INSULATION IN WINDOWS USING RESIN & AEROGEL MIXTURE

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Insulation in windows using resin & aerogel mixture

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MASTER OF SCIENCE

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ABSTRACT

Insulation materials are essential in building construction; this study proposed to use one such material called silica aerogel, which is known for its excellent thermal properties, and a UV acrylate resin that has been formulated to mix with the aerogel. In this experiment, existing methods of aerogel insulation are discussed and a novel method is investigated. U- value and R-values were obtained by LHICD (i.e., Laser Heating Infrared Camera Detecting method), and K -values were calculated using an equation for 0%, 22.5% and 45% volume of aerogel. The study suggests that using aerogel and resin coating on windows could help to improve the insulating properties of windows. i.e., low thermal conductivity and high thermal resistivity. The results obtained demonstrate that as we increase the percentage volume of aerogel in window coating, the window's thermal conductivity decreases, and the thermal resistance increases.

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DEDICATION

I dedicate this thesis to my sister, Rashmi Pujar. Without her, it would have been impossible for me to come this far in my life. She has always supported and encouraged me to pursue my dreams.

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LIST OF ABBREVIATIONS

AGU..Aerogel glazing unit

BTU………………………………………… British Thermal Unit

CPVC..Critical pigment volume concentration

K..Thermal conductivity

LHICD ....Laser-heating and infrared camera-detecting method

PMMA ....Polymethyl methacrylate

PVC…………………………………………Pigment Volume Concentration

R..Thermal resistance

Rf..Thermal resistance induced by the fused quartz

Rs ....Thermal resistance of the sample

Rsub ....Thermal resistance from the interface to the bulk Al

SEM ....Scanning electron microscope

TMPTA...Trimethylolpropane triacrylate

U..Thermal transmittance

LIST OF SYMBOLS

Δ ………………………………………………………………………………. Delta

CHAPTER 1. INTRODUCTION

Energy consumption in the United States (US) is tracked by the Energy Information Administration (EIA) in such sectors as transportation, building, and industry. The total annual primary energy consumption in the building sector is 17.6 quadrillion BTUs, with 18 percent from commercial (Ye, Zuo, and Wang 2019). Globally the building industry consumes approximately 40 percent of primary energy (Berthou et al. 2015) Typically, a building loses 30 percent of their energy through windows. This is 4-10 times more heat per square meter compared to other building components such as walls, roofs, and floors. (Dowson et al. 2011)

This data indicates that the construction industry is involved with projects that over time can become energy intensive and subsequently cause significant greenhouse gas emissions (Lolli and Andresen 2016). Sustainable development, therefore, plays a very important role in construction (Rostam, Mahdavinejad, and Rostam 2015). While the building sector consumes much energy in developed countries (Sadineni, Madala, and Boehm 2011), thermal insulation could reduce this consumption. Because of the super-insulating qualities of aerogel, many rely on this material (Rostam, Mahdavinejad, and Rostam 2015). A super-insulating material like aerogel may assist in preventing heat loss and thereby saving more energy. Aerogel has demonstrated better thermal resistivity, reduced thickness, and showed the potential to generate high-performance window components (Lorenzati et al. 2015; In and Naguib 2015).

Aerogel was invented in 1930 by Samuel Stephens Kistler. Aerogel was initially used for thermal insulation in high-performance textiles. Since then, it has been further developed and refined for use in sectors such as construction (Fricke et al. 1987; Cuce et al. 2014; Duer and Svendsen 1998). Aerogel has unique features such as being lightweight, transparent, and a good insulator, and it has high structural strength per unit weight (Jensen 1992; Hrubesh 1998; Sun, Longtin, and Norris 2001; Hostler et al. 2009). Despite having good thermal properties, aerogel is not widely used in building construction due to current lack of knowledge of its super insulation properties along with high initial costs (Lorenzati et al. 2015; Maleki, Durães, and Portugal 2014).

Recent results indicate a potential for increasing the global utility of aerogel in construction. Silica aerogel, for example, is a material with a combination of properties such as high solar transmittance and low thermal conductivity (Jensen, Schultz, and Kristiansen 2004). Therefore, it has been used in the insulation of walls, roofs, floors, and windows. In the past 15 years, aerogel has continued to improve the energy efficiency of windows in the US (Thiel et al. 2013), and aerogel's properties show a bright future for window insulation.

This study's research further develops a new method to insulate windows using aerogel, specifically with improved U - value and R - values. The U value (thermal transmittance) is the measure of how much energy is passed through the window in terms of temperature and area, and its unit are W/m2K (Virta 2016). R-value (thermal resistivity) is defined as the ratio of the temperature difference between the two faces of a material to the rate of heat flow per unit area, and its units are m2K/W (Venkataraman et al. 2014). K value is the measure of the rate at which heat is transferred through a unit area of the object cross the unit thickness, and its units are W/mK (Venkataraman et al. 2014).

Initially, the research investigates different methods of insulation. Next, the research will focus on insulation with aerogel. Finally, new methodology and materials are investigated in this research by testing U and R and K value.

1.1. Structure of Paper

This paper is organized in five chapters.

- Chapter 1 presents an introduction to the research.

- Chapter 2 is a review of existing insulation methods for windows and provides background about aerogel insulation, objectives, and hypothesis.
- Chapter 3 describes the new methodology and materials used in this project.
- Chapter 4 explains how U and R values were measured and how K values were calculated.
- Chapter 5 discusses the results.
- Chapter 6 discusses the limitations and future scope

Lastly, the overall conclusions are discussed.

CHAPTER 2. LITERATURE REVIEW & BACKGROUND

Energy demand steadily increases with population growth and modern lifestyles, making conservation of energy a very important factor. Because windows are one of the most prominent features of buildings and energy loss is more common through windows than walls, the heating demands of windows play a very important role (Schultz and Jensen 2008). But while energy loss through the wall is lower (better R-value) than that through windows, the latter has a function to fulfill, which is daylighting. Daylighting is very important for both good mental and physical human health (Reim et al. 2002).

Additionally, climate change is a major subject of this century, and the building sector is a major contributor (Walker and Pavía 2015; Zagorskas et al. 2014). Due to this fact, the US government has funded more than $400 million in building window retrofitting projects in the last ten years (Berardi 2015b). The difficult tradeoff between the need for daylighting and effective insulation might be solved using aerogel windows. They might provide sufficient daylight and manage issues of disability glare without blinds or other external shadings (Garnier, Muneer, and McCauley 2015). Aerogel also reduces energy consumption, keeping the indoors warmer than the outside for days after switching off a heating system. Aerogel also has one of the highest R values, meaning better insulation, and aerogel windows make it possible to use less energy in cold climates (Ihara et al. 2015).

