HPC were varied to determine the effect on cloud point. When increasing glycerol concentration, the cloud point decreased. The same effect was observed when increasing HPC concentration and HPC molecular weight. After establishing these trends, sodium dodecyl sulfate (SDS) was added to 50 wt% glycerol-water solutions with varying concentrations of HPC. The SDS surfactant increased the viscosity and cloud point of these solutions. When increasing the concentration of SDS from 0 wt% to 1 wt% in the 20 wt% HPC sample, the cloud point increased from 11°C to 24°C. Viscosity also greatly increased when SDS concentration was increased from 0 to 1 wt% in the 20 wt% HPC samples. To further increase the cloud point while maintaining high viscosity, the HPC concentration was reduced to 15 wt% (at 1 wt% SDS). This mixture of glycerol, SDS and HPC formed a gel with a cloud point 28°C. To determine the gel's performance in a smart window, this sample was tested in a heat shielding experiment. Under the heat of a 150 W incandescent light bulb, the gel was placed in a cell while the temperature of the inside of a box was monitored. The 15 wt% HPC 1 wt% SDS gel shielded the inside of the box by an average of 56% compared to 9% when only glass slides were used.

The experiments confirmed the direct relationship between cloud point temperature and HPC/SDS concentration and the indirect relationship between cloud point temperature and glycerol concentration/MW of HPC. While it was unknown if the HPC solution would retain its TR properties when formed into a gel with SDS, all of the HPC – SDS gels retained their TR properties and had an increased viscosity. From the heat shielding experiment, the 15 wt% HPC 1 wt% SDS gel provided excellent heat shielding and transitioned at an environmentally relevant condition for HVAC usage.

Some broader implications of this work include energy savings if applied at a widespread

level. Using a Solar Energy Density of 1000 $kW/m^2yr$ for a window, the cooling cost savings in Akron, OH were estimated to be \$60/yr if 15 wt% HPC 1 wt% SDS gel smart windows were implemented in a house with 10 – 2'x3' windows. For buildings that have a large area of windows - such as the Goodyear Polymer Building, the cost savings could be even greater. Using the same gel, the cost savings were estimated at \$122,000/yr (assuming a total window area of 9900 $m^2$). In addition to cost savings, the widespread implementation of self-supporting smart windows would help to reduce global emissions. Personal gains from this project included improving skills in problem solving, technical report writing, presenting and working in a lab.

Future work on this project should be focused primarily on cross-linking. While a TR gel with a high viscosity was developed during this project, cross-linking the TR gel would enhance the mechanical properties even more. The increased strength may reduce the thickness of glass needed on the outside of the polymer or provide enhanced insulation. Additionally, adding ionic liquids to the gel should be explored to determine if an electrochemical potential can be generated from the TR behavior. A full-scale window should also be produced to determine cost and feasibility.

## Introduction

With growing concerns about climate change and an increasing world population, there has been a strong emphasis on reducing energy consumption. Commercial buildings account for nearly 40% of the total energy consumption in the United States.[1] In particular, HVAC systems use a large amount of energy, ~ 50% of building consumption which is 20% of total energy use in the U.S.[2] With HVAC usage expected to rise, there is a strong interest in developing solutions for autonomous thermal management.

A smart window that can change its transmittance in response to an environmental change has drawn great attention. Windows are one the of the least energy efficient parts of a building[3] and a smart window offers a solution to decrease HVAC energy usage by tuning the solar transmission. Smart windows can be activated by many different stimuli[3] which include heat, electricity, light, and humidity. Thermoresponsive (TR) windows are activated by ambient temperature changes and are typically made from temperature-responsive polymers. Hydroxypropyl cellulose (HPC) is derived from the natural polymer cellulose and has been used in several designs of smart windows. Solutions with HPC exhibit high transmittance at low temperatures because the HPC molecules expand by interacting with water. As the temperature increases, the HPC phase separates by releasing the water. This release causes scattering, making the solution less transparent.[4] For window design, it is desired to keep a room warm during the winter and cool during the summer. A TR smart window offers a solution to this design criteria: at low temperatures, sunlight and heat can pass through the window and heat up the inside of a building. At high temperatures, the transmittance of the solution is low and blocks heat.[3]

Most TR systems reported are liquid based (polymer in solution). Nakamura et al [4] developed a freeze resistant TR system using hydroxypropyl cellulose (HPC) in solution with

glycerol and water. While Nakamura's system was effective at blocking solar transmission, it is subject to leaking if the window were cracked during transportation, installation or use. Depending on the TR solution, it may pose a safety concern to those in the area. This project focuses on developing a self-supporting system instead a liquid based system. A self-supporting system that retains its TR properties is more advantageous because the window will have a greater ease of handling and the highly viscous gel will not spill in the case of breakage. In addition to increasing the viscosity of the TR system, the project focuses on tuning the cloud point to occur at environmentally relevant conditions for a building. The cloud point must occur at the outside temperature that air conditioning is turned on so that below this temperature, heat will pass through the TR system and heat the building. Above the set cloud point temperature, the polymer will decrease in transmittance and block heat from entering and reduce air conditioning usage.

To create a self-supporting system that transitions at environmentally relevant conditions for a building, the effect of glycerol, HPC and SDS concentration and molecular weight were first assessed to determine their impact on cloud point temperature. Next, these variables were tuned to develop a system that retained cloud point behavior but at increased velocity to limit fluid flow. The highly viscous system was tuned to transition at 28°C. This final system, consisting of 50 wt% glycerol, 1 wt% SDS and 15 wt% HPC (MW = 140 000 g/mol) is a TR gel that displays strong heat shielding to provide a strong basis for use in a self-supporting smart window.

## Background

While TR hydrogels have typically been used in areas such as tissue engineering, drug delivery and sensors, they have recently found application in smart windows due to their high-performance transparency changes. At high temperatures, the TR hydrogels block solar light from entering a room – while at low temperatures the solar light can pass through (**Figure 1**). Several

TR hydrogels have been used for smart window application including – poly(N-isopropylacrylamide) (PNIPAm) and hydroxypropyl cellulose (HPC).[3] PNIPAm has a very high transmittance at room temperature and gives a large modulation to sunlight when heated to 30°C.[4] PNIPAm is limited by its complicated fabrication approach and poor freeze resistance. In cold conditions, PNIPAm, HPC and many TR polymers freeze, decreasing their transmittance of visible light. This is problematic for smart window use in areas with cold seasons because it decreases the inside temperature of a building.

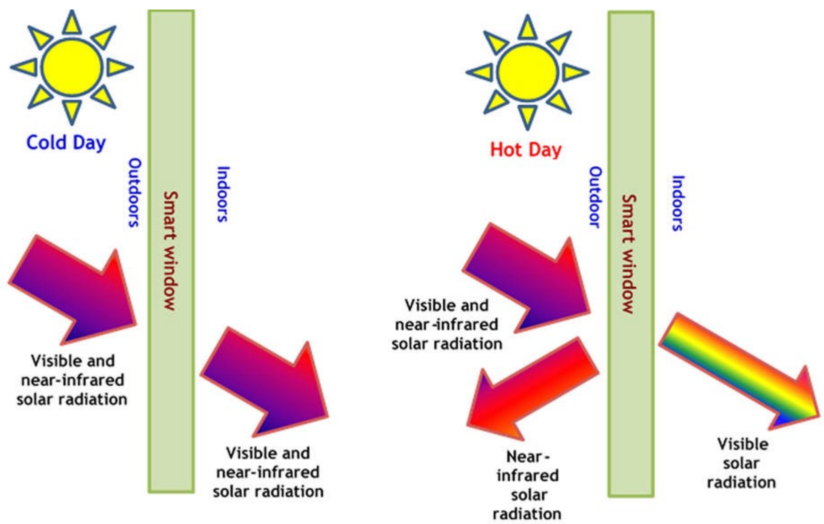



**Figure 1.** How a smart window functions by allowing or blocking solar light.

To produce a TR smart window with freeze resistance, Nakamura et al[4] mixed HPC (MW = 100 000 g/mol) in solution with glycerol and water. HPC gets its TR properties due to hydration and dehydration – reversible hydrophilic/hydrophobic phase transitions around the lower critical solution temperature (LCST). At low temperatures, the solution takes in water due to the hydrogen bonds dominating between the polymer chains and water molecules – causing the solution to be transparent. At high temperatures (above the LCST), the hydrogen bonds are broken, leading to a hydrophobic effect where the water is released. This removal of water causes scattering that can

be observed when heating solutions of HPC[5] (shown in **Figure 2**).