Aerogel can also reduce illuminance (glaring) by 10 percent during bright, sunny days (Cotana et al. 2014). Transparent openings are very important for natural lighting and should be as large as reasonably possible for visual comfort (Buratti and Moretti 2012b). Productivity increases with increased daylight. For example, Lockheed’s building 157 in Sunnyvale, California identified a 50 percent energy savings in lighting and ventilation; coincidently, it also showed a 15 percent reduction in absenteeism (Garnier, Muneer, and McCauley 2015). Windows have a double role in the thermal envelopes of buildings, and their thermal transmission needs to be as low as possible to reduce energy consumption. Light transmission characteristics also need to be as high as possible for visual comfort and energy saving (Buratti and Moretti 2012a). Thus, the application of aerogel as window insulation material fulfills these criteria

There are two types of aerogels: monolithic and granular. Monolithic aerogels have good transmittance compared to granular aerogels (Berardi 2015a). Monolithic silica aerogel is a material with an excellent combination of high solar transmittance and low thermal conductivity (Tewari, Hunt, and Lofftus 1985; Jensen, Schultz, and Kristiansen 2004). Many tests have been conducted to achieve a U value of about 0.5 to 0.7 W/m2k. Those attempts include such methods as multilayered, vacuum, and aerogel windows (Gao et al. 2014). Many methods and types of insulation materials have been explored, but the better insulation material is still not found. Below, some of the contemporary insulation methods are reviewed.

2.1. Review of Existing Methods

Arici, Karabay, and Kan (2015) studied heat transfer and heat loss in double, triple, and quadruple windows in different outdoor temperatures, concluding that heat usage can be reduced by increasing the number of panels and the gaps between panels. The maximum gap was 15mm, and a window with a quadruple pane was 80mm thick in total. 50 to 67 percent of energy can be saved if double glazing is replaced by triple or quadruple panes, but an additional glass pane increases the weight by 33 percent, and it needs stronger window frames than double glazed(Schultz and Jensen 2008, 1). Also, vacuum insulation panels of 5 to 50mm thickness have much less heat loss compared to conventional insulation of 250mm thickness (Abdul, Ashraf, and Alsuwayigh 2016; Schultz and Jensen 2008; Lolli and Andresen 2016; Lorenzati et al. 2015).

In 2015, the Department of Architectural Science at Ryerson University developed aerogel windows using two 4mm glass panels with 14mm monolithic silica aerogel filled in between. The transmittance of a monolithic panel and the panel between the glasses was measured using an Agilent Cary series UV-Vis-NIR spectrophotometer, between 200nm and 2000nm with 1nm accuracy. The author concluded that aerogel possessed good transmissibility, especially in the high spectrum range. The transmittance of monolithic aerogel was 0.6, granular 0.3, and without aerogel 0.7 (Berardi 2015b)

Gao et al. (2014) used a method for insulating windows where hydrophobic silica aerogel of size 3 to 5mm was ground, sieved, and then used in between two 4mm clear glass panels; aerogel of a 14mm thick layer was filled in between the panels, and the panels were sealed using silicon sealant. They concluded that by using this method, both the thermal and optical character of windows was affected because of particle size. AGU (aerogel glazing unit) with small aerogel particles (>0.5mm) showed a U-value of about 1.05W/m2 K, the transmittance of about 0.15, and a solar factor of about 0.27. On the other hand, aerogel with large granular size (3mm to 5mm) showed a U-value of about 1.19W m2/ K, the transmittance of about 0.50, and a solar factor of about 0.57. Gao et al. (2014) also concluded that AGUs showed improved thermal performance in comparison to double glazed window panels (63 percent and 58 percent respectively).

Reim et al. (2002) built an aerogel window with a method using two low-emissivity (low-e) coated glass panes and silica aerogel granules sandwiched between PMMA double skin sheets, used to avoid granular settlement. The space between sheets was then filled with krypton gas to optimize thermal insulation, thereby achieving a heat transfer coefficient of less than 0.4W (m2 K), the transmittance of 65 percent for 20mm thickness, and total transmittance of 35 percent. This setup or glazing has a thickness of less than 50mm, and this method is rapidly showing great potential to reduce heating and cooling demand (Cuce and Riffat 2015).

Kim et al. (2014) mixed pressure sensitive adhesive and aerogel (10, 15, and 20%) using homogenizer, and then applied this mixture to a glass pane to check thermal conductivity, which was measured ten times with the average value of all ten readings considered. The thermal conductivity results for the film not containing silica aerogel versus that with 20 percent (w/w) with aerogel was 0.773 W/mK and 0.528 W/mK, respectively. Based on this, the authors concluded that thermal conductivity decreases as the mass percentage of aerogel increases.

In another method, Morelli et al. (2012) used the secondary frame, i.e., extra glazing on one pane with a 20mm distance between two panes. They used low-e coating on the outside of both panels, yielding a U value of 1.09 W/m2 K (Morelli et al. 2012). In windows retrofitted with silica aerogel, the loss coefficient is reduced by a factor of three compared to two pane windows with low-e layer and filled with argon glass using aerogel spacers (Fricke et al. 1987).

2.2. Objectives & Scope

The objective of the research was to find a new method to insulate the windows and get good thermal properties while also making the window translucent. The method used in this research uses a super-insulating material called silica aerogel mixed with a UV acrylate resin to make coatings on glass panels. To support this objective, U and R values were calculated by using the laser-heating and infrared camera-detecting (LHICD) method. The K value was calculated using mathematically from the U and R values. Scanning Electron Microscopy was conducted out to understand the distribution of aerogel particles in the resin matrix.

The research question is as follows:

1. The proposed method gives good thermal properties to the windowpanes and gives enough daylighting. Also, this method makes the window glass thinner compared to conventional methods.

2.3. Hypothesis

The previous researchers used different methods of insulation. As discussed in the literature review section and achieved good thermal insulation properties. However, no research used silica aerogel and UV resin mixture to make a coating out of it. In this research, a novel method is proposed and used aerogel and resin mixture and achieved better results.

Based on the research questions, the following hypothesis was proposed.

1. Using silica aerogel and resin mixture would significantly increase the desirable thermal properties and transparency of windows compared to traditional methods of insulation. And as the aerogel percentage increases, the thermal conductivity would decrease.

CHAPTER 3. MATERIALS AND METHODOLOGY

In this research, we used two important materials, one is the aerogel, and the other is the resin.

3.1. Materials

The aerogel has very good insulating properties, and it is a very lightweight and low-density material. It gives good R-values and lowers thermal conductivity. A few specific properties of the aerogel that has been used in this thesis are shown in Table 1.

Table 1: Properties of aerogel.

Descriptions	Data
Source:	Bought from an online US manufacturer
Particle Size:	Ultrafine (varies)
Odor:	None
pH:	3.0 - 6.5
Vapor Pressure:	Not applicable
Boiling Point/Range:	2230°C after partial decomposition
Melting Point/Range:	1700°C after partial decomposition
Water Solubility:	Insoluble
Density:	60 - 150 kg/m3 @ 20°C
% Volatile (by Volume):	Negligible
Evaporation Rate:	Not applicable
Viscosity:	Not applicable
Partition Coefficient (n-octanol/water):	Not determined
Flash Point:	Not applicable
Explosion Limits in Air - Lower (g/m3):	220 g/m3 (dust)
Autoignition Temperature:	550°C
Method:	ASTM D-1929

The second material we used was resin. We formulated this resin with the help of the Department of Coatings and Polymeric Materials NDSU using five materials: 1,6 Hexanediol; Ebecryl 18402; Ebecryl 220; Trimethylol Propane Triacrylate; and Omnirad 1173 (Table 2).

Table 2: Quantity of each ingredient added in the resin.