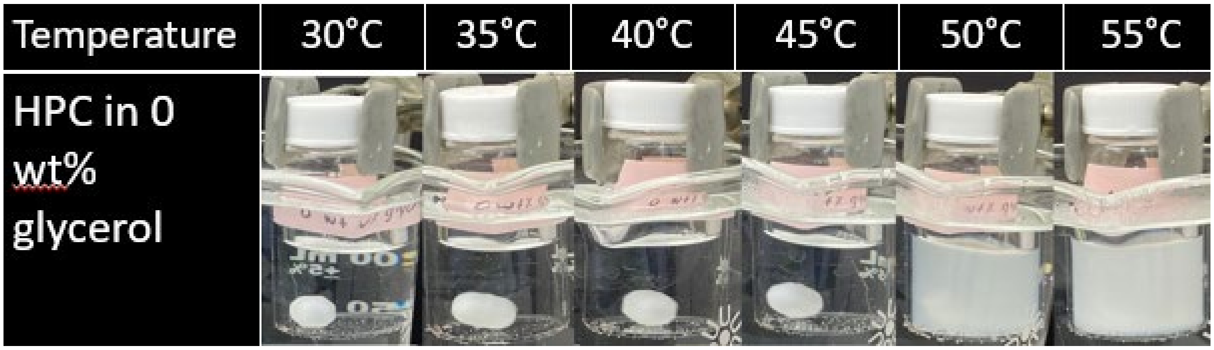



**Figure 2.** 140 000 g/mol HPC solution at various temperatures

When glycerol is added to the HPC in solution, water release is promoted due to strong hydrogen bonding between the water and the glycerol.[3] This hydrophobic effect causes the scattering/cloud point to occur at a lower temperature than the solution without glycerol. The hydrogen bonding between glycerol and water also prevents freezing.

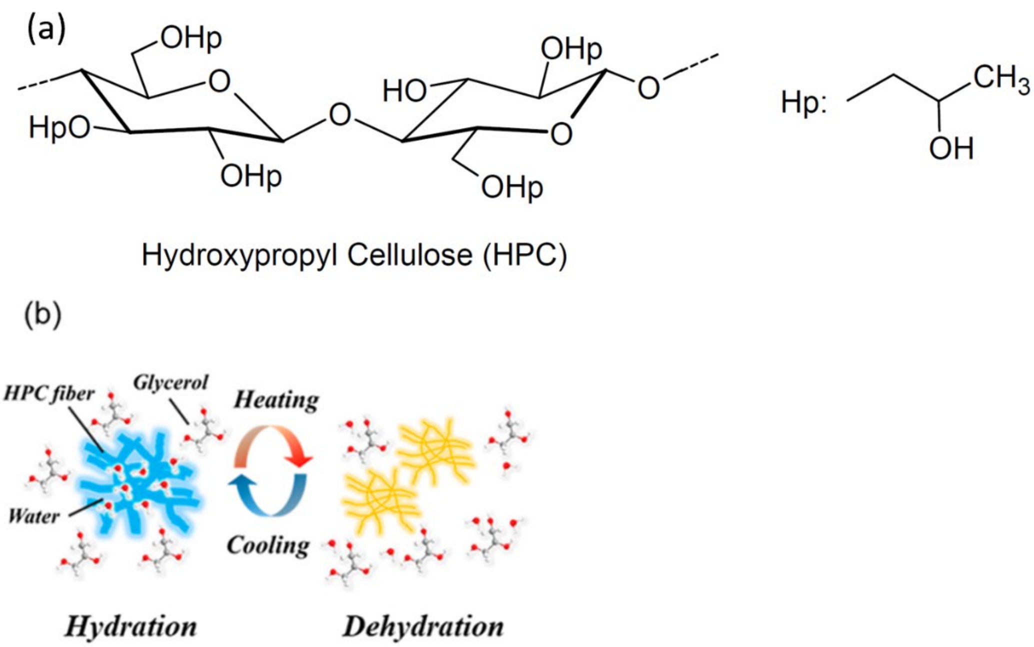



**Figure 3.** (a) The structure of HPC. (b) The hydration and dehydration of HPC when heating and cooling that leads to light scattering.

During the experiments, Nakamura created 0, 20, 33 and 50 wt% glycerol-water solutions combined with 0.05 wt% HPC. To characterize the samples, UV-vis spectroscopy and cloud point measurements were used. When increasing the glycerol concentration from 0 to 33wt%, the cloud point shifted from 50°C to 30°C. Nakamura measured the heat shielding of a smart window by filling acrylic cells with water, HPC/water and the 33wt% solution and, an empty reference cell. He placed these cells in the top of a Styrofoam box. The cell was exposed to the heat of a 100 W incandescent light while a thermo-camera recorded thermographic images and temperatures. The 33 wt% glycerol solution reduced the heating of the paper by an additional 40% compared the cell with air.

Other additives besides glycerol have been explored to modify the cloud point of a TR solution – including salts, alcohols, and surfactants.[6] Surfactants are known to increase the cloud point of a TR solution because of their ability to act as mediators between phases that are not attracted to each other. In the case of HPC and water, a surfactant helps to extend the favorability of interaction between these components. When increasing temperature, the hydrogen bonds between HPC and water break. The surfactant lengthens the window of favorability between HPC and water, requiring a higher temperature for the HPC and water to separate, increasing the cloud point. Sodium dodecyl sulfate (SDS) is a well-known long chain alkylsulphate[7] (also known as sodium lauryl sulfate) that is used in many cleaning and hygiene products. SDS has a strong effect on cloud point temperature because of its higher water compatibility that allows for solubilization of polymer hydrophobic domains.[7] SDS also forms a lamellar gel when mixed with glycerol.[8] At concentrations as low as 2 wt% SDS, the SDS self assembles in the glycerol due to H-bonding.

Molecular weight is another variable that effects cloud point. The relationship between molecular weight and cloud point has been studied for PNIPAm.[9] As molecular weight increases,

the cloud point decreases. This inverse molecular weight dependence of phase separation is due to an increase in hydrophobic interactions as chain length increases. The increased hydrophobic interactions promote HPC to separate from the water at lower temperatures.

# Experimental Methods

## Solution Preparation

Solutions were prepared in 20 mL vials. First, the glycerol and water were added and mixed using a magnetic stir bar. For samples with surfactant, the surfactant was added next. For all samples, the HPC was added last. A Vortex mixer was used to facilitate the mixing of samples with high concentrations of surfactant and/or HPC. Samples were stirred overnight. In the case of poor solubility, the vial was heated to ~ 70°C to liquify the solution so it could be re-mixed.

## Sample Characterization

### UV-vis Spectroscopy

Optical spectra of the 140 000 and 1 000 000 g/mol HPC-glycerol solutions were measured using an ultraviolet-visible (UV-vis) spectrophotometer. Baseline corrections were run using samples containing 0, 20 or 33 wt% glycerol with no HPC added. Samples were tested at room temperature (23°C) and at 30, 40, 50 and 60°C by immersing a cuvette filled with solution in a hot water bath. The cuvette was immediately dried and placed in the spectrophotometer. To minimize the effects of cooling, the “Fastest” scan rate was selected.

### Cloud point Testing

The cloud point is defined as the point where a solution starts to phase separate. For HPC, this occurs at the LCST. To determine the cloud point temperatures, each solution was submerged in a hot water bath. Samples were heated to a set temperature and observed for five minutes. If the solution did not show any changes in transmittance, the temperature was increased by 5°C. This

process was repeated until the solution reached its cloud point, indicated by a cloudy solution that blocked the view behind the vial. The solutions were tested again, but at 1°C intervals around the first reading to verify the original value and obtain a more precise cloud point measurement. The set-up is shown in **Figure 4.**

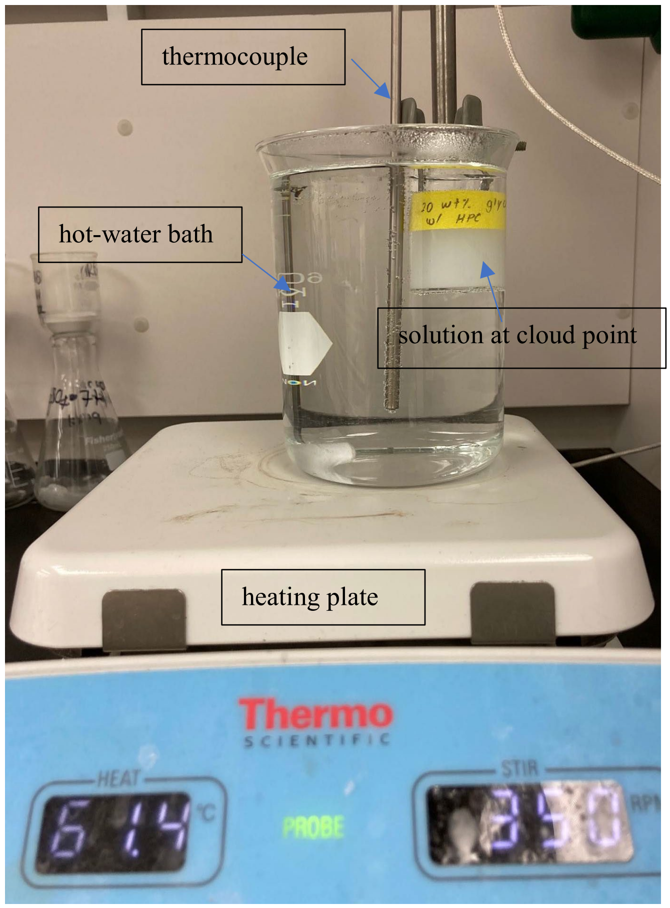



**Figure 4.** Shows a glycerol-HPC sample after reaching cloud point.

## Heat Shielding Setup

The heat shielding of the smart window was measured by shinning a heat lamp with a 150 W bulb onto the smart window cell on the top of the experimental setup (**Figure 5**). The setup was created using a Styrofoam box with the dimensions of 7.5. x 6.5 x 6 $in^3$ and a hole in the top to place the solution cell in, with the dimensions of 1 x 3 $in^2$. Silicone putty was used to seal the edges

and top of the box to prevent heat leaks. A thermocouple was placed at the top of the box to measure the outside temperature and the heat from the light bulb. A second thermocouple was positioned inside the box to measure the inside temperature. The inside temperature is the dependent variable, representing the inside of a building and is used to measure the heat shielding provided from the window. To adjust the outside temperature (the independent variable), the stand was raised/lowered to position the light bulb between $3^{5/8}$ in. and 7.5 in. from the bulb to the top of the box.