UV resin formulation	Weight %	Amount (g)	Actual Amount Added (g)
1,6 Hexanediol (HDDA)	11	22	22.066
Ebecryl 18402	37.5	75	75.020
Ebecryl 220	37.5	75	75.312
Trimethylol Propane Triacrylate (TMPTA)	10	20	20.162
Omnirad 1173	4	8	8.102

The resin system is a UV-initiated free radical polymerization of polyacrylate monomers/oligomers. The resin formulation has many monomers with vinyl groups that can react with free radical-containing species and rapidly form a highly crosslinked network. The Ebecryl components are very viscous polyacrylates that also have urethane, which gives good solvent resistance and toughness. TMPTA and HDDA are reactive diluents, meaning that they are added to lower the viscosity of the other components, but they also have acrylate functionality and can become part of the network. The Omnirad is the free-radical photoinitiator. When it comes in contact with the UV light, it rapidly decomposes into radical species and reacts with the vinyl groups on the monomers which then become macroradicals and react with other vinyl groups, etc., until the number of these groups on the chains reaches infinity and a solid coating remains.

3.2. Methodology

In this section, the methods used for sample preparation and preliminary steps conducted before sample preparation are explained. Following are the important steps.

3.2.1. Finding The CPVC

Pigment volume concentration (PVC)has found almost universal acceptance in the paint industry. The PVC of paint is the volumetric percentage of pigment present in the total solids of a paint system and excludes all volatile from the calculation. The critical PVC (CPVC) is the sweet spot where the pigment is at its maximum loading while still having all the air between the particles completed filled with a binder. These concepts are applicable to this work when the "pigment" is aerogel, and the "binder" is resin. We wanted to find the point where there was sufficient resin to wet all aerogel particles and fill all the interstitial spaces between them. To calculate this, we used the density of aerogel (60 - 150 kg/m3) to calculate the weight of aerogel to be added in resin. Then we attempted to measure the viscosity of UV-acrylate resin with varying volume concentrations via a Brookfield Viscometer. This failed at 10% volume containing fine aerogel. Subsequent measurements were completed with an Ares Rheometer using a steady rate sweep from 0-100 rpm. In this test, aerogel and resin mixture was placed in between two plates, torque was applied to the upper plate using a steady rate sweep from 0-100 rpm, and the resulting shear rate was measured.

3.2.2. Sample Preparation

In this step, glass panels of 4"x4" were used, cleaning with acetone before use. The resin and aerogel were mixed using the quantities as shown in Table 2; then the mix was applied to the glass panels using the drawdown bar (Figure 2) using 45%,22.5%, and 0% aerogel in one and two layers. The first layer was applied using a drawdown bar, making a 4mils thick aerogel coating. It was then cured under a Dymax UV curing machine (105 mW/CM^2 intensity) with a 400watt EC supply) (Figure 1) for approximately one minute until the coating was solidified. For the two-layered samples, the second layer of 4mils was applied and cured for approximately one more minute until it solidified. The UV cured aerogel glass panels are shown in Figure 3.

Figure 1: Dymax UV curing machine

Figure 2: Drawdown bar

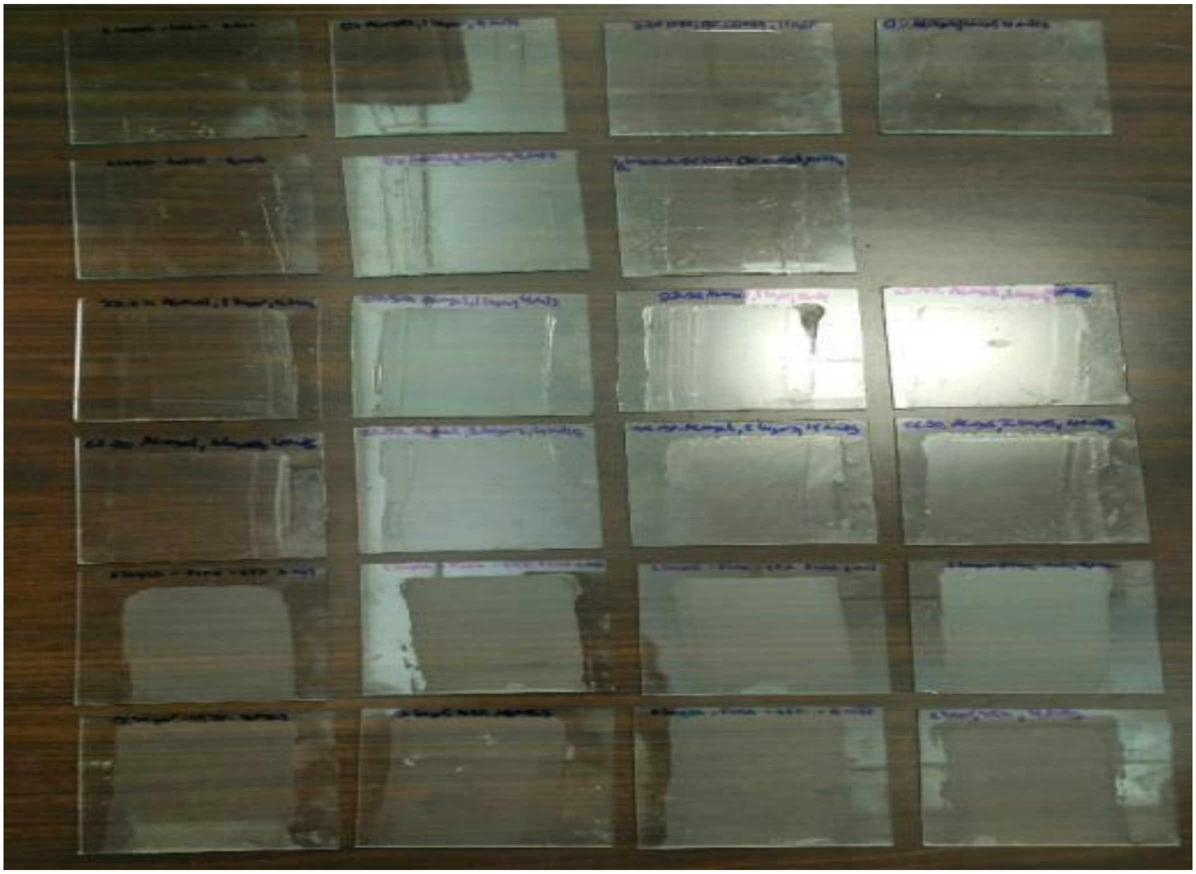

Figure 3: UV cured aerogel glass panels

Once the samples were prepared, they were tested for transparency. The samples, including a plain glass control, were placed in front of an image (Figure 4). The image below shows the different samples with different layers and the percentage volume of aerogel. We concluded that with the 45% two-layer coating, we could still see the image, but it made the glass translucent, so the image was a little blurred. With the 22.5% one-layer coating, we could see the image clearly.