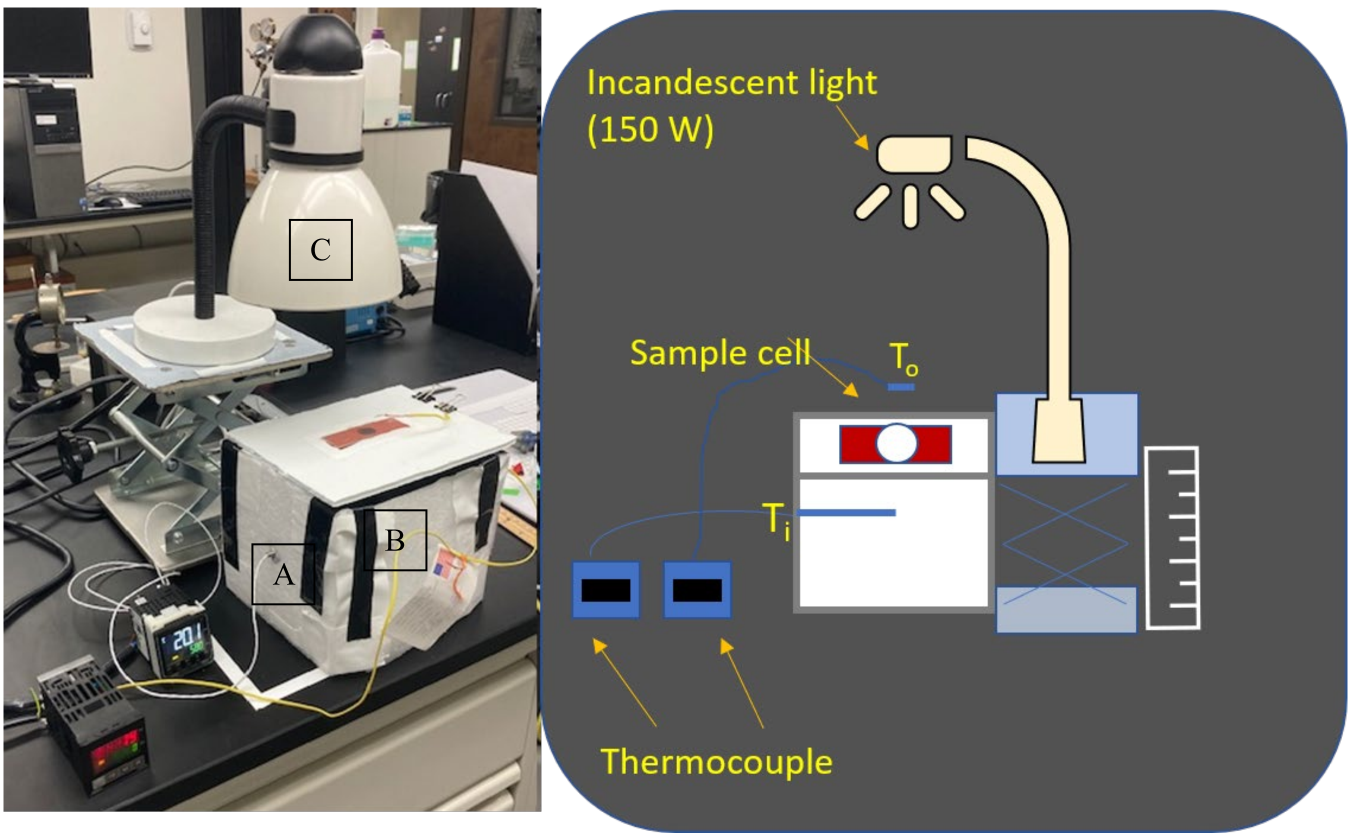



**Figure 5.** Setup for the heat shielding experiments. A – thermocouple for inside temperature. B – thermocouple for outside temperature. C – Heat source: 150 W Incandescent light bulb.

Samples were placed in a cell shown in **Figure 6.D**. The cell was constructed by two 1x3" microscope slides and a rubber gasket. To compare the heat shielding of the solution to the gasket and glass, cells were created with glass only (**Figure 6.B**), a cell with no solution (**Figure 6.C**)

and compared to an open box (**Figure 6.A**).

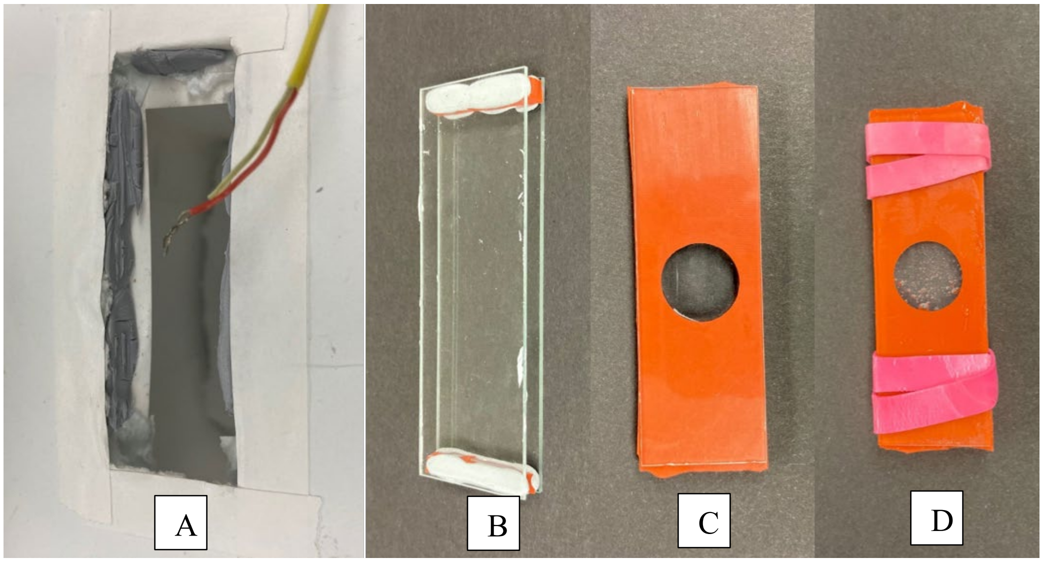



**Figure 6.** Cells used for the heat shielding experiment. A – open box. B – glass only. C – gasket only. D – solution (15 wt% HPC, 1 wt% SDS).

## Heat Shielding Experiments

The goal of the heat shielding experiment was to evaluate the performance of the HPC-glycerol-SDS gel on a warm day. First, a correlation was developed between the stand height and the outside temperature by recording $T_o$ at stand intervals of 1" (**Figure 16** in **Data and Results**). Because the performance on a warm day was desired, the bulb was positioned so that $T_o$ would be greater than 27°C. Using this correlation, the bulb was positioned at a stand height range of 7-11", approximately 28-36°C.

Next, the cell was filled with solution and sealed by the top slide to limit the number of air bubbles that formed and to ensure the cell was completely full. At the beginning of each trial, the stand height was positioned at 11" and the bulb was turned on, as shown in **Figure 7**. $T_i$ and $T_o$ measurements were recorded vs. time. The inside temperature was monitored for a steady state temperature. When $T_i$ did not change for 5 minutes, it was considered steady state and the stand was lowered to 10". This process was repeated for the 9, 8, and 7" stand heights. Once the sample

reached steady state at 7”, the bulb was turned off. Using this procedure, baseline data for the open box, glass and gasket samples was also collected.

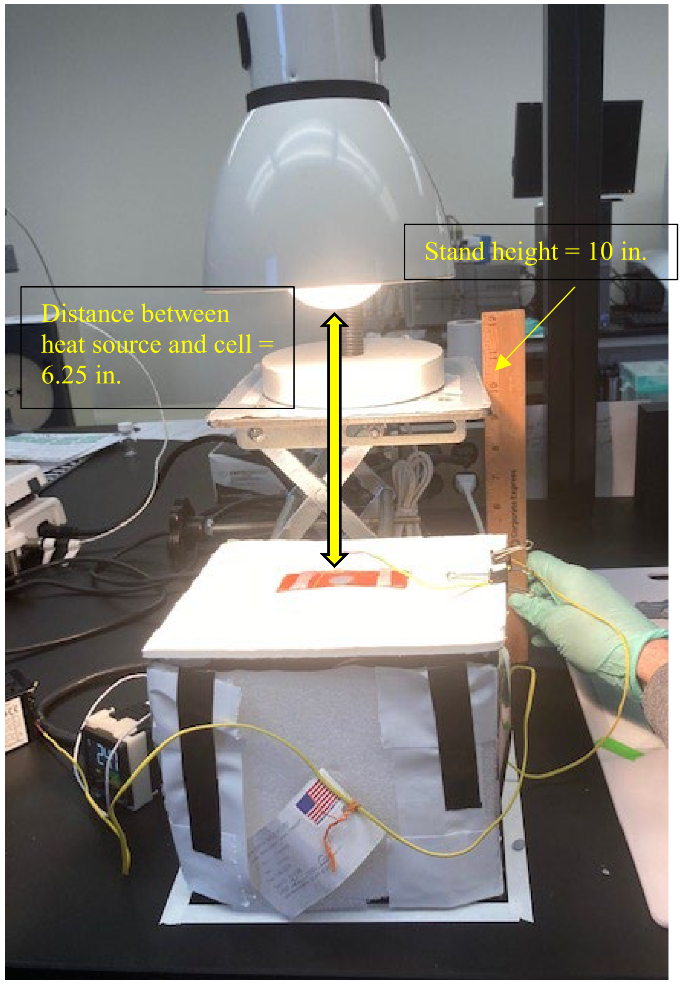



**Figure 7.** Shows the stand height and heat shielding set-up during an experiment.

# Data and Results

## Sample Characterization

### Cloud point Testing

The 0.05 wt% HPC-glycerol solutions are shown at different temperatures in **Figure 8**. As temperature increases, the solutions become less transparent. As the glycerol concentration is increased, the samples become transparent at lower temperatures. When the molecular weight of