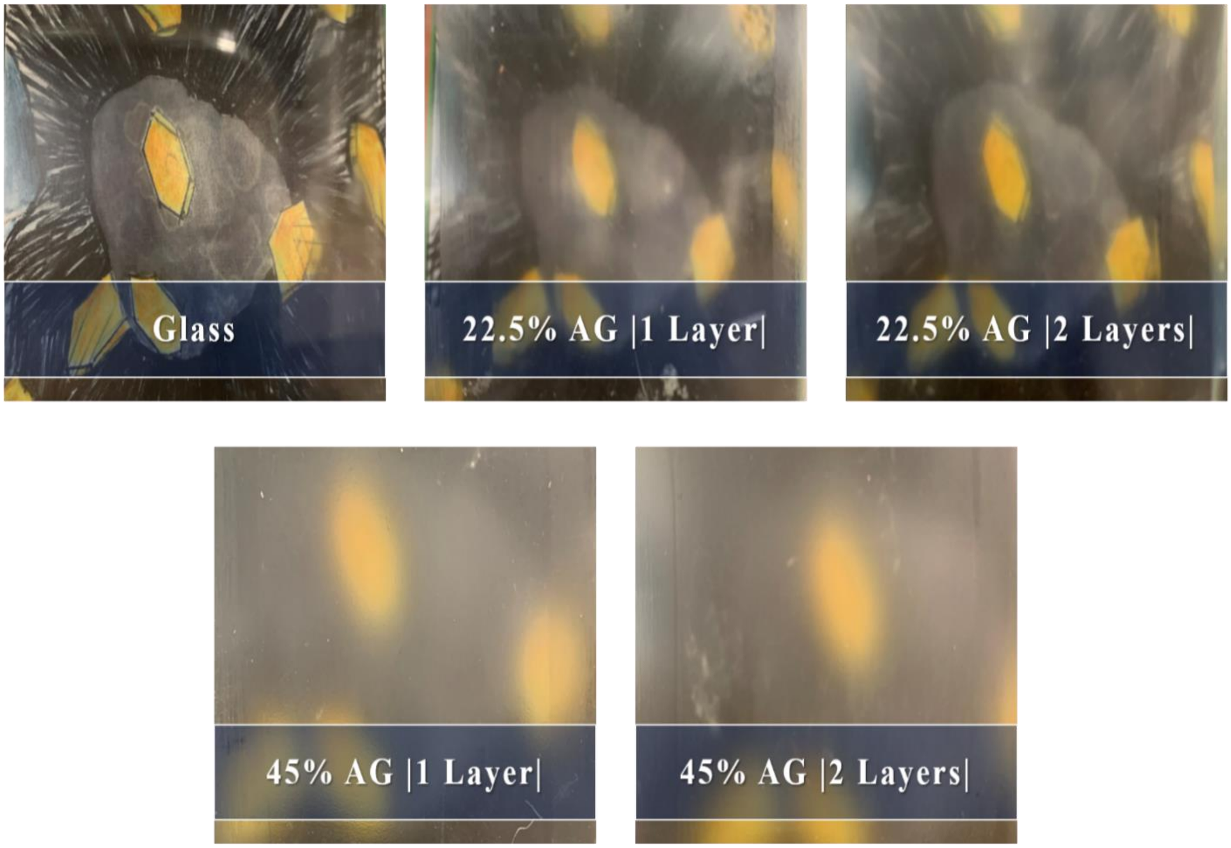

Figure 4: Different volume percentage of aerogel coating tested for transparency
(*AG is Aerogel Glazing)

CHAPTER 4. MEASURING R AND U VALUES

4.1. Tests to Find U-Value and R-Value

The thermal conductance of the prepared samples was measured by using a laser-heating and infrared camera-detecting (LHICD) method. Figure 5 shows a schematic of the experiment. In the LHICD measurement, the sample is attached to a bulk Aluminum (Al 6061) by thermal grease. A continuous laser is used to heat the sample surface where the temperature is detected by an infrared camera.

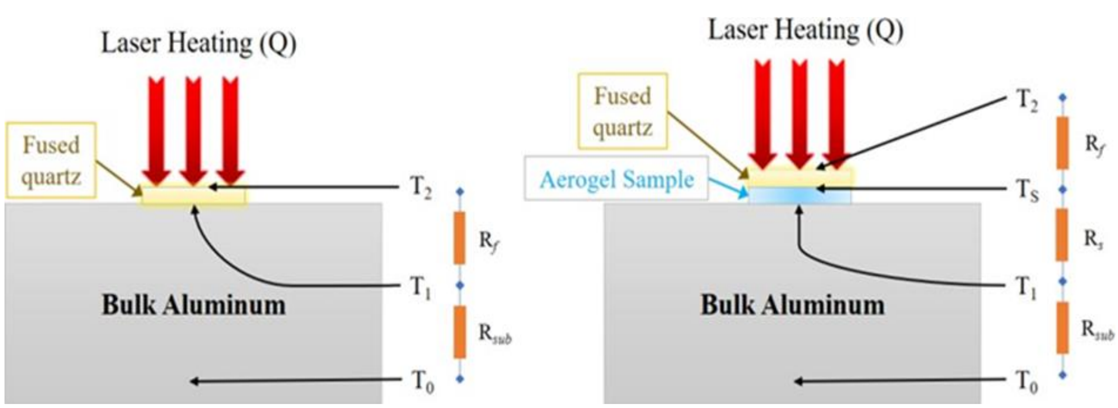

Figure 5: Setup showing the laser heating and infrared camera detecting method

According to Fourier's law, the thermal resistance of the sample (*Rs*) can be derived as the following equation:

$$Rs = \frac{d}{Aks} = \frac{\Delta T}{Q} = \frac{(T2 - T1)}{Q} \quad (1)$$

Where *Q* is the laser energy absorbed by the upper surface of the heat flow across the sample; *A* is the surface area; *d* is the thickness; and *T*1 and *T*2 are the temperatures at the bottom and upper surfaces, respectively. Theoretically, with the absorbed laser energy and the temperature difference, the thermal resistance and conductance can be calculated precisely. However, *Q* and

$T1$ are not easy to directly measure in real situations. In this case, the thermal resistance from the interface to the bulk Al (*Rsub*) was taken into consideration. The total thermal resistance can be serially expressed as (1)

$$Rs + Rsub = \frac{\Delta T}{Q} = \frac{(T2 - T0)}{Q} \tag{2a}$$

$$Rsub = \frac{\Delta T}{Q} = \frac{2Lc}{(qss*kalAs)} \tag{2b}$$

Here, Lc $= (As/\,4\pi)^{1/2}$ is a characteristic length. As is twice interface area here, Kal is the thermal conductivity of the bulk aluminum; qss* is a dimensionless conduction heat rate and is taken as 0.932 for the square interface area[1]; and $T0$ is the temperature of the bulk Al, which is equal to the environmental temperature and stays constant during the measurement due to the much larger thermal conductivity and dimension of the Al heat sink compared with our samples. Here in Eq. (2a), Q is still not determined, as the absorptivity of the sample's surface is unknown. Instead of measuring Q directly, the experiment is performed first on fused quartz and then with the sample sandwiched between the fused quartz and the bulk Al, as shown in Fig. 1a and 1b, respectively. The surface is heated with the same laser energy, which should lead to the same heat flow across the sample. The total thermal resistance can be expressed as:

$$Rf + Rsub = \frac{\Delta T}{Q} = \frac{(T2 - T0)}{Q} \tag{3a}$$

$$Rf + Rs + Rsub = \frac{\Delta T}{Q} = \frac{(T2 - T0)}{Q} \tag{3b}$$

with Rf, the thermal resistance induced by the fused quartz and expressed as

$$Rf = \frac{df}{kf} \tag{4}$$

Combing Eq. (2a) and (3) we have:

$$\frac{(Rf+Rsub)}{(Rf+Rs+Rsub)} = \frac{(\Delta T/Q)f}{(\Delta T/Q)f} + s \quad (5)$$

Rf and *Rsub* can be calculated with *kf* and *kAl* took as known parameters (1.38 and 167 W/mK, respectively). With the temperature differences from the experiment, *Rs* is determined.