HPC decreases to 40 000 g/mol, the solutions become more transparent. When the molecular weight of HPC is increased to 1M g/mol, the solutions become less transparent. The data from **Figure 8** is shown quantitatively as cloud point measurements of the 0, 20 and 33 wt% glycerol 0.05 wt% HPC solutions in **Figure 9**. As the glycerol concentration is increased, the cloud points decrease. As molecular weight increases, the cloud points also decrease. The cloud point can be observed when the solution goes from high transmittance to low transmittance (ex. for the 0 wt% glycerol sample, the image at 50°C).

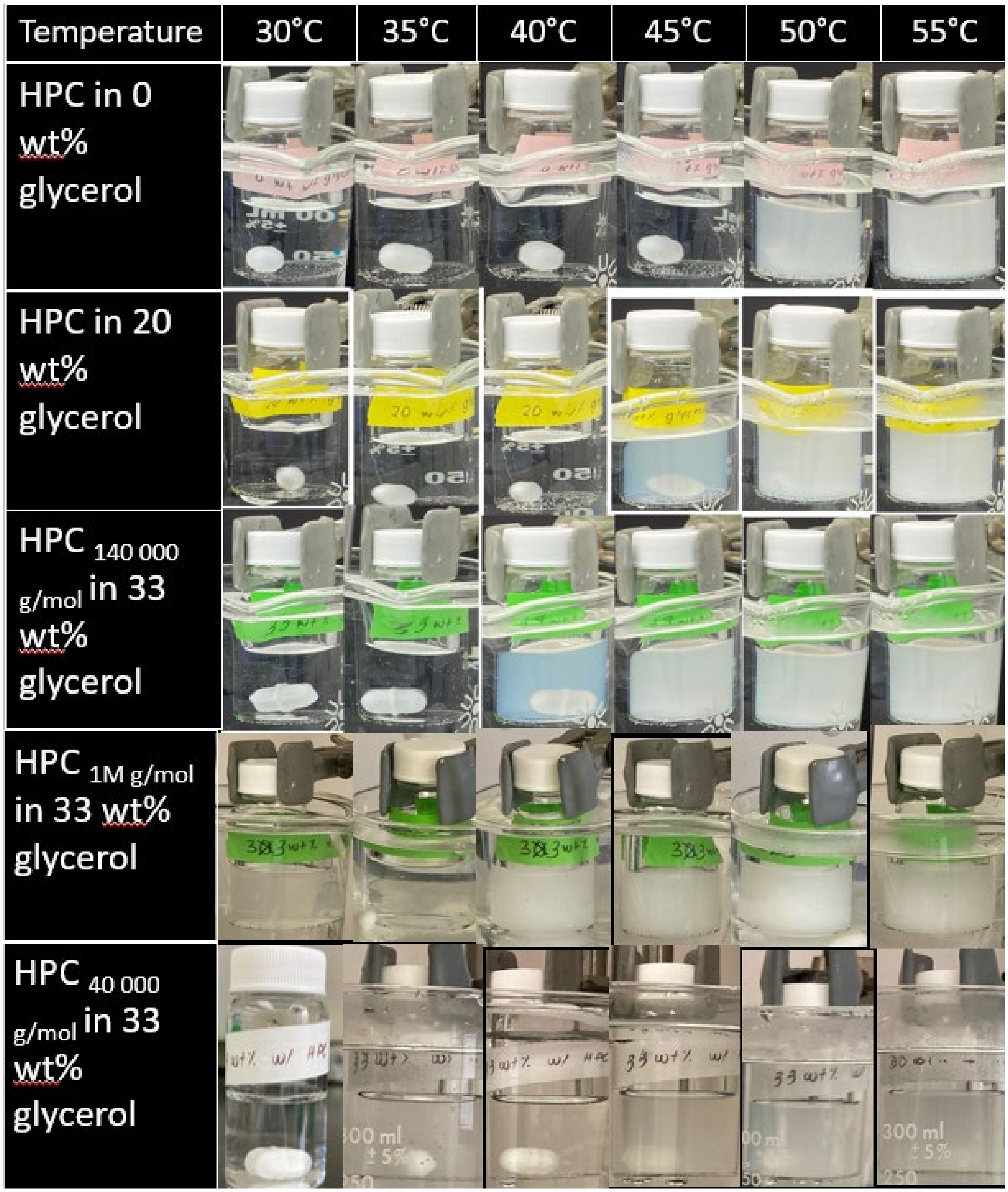



**Figure 8.** Shows the samples at different temperatures when varying wt% glycerol and molecular weight. Cloud points reported in Figure 9.

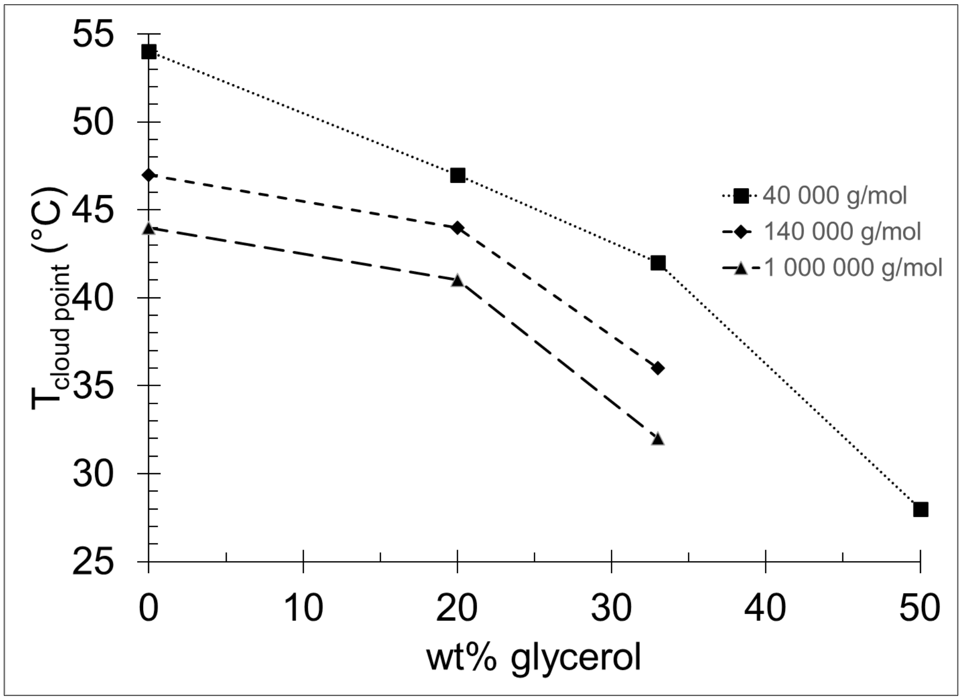



**Figure 9.** Cloud point temperatures when increasing glycerol concentration and varying the molecular weight of the 0.05 wt% HPC solutions.

## UV-vis Spectroscopy

The results from UV-vis spectroscopy help to give a more precise measurement of the transmittance of a solution when varying glycerol and molecular weight. **Figures 10-12** show the change in transmittance across ultraviolet (UV), visible and near-infared regions when increasing temperature. At low temperatures ~ 23°C, the samples are all at nearly 100% transmittance. When glycerol is increased in **Figure 10c**, **d**, **e** and **f**, the %T decreases. For **Figure 10a, c** and **e**, there is a transition region that is at medium transmittance in visible light. As glycerol increases, the temperature at which this transition region occurs decreases. When the molecular weight is changed from 140 000 g/mol to 1M g/mol, the transmittance also decreases.

**Figure 11** shows the %T vs temperature at 500nm for the 140 000 g/mol solutions. At low temperatures and high temperatures, the samples are all at similar transmittance values. Between 30 and 50°C, there is a sharp difference between the transmittance values.

In **Figure 12,** the %T vs. temperature for the 1M g/mol samples are plotted at 500nm. There is a drastic drop from high transmittance to low transmittance between 32 and 40°C. For the 1M samples there were no samples that in the transition region. The values recorded were either at high or low transmittance.