The same experimental measurement and calculation were performed on all the samples, and thermal resistance and conductance of the samples were determined. The measurement was performed on the glass only under the coating sample, and the thermal conductivity was determined at 0.85 W/mK. Note that, *Rsub* can be ignored here, due to the high thermal conductivity of Al substrate.

4.2. Calculating K Value

After knowing R (thermal resistance), and U (thermal transmittance) values, K (thermal conductivity) can be calculated by using the following formula.

$1/R = K/\Delta x$

Here**,**

K = Thermal conductivity

Δx = Thickness of sample

R = Thermal resistance

CHAPTER 5. RESULTS AND DISCUSSION

5.1. SEM Results

Scanning electron microscopy was done to see the bonding between layers and determine whether the aerogel was getting distributed evenly, and the CPVC value was reached. Figure 6 shows the SEM image of a 45%, two-layer coating sample.

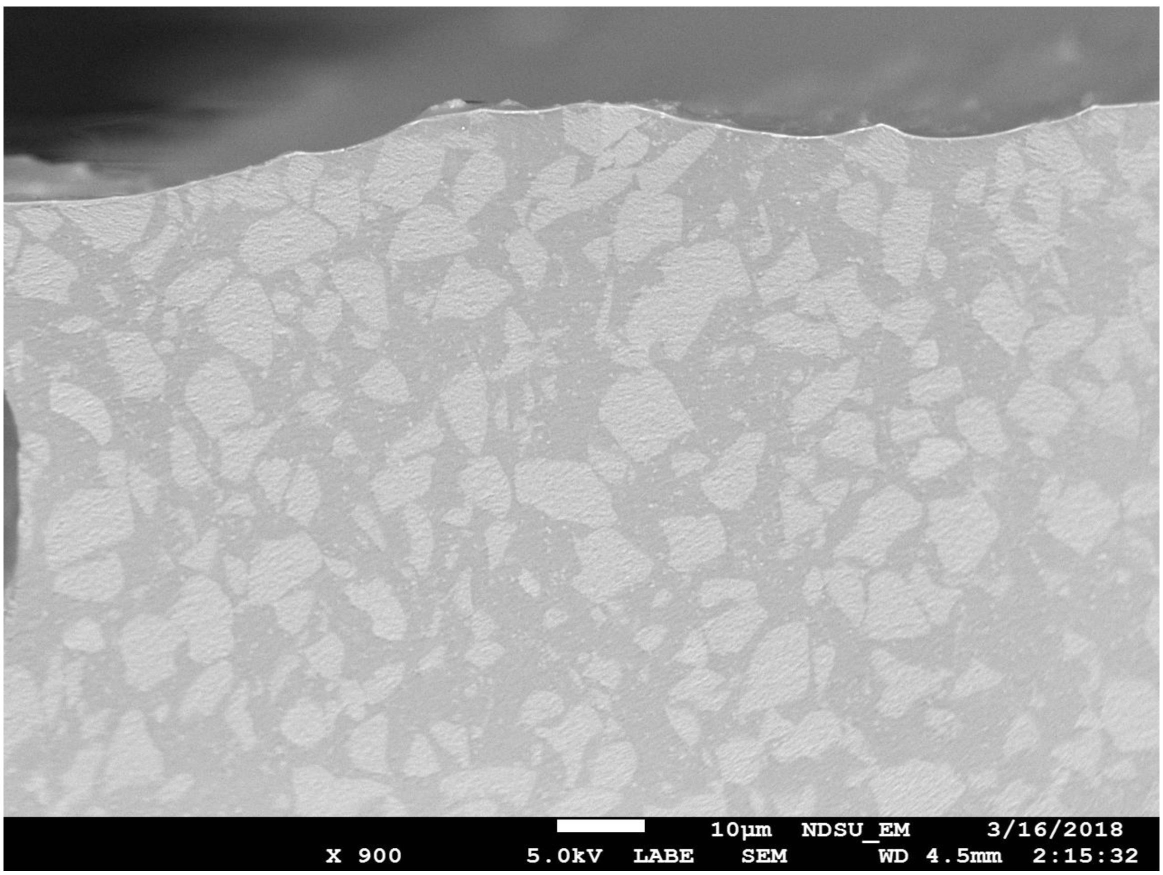

Figure 6: SEM image of the aerogel sample (45% volume aerogel with magnification x900)

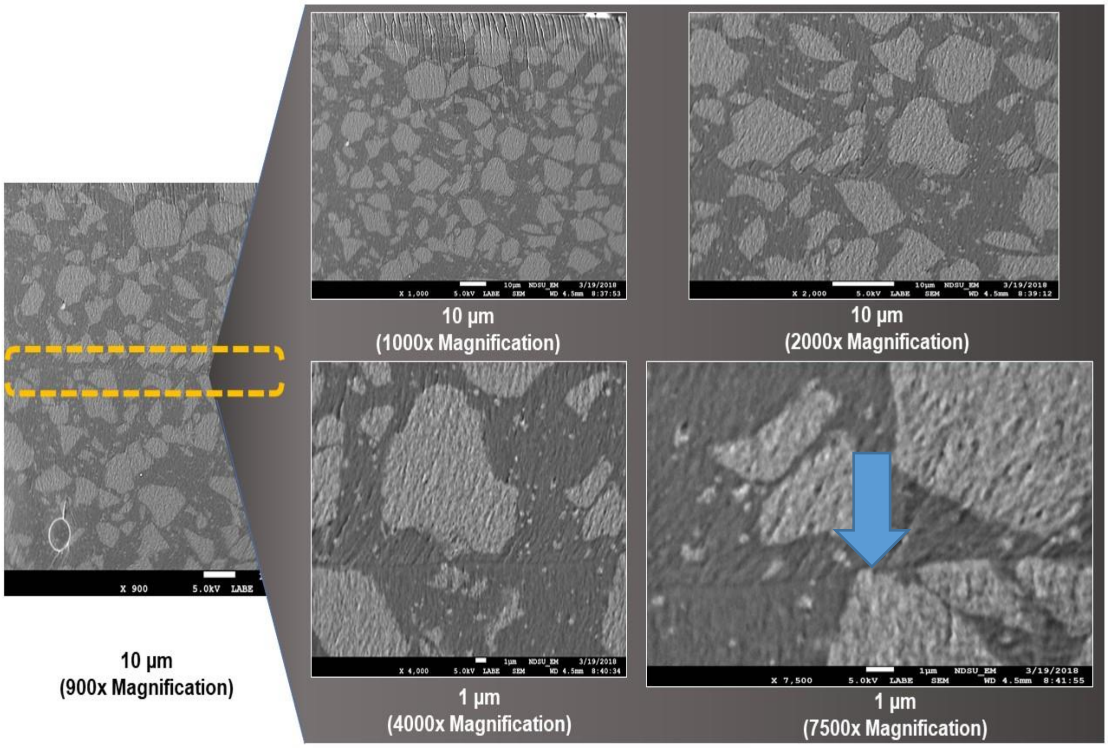

Figure 7: SEM image of a sample (45% volume of aerogel with two layers 8mils thick coating)

In the above figure, the arrow mark shows the bond between layer 1 and layer 2, demonstrating that there is no gap between two layers.

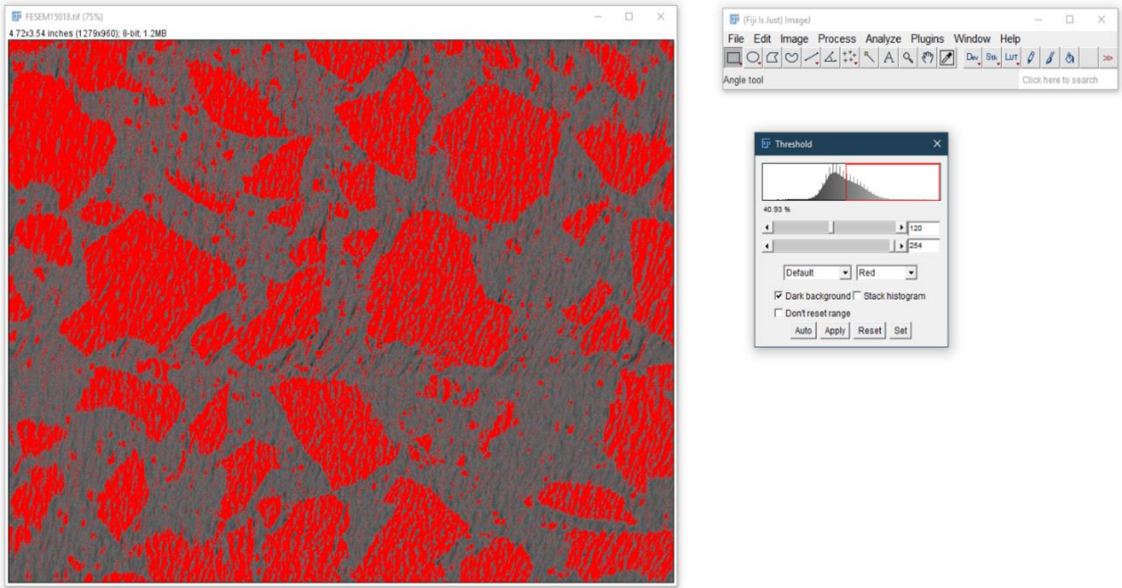

Figure 8: SEM analysis of a sample (45% volume of aerogel with two layers 8mils thick coating)

From SEM images, we conclude that the new method of incorporating aerogel in resin worked, that the aerogel particles distributed well, but there are some gaps, and the aerogel particles are not densely packed. Therefore, a method to make more layers or coatings in which the aerogel particles can be more densely packed could help increase the thermal properties.

To test the percentage of aerogel and resin after the samples were prepared, ImageJ (Java-based image processing software) was used. For the 45% two-layer sample, the aerogel percentage was 41%, and the resin percentage was 58%.

5.2. Finding CPVC

As mentioned earlier, viscosity measurements were completed with an Ares Rheometer using a steady rate sweep from 0-100 rpm. 0%, 10%, 20%, 30%, 35%, 40%, and 45% fine aerogel volume concentration were mixed with 100 mL resin. The mixture steadily became increasingly viscous. Because shear thinning was still noticed in the high-volume measurements, thus indicating CPVC still had not been reached, the mixing of further aerogel and the high viscosity was deemed problematic. At 45% it was decided coatings would be made. The amount of aerogel added is shown in Table 3.

Table 3: The amount of aerogel added.

% volume of aerogel	Amount (g)	Actual Amount (g)
0	N/A	N/A
10	0.666	0.6783
20	1.5	1.523
30	2.57	2.606
35	3.23	3.287
40	4	4.060
45	4.909	4.995

Figure 9 and Figure 10 show the shear rate of resin and aerogel mixture with different percentages of aerogel

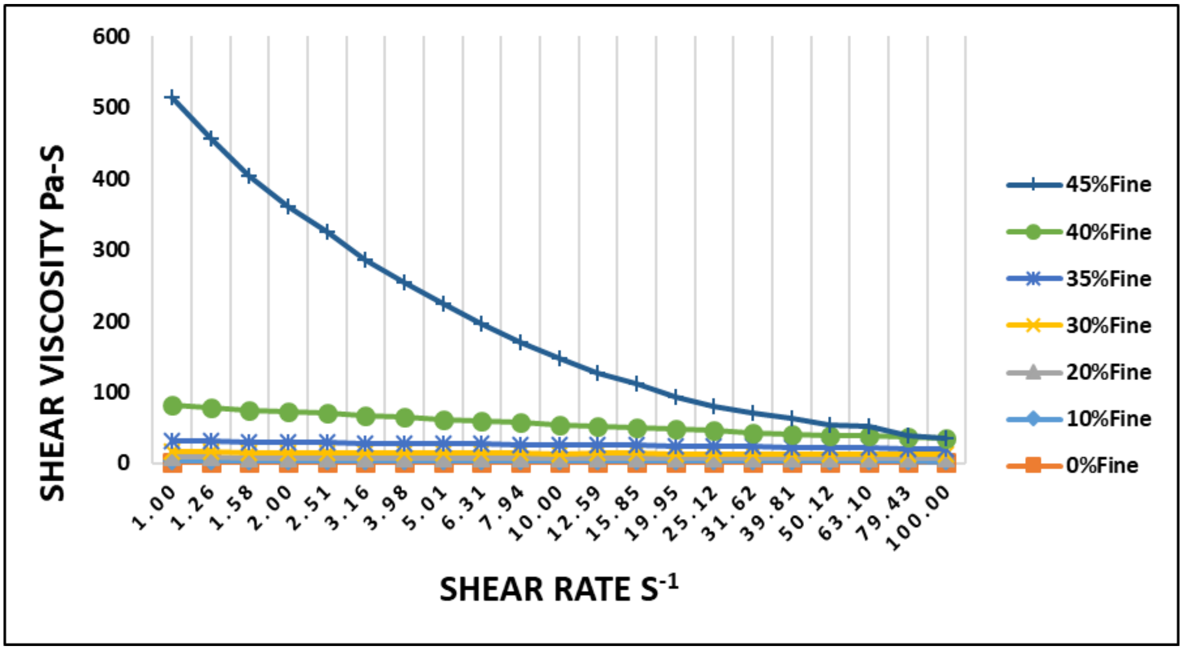

Figure 9: Viscosity of aerogel and resin mixture.