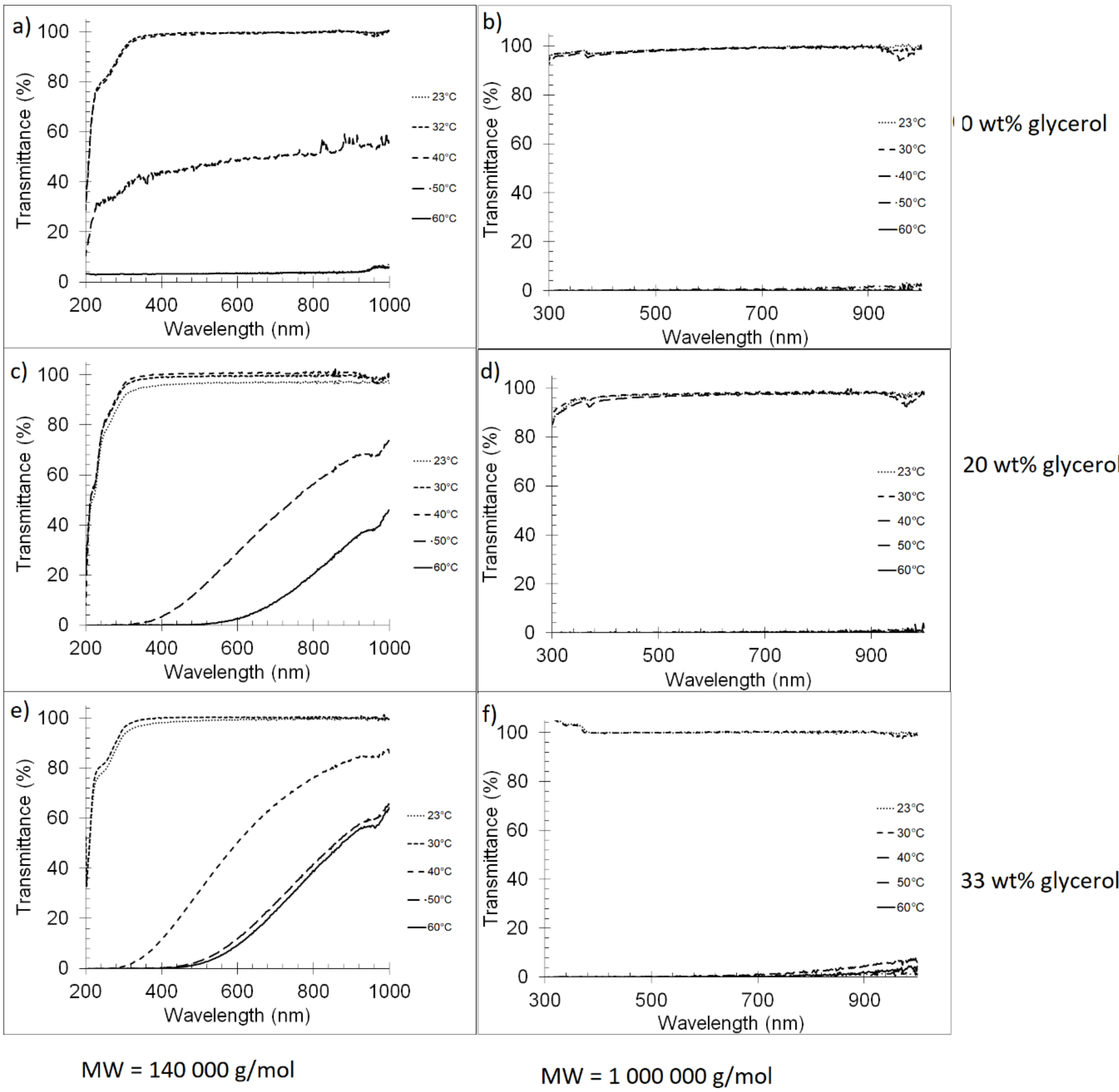



**Figure 10**. Optical properties of the samples. (a) Transmittance of 140 000 g/mol HPC in a 0 wt% glycerol mixture. (b) Transmittance of 1M g/mol HPC in a 0 wt% glycerol mixture. (c) Transmittance of 140 000 g/mol HPC in a 20 wt% glycerol mixture. (d) Transmittance of 1M g/mol HPC in a 20 wt% glycerol mixture. (e) Transmittance of 140 000 g/mol HPC in a 33 wt% glycerol mixture. (f) Transmittance of 1M g/mol HPC in a 33 wt% glycerol mixture.

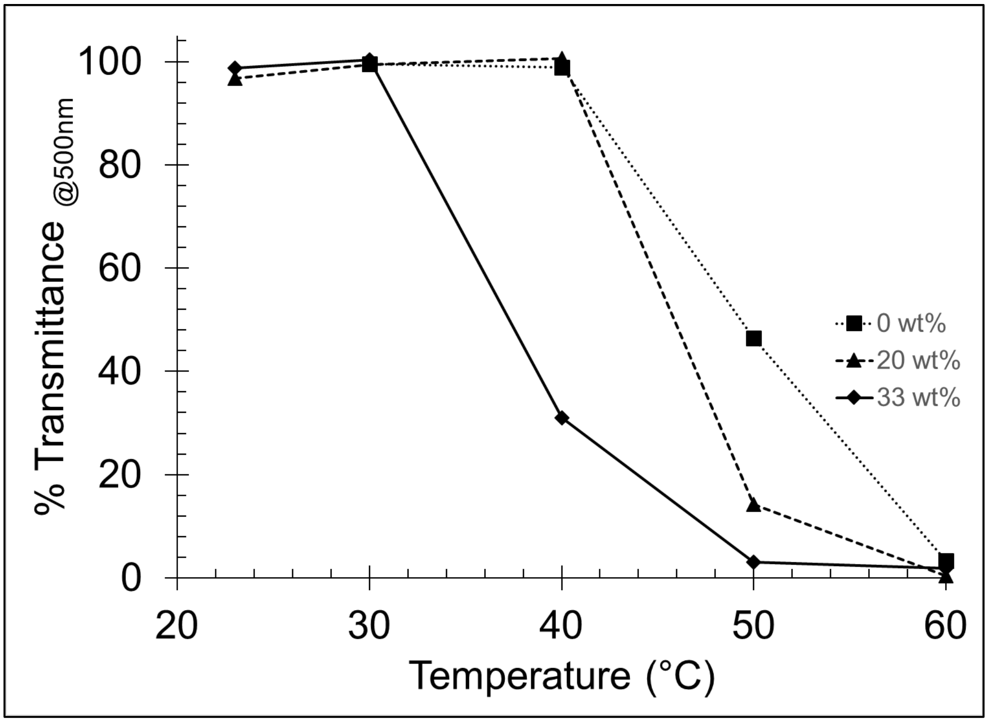



**Figure 11.** Transmittance change when increasing temperature for the 140 000 g/mol HPC solutions.

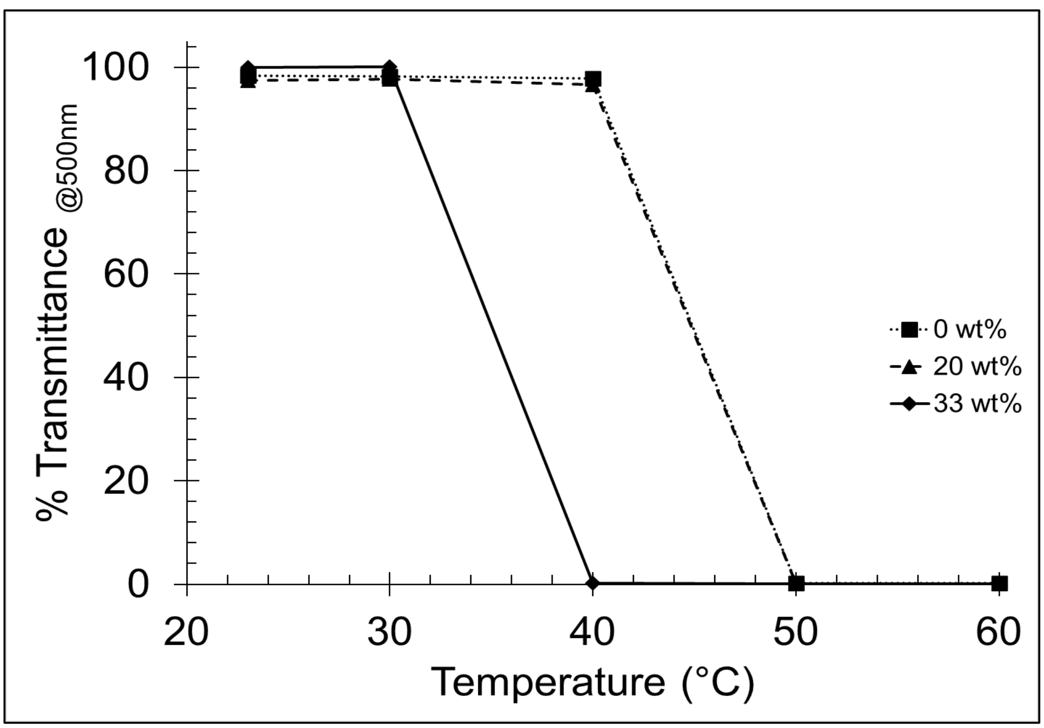
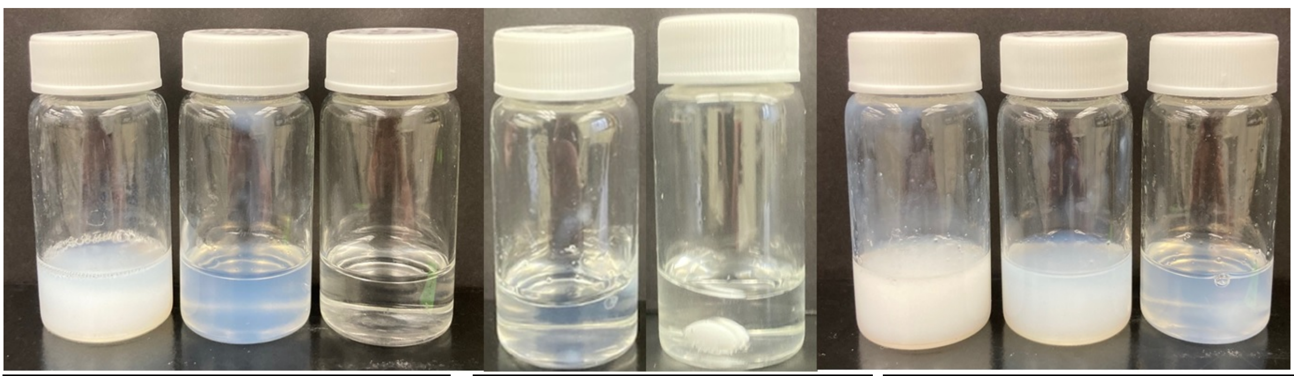



**Figure 12.** Transmittance change when increasing temperature for the 1M g/mol HPC solutions.

# Addition of SDS

Gels were created by increasing the concentration of HPC and SDS in each sample. **Figure 13** shows the 8 gel samples at room temperature. As the HPC concentration is increased, the cloud point decreases. At equivalent concentrations of SDS, the 10 wt% HPC samples show the highest transmittance. As surfactant concentration (SDS) is increased, the cloud point increases. The samples are clear at low concentrations of HPC and high concentrations of SDS (1-2 wt%), indicating that cloud point is above room temperature. The cloud points measurements are reported in **Figure 15** and reiterate these trends. At high SDS concentrations, the gel samples have a high viscosity. **Figure 14** shows the gel samples inverted.



10 wt% HPC (0, 0.1 & 1 wt% SDS) | 15 wt% HPC (1 & 2 wt% SDS) | 20 wt% HPC (0, 0.1 & 1 wt% SDS)

**Figure 13.** Gel samples created using high concentrations of HPC and SDS. Samples shown at room temperature ~ 21°C.

10 wt% HPC (0, 0.1 & 1 wt% SDS) | 15 wt% HPC (1 & 2 wt% SDS) | 20 wt% HPC (0, 0.1 & 1 wt% SDS)

**Figure 14.** Gel samples inverted to show viscosity.

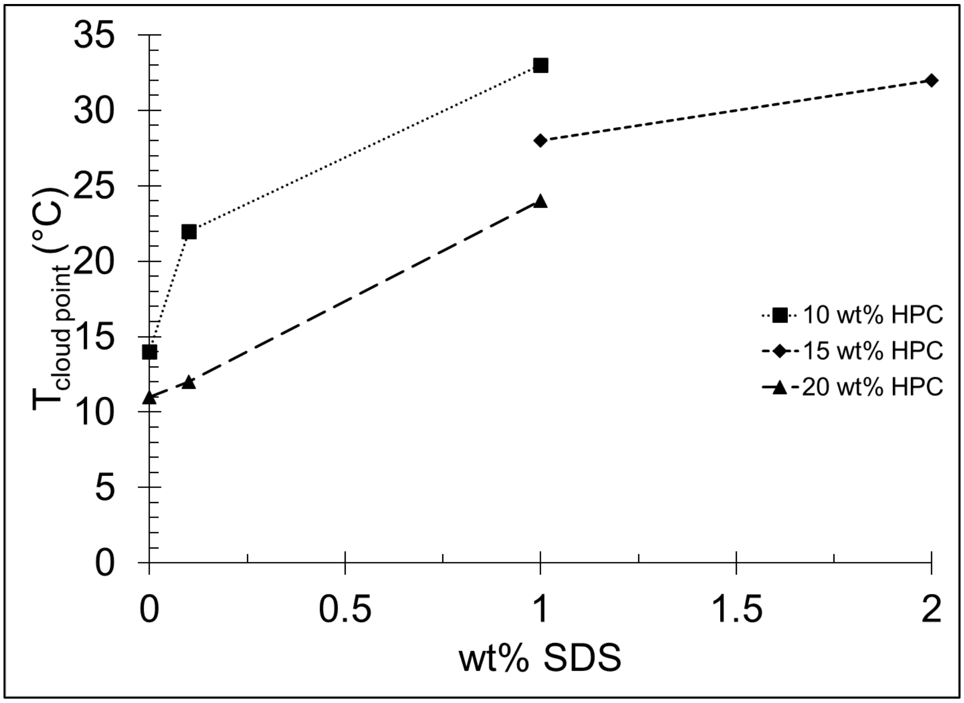



**Figure 15.** Shows the gel cloud point temperatures as SDS and HPC concentration are increased (140 000 g/mol HPC used across all samples).

## Heat Shielding

The 15 wt% HPC, 1 wt% SDS sample was tested for its performance in a smart window. First, the outside temperature from the bulb was determined at each stand height. These temperatures are plotted in **Figure 16.** The stand heights that replicate the temperature of a summer day occur at 8, 9, 10 and 11" - 29°C, 30°C, 31°C and 33°C, respectively. The heat shielding experiment outlined in **Methods** was ran for the open box, glass only and gasket apparatuses, shown in **Figure 6.** The steady state inside temperature, $T_{i,ss}$, average outside temperature and heat shielding values at each height are shown in **Table 1.** The 15 wt% HPC, 1 wt% SDS solution was tested after the baseline samples. The open box provided no heat shielding. When using the glass slides, the average heat shielding increased to 9.1%. Adding the gasket between the glass slides increased the heat shielding to 33%. In **Figure 17,** the solution can be seen at room temperature and during

the experiment as heat is applied. The 15 wt% HPC 1 wt% SDS sample was at its cloud point at all stand heights. A heat shielding of 51%, 55%, 64% and 61% was recorded at stand heights of 11, 10, 9 and 8” (~$T_o$ of 29, 31, 34 and 37°C). To isolate the solution’s decrease in transmittance as the source of the heat shielding, a second solution was tested where the cloud point was above the $T_o$. Increasing the concentration of SDS from 1 wt% to 2 wt% increased the cloud point from 28°C to 32°C. While it was desired to make this sample have an even higher cloud point, the SDS was not soluble in the 15 wt% HPC + 50 wt% glycerol at concentrations greater than 2 wt%. The 2 wt% gel was placed in a cell and tested in the heat shielding setup. For heights of 11 and 10”, the solution remained clear. At 9” and 8” the transmittance decreased as the solution phase separated and the $T_o$ exceeded the gel’s cloud point temperature. The average heat shielding achieved was 34%, compared to 56% for the 1 wt% gel. The heat shielding was 56%, 22%, 27% and 30% at the respective stand heights of 11, 10, 9 and 8”. The average heat shielding values are presented in **Figure 18**. The heat shielding values at each stand height are shown in **Table 1**.

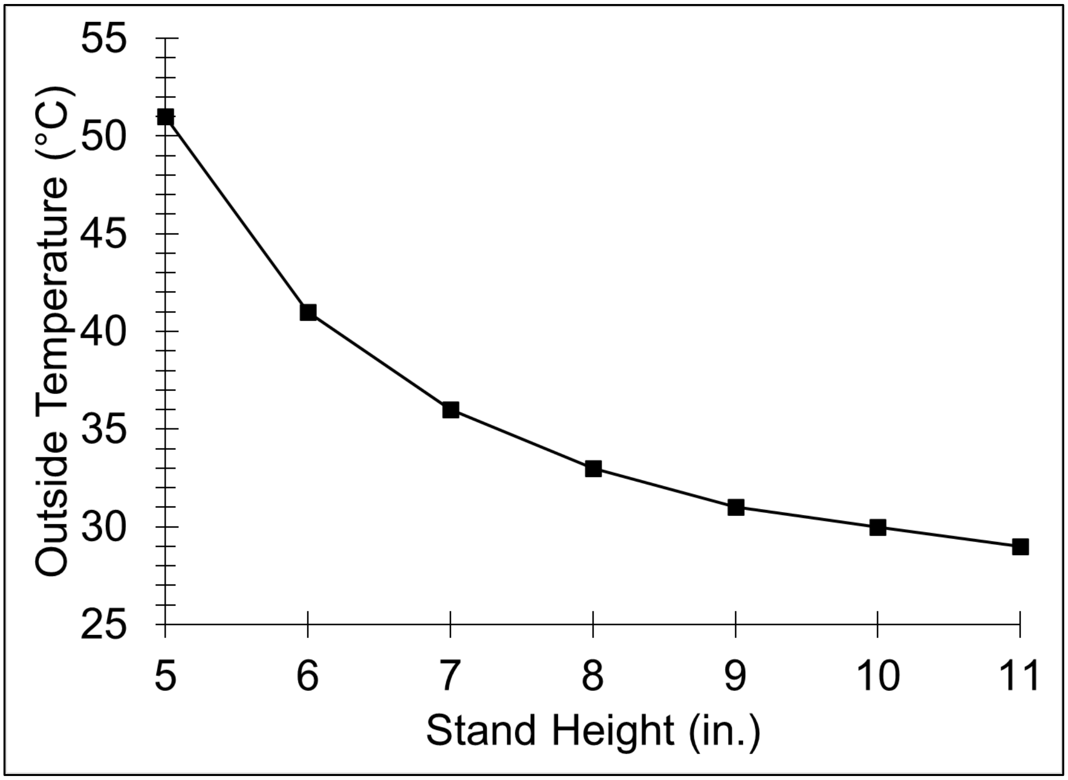



**Figure 16.** Outside temperature vs. stand height correlation developed to determine where to position the 150 W bulb from the sample cell.