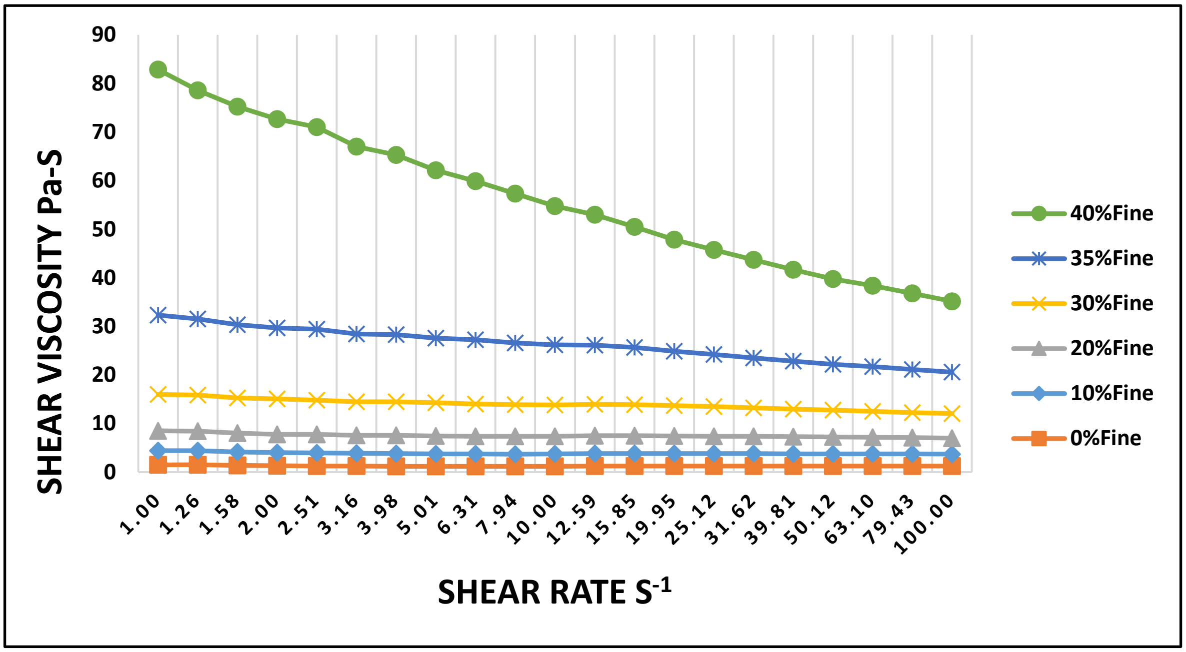

Figure 10: Viscosity of aerogel and resin mixture.
(Note: Fig 10 is Same as Fig 9 but with the 45% sample removed)

5.3. Thermal Properties of Aerogel

Table 4: Thermal properties of aerogel windows.

Sample	Aerogel volume%	Thickness (mils)	Layers	Thermal resistance (Km2/W) (R)	Thermal conductance (W/m2 K) (U)
Glass only	0%	-	-	0.0026	383
Sample 1	22.5%,	4	1	0.0120	81.72
Sample 2	22.5%	8	2	0.0126	79.36
Sample 3	45%,	4	1	0.0143	69.51
Sample 4	45%	8	2	0.0176	56.94

5.4. Calculating K Value

To find the K value, the formula below was used:

$1/R = K/\Delta x$

Here,

K = Thermal conductivity

Δx = Thickness of sample

R = Thermal resistance

Glass $1/R = K/\Delta x$

$K = \Delta x/R$

= 0.0022/2.61*10-3

= 0.8426 W/mK

1. 22.5% aerogel with one layer (Total thickness = 2.2+0.1016 = 2.3016)

$1/R = K/\Delta x$

$K = \Delta x/R$

= 0.0023016/0.0120

= 0.1918 W/mK

2. 22.5% aerogel with two layers (Total thickness = 2.2+0.2032 = 2.4032)

$1/R = K/\Delta x$

$K = \Delta x/R$

= 0.0024032/0.0126

= 0.1907 W/mK

3. 45% aerogel with one layer (Total thickness = 2.2+0.1016 = 2.3016)

$1/R = K/\Delta x$

$K = \Delta x/R$

= 0.0023016/0.0143

= 0.1609 W/mK

4. 45% aerogel with two layers (Total thickness = 2.2+0.2032 = 2.4032)

1/R = K/Δx

K = Δx/R

= 0.0024032/0.0176

= 0.1365 W/mK

Table 5: Thermal conductivity of aerogel layers.

Aerogel mass %	Layer	Thermal Conductivity
0%	-	0.8426
22.50%	1 layer	0.1918
22.50%	2 layer	0.1907
45%	1 layer	0.1609
45%	2 layer	0.1365

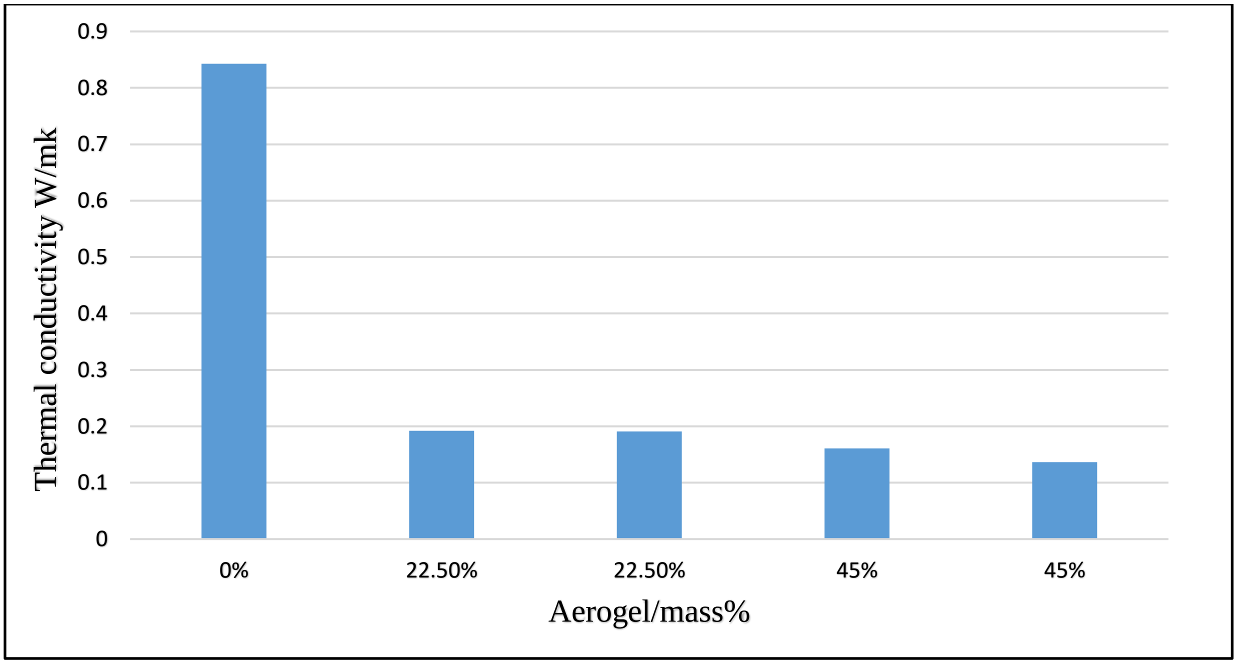

Figure 11: Thermal conductivity of samples.

CHAPTER 6. LIMITATIONS AND FUTURE SCOPE

As there are many advantages to this research, there are few limitations to this method.

1. The type of aerogel was limited to just one i.e. silica aerogel, and the results might differ when a different type of aerogel is used.

2. The type of resin was limited to just one, and, i.e. UV acrylate resin, and results might differ when a different type of resin is used.

3. The aerogel used was ultra-fine silica aerogel, and the methods might not be applicable for granular aerogel.

4. Granular aerogel is better in thermal properties than monolithic aerogel, but when the granular aerogel was mixed with resin, it made the panels opaque, and it was difficult to make the coatings out of it.