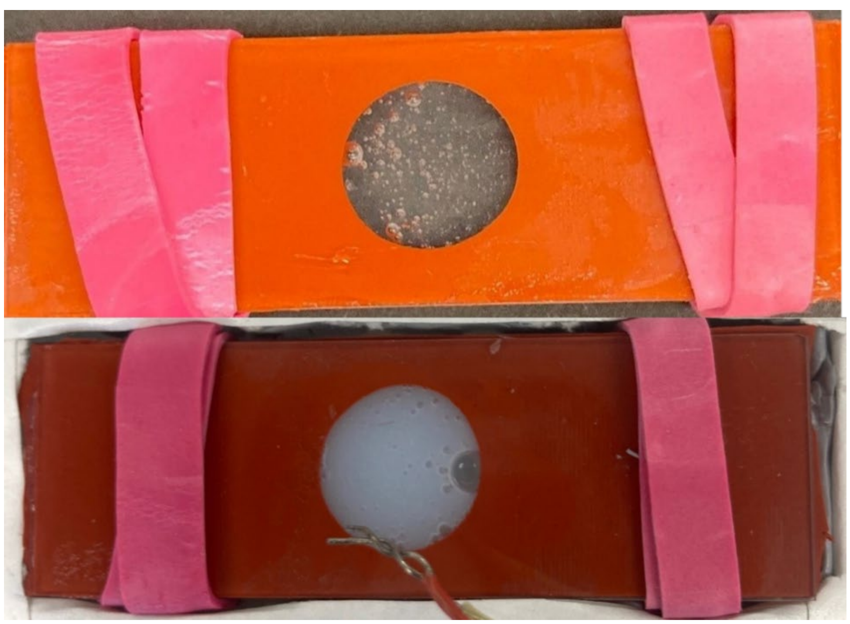


**Figure 17.** Shows the 15 wt% HPC, 1 wt% SDS sample before and after heat is applied (Gasket + Solution and 15% HPC + 1% SDS).

**Table 1.** Heat shielding data collected during experiment used to determine heat shielding compared to an open box.

| Trial (150 W bulb) | Height (in) | Ti,ss (°C) | To,avg (°C) | ΔT | Heat Shielding |
|---|---|---|---|---|---|
| Open | 11 | 26 | 29.0 | 3.0 | |
| Glass only | 11 | 25.2 | 29.0 | 3.8 | 26.6% |
| Gasket (no solution) | 11 | 24.6 | 28.4 | 3.8 | 27.2% |
| 15% HPC 1% SDS | 11 | 24.5 | 29.0 | 4.5 | 51.0% |
| 15% HPC 2% SDS | 11 | 24.6 | 29.2 | 4.6 | 56.0% |
| Open | 10 | 27.4 | 31.4 | 4.0 | |
| Glass only | 10 | 26.2 | 30.4 | 4.2 | 5.2% |
| Gasket (no solution) | 10 | 25.2 | 30.1 | 4.9 | 23.5% |
| 15% HPC 1% SDS | 10 | 25.1 | 31.3 | 6.2 | 55.1% |
| 15% HPC 2% SDS | 10 | 25.1 | 30.0 | 4.9 | 22.1% |
| Open | 9 | 28.9 | 33.7 | 4.8 | |
| Glass only | 9 | 27.4 | 32.4 | 5.0 | 4.2% |
| Gasket (no solution) | 9 | 26.5 | 33.5 | 7.0 | 47.0% |
| 15% HPC 1% SDS | 9 | 26.1 | 34.0 | 7.9 | 64.1% |
| 15% HPC 2% SDS | 9 | 26.1 | 32.2 | 6.1 | 26.5% |
| Open | 8 | 30.6 | 36.8 | 6.2 | |
| Glass only | 8 | 29 | 35.3 | 6.3 | 0.6% |
| Gasket (no solution) | 8 | 27.4 | 35.8 | 8.4 | 34.9% |
| 15% HPC 1% SDS | 8 | 27.2 | 37.2 | 10.0 | 60.6% |
| 15% HPC 2% SDS | 8 | 27.4 | 35.5 | 8.1 | 30.4% |

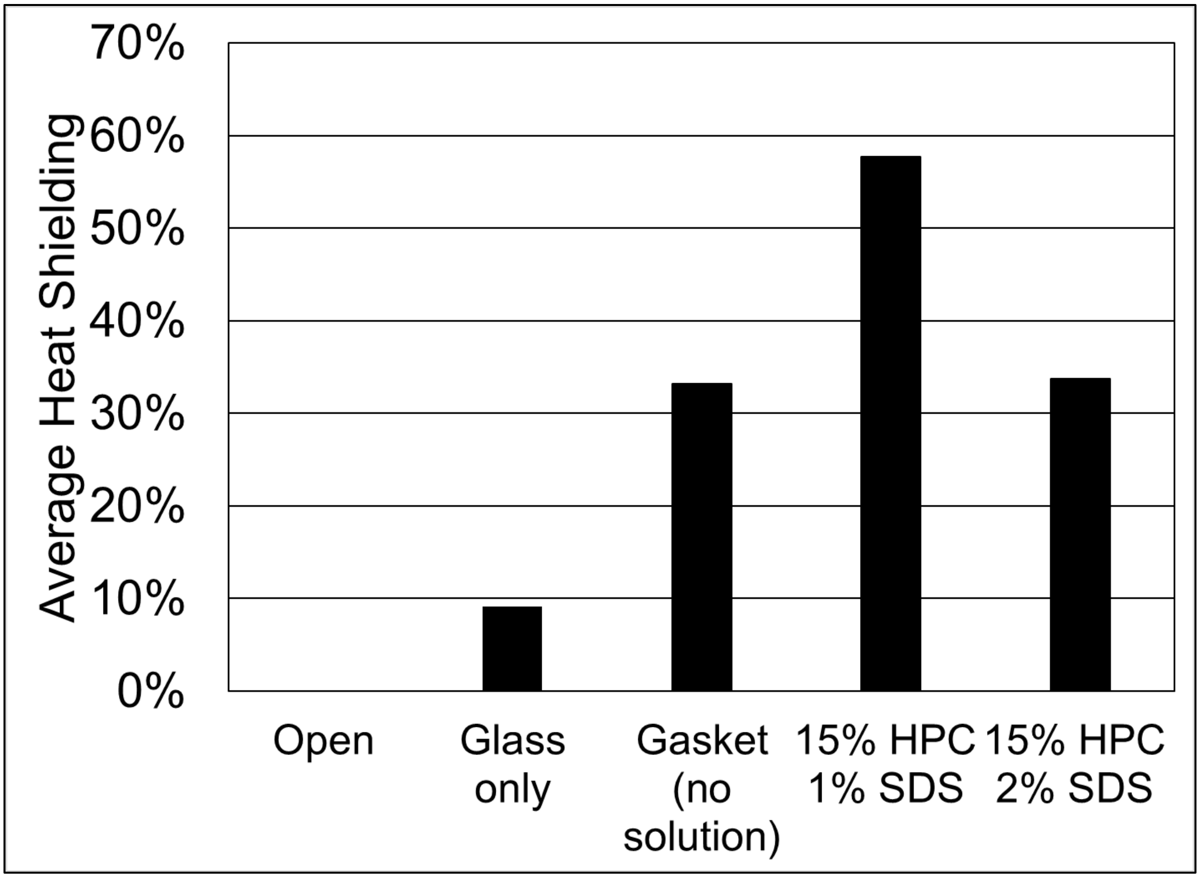



**Figure 18.** Average heat shielding for each cell across 8, 9, 10 and 11" stand heights.

## Cost Savings Estimation

A cost savings estimation based on a decrease in cooling costs due to implementing the smart window is outlined below:

The total solar energy density falling onto a south facing window in a year is ~ 1000 kWh/m$^2$yr.[10] In Akron, OH, the number of Cooling Degree Days (CDD) above 82°F (the cloud point of the 15 wt% HPC 1 wt % SDS gel) is 77.1.[11] This value was obtained by integrating the total time and degrees above 82°F in Akron for the past year. To estimate the time that it would be both sunny and above 82°F the total solar energy density was multiplied by 77.1/365:

The heat shielding of each window design was applied to the total solar energy density value. To determine the cost/year the energy rate of $0.12/kWh was used.

For a standard house (10 - 2'x3' windows), the following cost savings are obtained:

**Table 2.** Cooling costs savings for an average home (10 - 2'x3' windows).

| ***Type*** | **Average Heat Shielding** | **Solar Energy Density kW/m²yr** | **Cost $/m²** | **Cost/yr home** | **Savings from Glass** |
|---|---|---|---|---|---|
| *Open* | 0% | 211.0 | 25.3 | $ 141.2 | $ (12.9) |
| *Glass only* | 9% | 191.7 | 23.0 | $ 128.3 | $ - |
| *Gasket (no solution)* | 33% | 141.0 | 16.9 | $ 94.3 | $ 34.0 |
| ***15% HPC 1% SDS*** | **58%** | **89.2** | **10.7** | **$ 59.7** | **$ 68.6** |
| *15% HPC 2% SDS* | 34% | 139.8 | 16.8 | $ 93.5 | $ 34.7 |

For a larger building, the cost savings are even greater. An estimation of the polymer building in Akron, OH was made by using the building's height and square footage to estimate the surface area of the completely windowed building. The window area was estimated at ~9900 $m^2$. Using this area, the following cooling savings were achieved:

**Table 3.** Approximate cooling cost savings for the Goodyear Polymer Building (~9900 $m^2$ of windows).

| ***Type*** | **Average Heat Shielding** | **Solar Energy Density kW/m²yr** | **Cost $/m²** | **Cost/yr Polymer** | **Savings from Glass** |
|---|---|---|---|---|---|
| *Open* | 0% | 211.0 | 25.3 | $ 252,000.8 | $ (22,976.6) |
| *Glass only* | 9% | 191.7 | 23.0 | $ 229,024.1 | $ - |
| *Gasket (no solution)* | 33% | 141.0 | 16.9 | $ 168,410.1 | $ 60,614.0 |
| ***15% HPC 1% SDS*** | **58%** | **89.2** | **10.7** | **$ 106,607.7** | **$ 122,416.5** |
| *15% HPC 2% SDS* | 34% | 139.8 | 16.8 | $ 167,001.7 | $ 62,022.4 |

## Discussion/Analysis

When glycerol concentration was increased in **Figures 8** and **9**, the cloud point temperature decreased. This trend was also reported by Nakamura. These results show glycerol promoting the release of water from HPC due to hydrogen bonding between the glycerol and water. Even at lower temperatures, the phase separation occurs. This trend is also shown through decreasing %T values in **Figures 10-12**.

As molecular weight of HPC increases, the cloud point decreases in **Figures 8** and **9**. The increase in HPC polymer chain length promotes hydrophobic bonding[9] - leading to the release of water at a lower temperature and thus, a lower cloud point. The results from the UV-vis spectroscopy in **Figures 9-11** also help to confirm this trend.

While SDS has been known to form a gel in glycerol at concentrations as low as 2 wt%[8], it was unknown how the system would interact when HPC was added and if the gel/solution formed would retain its TR properties. As shown in **Figure 14,** a highly viscous gel forms at 10 wt% HPC, 0.1 wt% SDS, at 15 wt% HPC (1 and 2 wt% SDS) and at 20 wt% HPC, 1 wt% SDS. All samples retain their TR properties in **Figure 13**. Originally, two solutions with 50 wt% glycerol were combined with 2 and 20 wt% HPC. These solutions were cloudy at room temperature (21°C), too low to be used in a smart window. The 2 and 20 wt% HPC solutions were also not viscous enough to be self-supporting. To help increase the cloud point and increase viscosity, SDS was added at varying concentrations. When increasing the concentration of SDS, the cloud point increases, shown in **Figure 14**. This increase in cloud point shows the SDS's ability to solubilize the hydrophobic domains as temperature increases. By decreasing hydrophobic interactions, the window of favorability between the HPC and water is extended and requires a higher temperature to phase separate.

The 1 wt% SDS, 15 wt% HPC sample showed high viscosity and a cloud point temperature of 28°C – in the desired region to be implemented into a smart window for use on a warm day. The results from the heat shielding experiment show the effectiveness of this sample to shield heat as temperature increased. The average heat shielding was 56%, compared to the 9% shielding by the glass slides (**Figure 17)**. As the TR gel was heated, scattering occurred due to the release of the water, blocking some of the heat from the 150 W bulb. Some of the results from the heat shielding experiment are questionable. As shown in **Figure 17**, bubbles form in the gel when it is spread between the microscope slides and gasket. These air bubbles have a lower transmittance than the TR gel. This likely caused the heat shielding to be lower for the gel samples. For future work, there should be a procedure made to remove the bubbles using a vacuum or a similar apparatus. For the 15 wt% HPC, 2 wt % SDS sample, the sample had the highest heat shielding at 11" (29°C). It was expected for the heat shielding to be the lowest here because the gel was below its CP. The average heat shielding for the 2 wt% is 34%, compared to the gasket's average shielding of 33%. Because the 2 wt% sample was at its cloud point for half of the stand heights, the shielding was expected to be significantly higher than the gasket's shielding. The 2 wt% sample should be retested to ensure the accuracy of experiment and create a more accurate comparison to its performance vs. the 1 wt% SDS sample.

The data from the heat shielding experiment was used to calculate the cooling costs savings from implementing TR smart windows into a standard home and the Goodyear Polymer Building. In **Tables 2** and **3**, the cost savings of the 15 wt% HPC, 1 wt% SDS solution was the greatest – \$68.6/yr for a standard home and \$122,416.5 /yr for the Goodyear Polymer Building. These cost savings are on the assumption that the windows in place now provide the same amount of heat shielding as two microscope slides placed together. Further analysis should be run to determine

the costs associated with production and installation.

## Literature Cited

[1] Ge D, Lee E, Yang L, Cho Y, Li M, Gianola DS, Yang S. A robust smart window: reversibly switching from high transparency to angle-independent structural color display. Adv Mater. 2015 Apr 17;27(15):2489-95. doi: 10.1002/adma.201500281. Epub 2015 Mar 2. PMID: 25732127.

[2] K.J. Chua, S.K. Chou, W.M. Yang, J. Yan. Achieving better energy-efficient air conditioning – A review of technologies and strategies. Applied Energy, Volume 104, 2013, Pages 87-104

[3] Zhou, Y., Dong, X., Mi, Y., Fan, F., Xu, Q., Zhao, H., ... & Long, Y. (2020). Hydrogel smart windows. Journal of Materials Chemistry A, 8(20), 10007-10025.

[4] Chiaki Nakamura, Takashi Yamamoto, Kengo Manabe, Takuto Nakamura, Yasuaki Einaga, and Seimei Shiratori. Thermoresponsive, Freezing-Resistant Smart Windows with Adjustable Transition Temperature Made from Hydroxypropyl Cellulose and Glycerol
Industrial & Engineering Chemistry Research 2019 58 (16), 6424-6428
DOI: 10.1021/acs.iecr.9b00407

[5] Zhou, Y.; Cai, Y.; Hu, X.; Long, Y. Temperature-Responsive Hydrogel with Ultra-Large Solar Modulation and High Luminous Transmission for "smart Window" applications. J. Mater. Chem. A 2014, 2, 13550−13555.

[6] Boscornea, Cristian & David, Adelina & Ioan, Livia & Teodorescu, Mircea. (2013). Effect of additives upon the phase transition temperature of α,ω-(2- hydroxyethoxy) oligo(propylene oxide) in aqueous solutions. MATERIALE PLASTICE. 50. 163-166.

[7] Martins, Ricardo M. de, Silva, Carolina A., Becker, Cristiane, Samios, Dimitrios, Bica, Clara I. D., & Christoff, Marcelo. (2002). Studies on Anionic Surfactant Structure in the Aggregation with (Hydroxypropyl)cellulose. Polímeros, 12(2), 109-114. https://dx.doi.org/10.1590/S0104-14282002000200010

[8] Lauren Matthews, Żaneta Przybyłowicz, Sarah E. Rogers, Paul Bartlett, Andrew J. Johnson, Robert Sochon, Wuge H. Briscoe, The curious case of SDS self-assembly in glycerol: Formation of a lamellar gel, Journal of Colloid and Interface Science, Volume 572, 2020, Pages 384-395, ISSN 0021-9797,
https://doi.org/10.1016/j.jcis.2020.03.102.

[9] Tong, Z., Zeng, F., Zheng, X., & Sato, T. (1999). Inverse Molecular Weight Dependence of Cloud Points for Aqueous Poly(N-isopropylacrylamide) Solutions. Macromolecules, 32(13), 4488–4490. doi:10.1021/ma990062d

[10] Azens, .A., Granqvist, .C. Electrochromic smart windows: energy efficiency and device aspects. *J Solid State Electrochem* **7,** 64–68 (2003). https://doi.org/10.1007/s10008-002-0313-4

[11] "Degree Days Calculated Accurately for Locations Worldwide." *Degree Days.net*, www.degreedays.net/#generate.

# Appendix A – Sample Calculations

## Heat Shielding Calculation

**Equation 1.** Equation used for calculation of heat shielding.
Heat Shielding = $\Delta T - \Delta T_{open}/\Delta T_{open}$

Example:
For 15% HPC 1 wt% SDS @ 11",
Heat Shielding = (29.0°C – 24.4°C)-(29°C - 26°C)/(29°C - 26°C) = 51%

## Cost Savings Estimation

**Table 4.** Solar Energy Density calculation when T>82°F in Akron, Ohio. SED calculated by multiplying total SED by CDD and chance T>82°F.

| | |
|---|---|
| **1000** | $kW/m^2yr$ (Solar Energy Density on a window) |
| **77.1** | CDD (total degrees * days of temperature > 82°F) |
| **0.21** | % Chance T > 82°F |
| **<u>211.0</u>** | $kW/m^2yr$ --> Total Solar Energy Density when T >82°F |