5. Although aerogel windows provide very good daylighting and reduce the illuminance, they can't provide an unobstructed outside view.

6. The coatings were two layers, so can not say how thermal properties would change when the thickness is more.

7. These windows might provide good economic value in the long-term but can be very expensive initially.

CHAPTER 7. OVERALL CONCLUSIONS

Considering the existing windows insulation requirements, and to find a good method for increasing their insulation properties, this experiment was designed. In this study, the silica aerogel was mixed with resin using different volume percentage of aerogel. U and R values were experimentally determined, and K values were calculated. The aerogel-coated glass provided a K value of 0.1365 W/mK compared to the normal glass K value of 0.8426 W/mK. Based on the data collected, we conclude that the aerogel glass panels provide good thermal properties, i.e., low thermal conductivity and high thermal resistance, with desirable translucency.

It was possible to establish that the thermal conductivity of the film containing 45% aerogel has 83.80% less thermal conductivity than the thermal conductivity of film not containing any silica aerogel. With these values, we can conclude that as we increase the volume percentage of aerogel the thermal conductivity decreases and thermal resistance increases.

REFERENCES

Arici, Müslüm, Hasan Karabay, and Miraç Kan. 2015. "Flow and Heat Transfer in Double, Triple and Quadruple Pane Windows." *Energy and Buildings* 86: 394–402. doi:10.1016/j.enbuild.2014.10.043.

Berthou, Yannick, Pascal Henry Biwole, Patrick Achard, Hébert Sallée, Mireille Tantot-Neirac, and Frédéric Jay. 2015. "Full Scale Experimentation on a New Translucent Passive Solar Wall Combining Silica Aerogels and Phase Change Materials." *Solar Energy* 115: 733–42. doi:10.1016/j.solener.2015.03.038.

Cuce, Erdem, Pinar Mert Cuce, Christopher J. Wood, and Saffa B. Riffat. 2014. "Optimizing Insulation Thickness and Analysing Environmental Impacts of Aerogel-Based Thermal Superinsulation in Buildings." *Energy and Buildings* 77. Elsevier B.V.: 28–39. doi:10.1016/j.enbuild.2014.03.034.

Dowson, Mark, David Harrison, Salmaan Craig, and Zachary Gill. 2011. "Improving the Thermal Performance of Single-Glazed Windows Using Translucent Granular Aerogel." *International Journal of Sustainable Engineering* 4 (3): 266–80. doi:10.1080/19397038.2011.558931.

Duer, K., and S. Svendsen. 1998. "Monolithic Silica Aerogel in Superinsulating Glazings." *Solar Energy* 63 (4): 259–67. doi:10.1016/S0038-092X(98)00063-2.

Fricke, J., R. Caps, D. Büttner, U. Heinemann, and E. Hümmer. 1987. "Silica Aerogel — a Light-Transmitting Thermal Superinsulator." *Journal of Non-Crystalline Solids* 95–96 (December). North-Holland: 1167–74. doi:10.1016/S0022-3093(87)80730-5.

Hostler, S. R., A. R. Abramson, M. D. Gawryla, S. A. Bandi, and D. A. Schiraldi. 2009. “Thermal Conductivity of a Clay-Based Aerogel.” *International Journal of Heat and Mass Transfer* 52 (3–4). Elsevier Ltd: 665–69. doi:10.1016/j.ijheatmasstransfer.2008.07.002.

Hrubesh, Lawrence W. 1998. “Aerogel Applications.” *Journal of Non-Crystalline Solids* 225: 335–42. doi:10.1016/S0022-3093(98)00135-5.

In, E., and H. Naguib. 2015. “Fabrication and Characterization of Silica Aerogel as Synthetic Tibues for Medical Imaging Phantoms.” *AIP Conference Proceedings* 1664. doi:10.1063/1.4918495.

Jensen, Karsten I. 1992. “Passive Solar Component Based on Evacuated Monolithic Silica Aerogel.” *Journal of Non-Crystalline Solids* 145 (C): 237–39. doi:10.1016/S0022-3093(05)80463-6.

Jensen, J. M. Schultz, and F. H. Kristiansen. 2004. “Development of Windows Based on Highly Insulating Aerogel Glazings.” *Journal of Non-Crystalline Solids* 350: 351–57. doi:10.1016/j.jnoncrysol.2004.06.047.

Lolli, Nicola, and Inger Andresen. 2016. “Aerogel vs. Argon Insulation in Windows: A Greenhouse Gas Emissions Analysis.” *Building and Environment* 101: 64–76. doi:10.1016/j.buildenv.2016.03.001.

Lorenzati, Alice, Stefano Fantucci, Alfonso Capozzoli, and Marco Perino. 2015. “Coupling VIPs and ABPs: Assessment of Overall Thermal Performance in Building Wall Insulation.” In *Energy Procedia*, 78:2760–65. doi:10.1016/j.egypro.2015.11.620.

Maleki, Hajar, Luisa Durães, and António Portugal. 2014. “An Overview on Silica Aerogels Synthesis and Different Mechanical Reinforcing Strategies.” *Journal of Non-Crystalline Solids* 385: 55–74. doi:10.1016/j.jnoncrysol.2013.10.017.

Rostam, N. Gholami, M.J. Mahdavinejad, and M. Gholami Rostam. 2015. “Commercializing Usage of Nano-Insulating Materials in Building Industry and Future Architecture.” *Procedia Materials Science* 11: 644–48. doi:10.1016/j.mspro.2015.11.004.

Sadineni, Suresh B., Srikanth Madala, and Robert F. Boehm. 2011. “Passive Building Energy Savings: A Review of Building Envelope Components.” *Renewable and Sustainable Energy Reviews* 15 (8). Elsevier Ltd: 3617–31. doi:10.1016/j.rser.2011.07.014.

Sun, J., J. P. Longtin, and P. M. Norris. 2001. “Ultrafast Laser Micromachining of Silica Aerogels.” *Journal of Non-Crystalline Solids* 281 (1–3). North-Holland: 39–47. doi:10.1016/S0022-3093(00)00426-9.

Thiel, Cassandra L., Nicole Campion, Amy E. Landis, Alex K. Jones, Laura A. Schaefer, and Melissa M. Bilec. 2013. “A Materials Life Cycle Assessment of a Net-Zero Energy Building.” *Energies* 6 (2): 1125–41. doi:10.3390/en6021125.

Venkataraman, Mohanapriya, Rajesh Mishra, Jiri Militky, and Lubos Hes. 2014. “Aerogel Based Nanoporous Fibrous Materials for Thermal Insulation.” *Fibers and Polymers* 15 (7): 1444–49. doi:10.1007/s12221-014-1444-9.

Virta, Mikko. 2016. “Mikko Virta Energy Efficient Shape Optimization of Multiple Buildings.” https://aaltodoc.aalto.fi/bitstream/handle/123456789/24006/master_Virta_Mikko_2016.pdf?sequence=1.

Ye, Yunyang, Wangda Zuo, and Gang Wang. 2019. “A Comprehensive Review of Energy-Related Data for U.S. Commercial Buildings.” *Energy and Buildings* 186. Elsevier B.V.: 126–37. doi:10.1016/j.enbuild.2019.01.020.