

Design and Development of High Performance Vacuum Insulation Panels (VIP) with Kevlar Thread Support

V. Sood

University of Illinois at Chicago, Chicago, IL 60607

A. Feinerman

*Department of Electrical and Computer Engineering,
University of Illinois at Chicago, Chicago, IL 60607*

Vacuum insulation is an advanced thermal insulation technology that significantly outperforms conventional materials, such as foam or fiber. The study of this new technology is the first step towards making improvements in the applications of insulation panels to provide energy-efficient and cost saving solutions. The focus this summer has been on creating prototypes using acrylic and Kevlar thread to further improve the quality of insulation panels and make them more efficient. Using a carbon dioxide laser system, acrylic was cut and small prototypes were produced. The insulation panel was sealed in a plastic bag and a small vacuum pump was used to evacuate the air. The results gathered during the research program indicate that Kevlar thread is strong and can provide support without breaking, making the insulation panel effective. Stronger conclusions will arise after further testing and research in this area.

Introduction

The study of heat transfer is concerned with two main things: temperature, and the flow of heat.¹ Temperature represents the amount of thermal energy available, while heat flow represents the movement of thermal energy from one place to another. On an atomic scale, thermal energy is related to the kinetic energy of molecules. The greater the temperature of a material, the higher its kinetic energy will be. Regions with greater molecular kinetic energy pass this energy to regions with less kinetic energy. Therefore, heat flows from higher to lower temperature.

Heat transfer between regions can be grouped into three main categories - conduction, convection, and radiation. In conduction, the flow of heat occurs through collisions between atoms and molecules in the substance and the subsequent transfer of kinetic energy. Different materials transfer heat by conduction at different rates, which is measured by the material's thermal conductivity. Materials with a large thermal conductivity, such as copper, transfer large amounts of heat over time. Materials which have a high thermal conductivity have a low thermal resistance, therefore, making them poor heat insulators. Convection is the flow of heat through a macroscopic movement of matter from a hot region to a cool region, as opposed to the microscopic transfer of heat between atoms involved with conduction. Heating a pot of water on a stove is a good example of the transfer of heat by convection. When water starts boiling, bubbles begin to form at the top. These bubbles are regions of hot water that rise to the surface and transfer heat to the cooler water at the top by convection. The third and final form of heat transfer is that of radiation. Radiation heat transfer is energy transport due to the emission of elec-

tromagnetic waves or photons from a surface or volume. Radiation does not require a heat transfer medium, and can occur in a vacuum. When thermal radiation strikes a body, a fraction of radiation gets absorbed, reflected or transmitted through the body. When an object absorbs all the radiation falling on it, it is referred to as black-body radiation because no radiation is reflected by the object.

Vacuum Insulation Panels, commonly called VIP, are insulating structures that take advantage of the better insulating properties of an evacuated space. In typical vacuum gap insulation systems, such as a thermos bottle, the space between two surfaces is evacuated and sealed. With no matter inside the vacuum space to support conduction or convection these two modes of heat transfer are eliminated across the evacuated space itself. Radiation is the only mechanism by which heat can be transferred because it does not require a means to transfer heat, which makes it possible to transfer heat in a vacuum. One of the advantages of Vacuum Insulation Panels is that it has a higher R-value than other insulation panels, but is also relatively thinner. The R-value describes a material's resistance to heat flow and the effectiveness of insulation. Vacuum Insulation Panels are known to be three to five times more effective than other insulation material meaning their R-value is three to five times greater.

A 100 Watt carbon dioxide (CO_2) laser is the main tool used for cutting acrylic and building prototypes. The laser manual needs to be read completely before using the equipment for the first time. The system has interchangeable lenses, and depending on the method of cutting, a different lens might be needed. Figure 1 provides information regarding different lenses available from Universal Laser Systems, Inc. This project primarily used the two-inch normal lens and the two-inch high power

density lens for acrylic with thicknesses of 0.060, 0.125, and 0.180 inches.

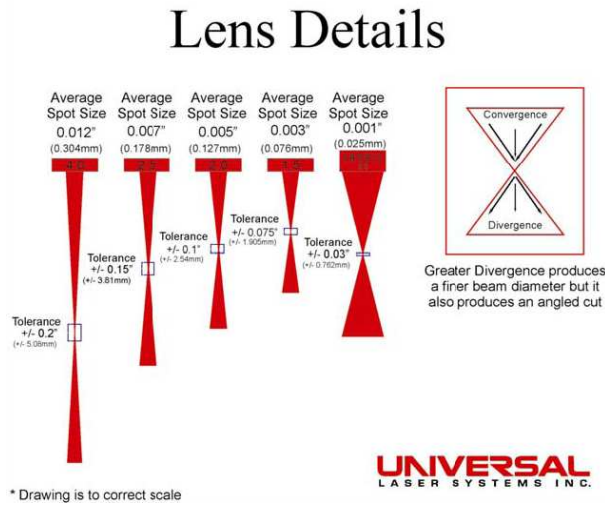


FIG. 1: Information about different lenses.

Vacuum Insulation Panels need support between the upper and lower surfaces in order to make sure that those two surfaces do not touch each other. The use of pillars and rods is a common way to keep the two surfaces from touching each other. However, under a lot of weight or pressure, these pillars are known to wrinkle and collapse. This problem can be easily fixed by connecting numerous pillars to crossed Kevlar thread in tension. Figure 2 shows the detailed design of the VIP that is to be built.

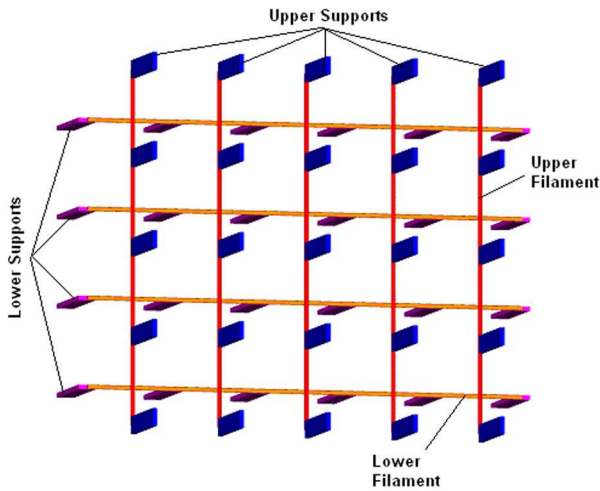


FIG. 2: 3D view of the Vacuum Insulation Panel.

Kevlar is a flexible material which is strong, tough, firm, high-melting and well suited for uses such as heat or flame-resistant fabrics, making airplane parts, and bullet-proof clothing. With the use of Kevlar, not only can the

buckling be eliminated, but the material's very low thermal conductivity also prevents heat transfer. Fibers of Kevlar consist of long molecular chains produced from poly-paraphenylene terephthalamide. Strong inter-chain bonding results in unique combination of properties such as high tensile strength at low weight, low chemical conductivity, high chemical resistance, low thermal shrinkage, high toughness, high cut resistance and flame resistant. Figure 3 below shows the top view of the 3D drawing showing the crossed Kevlar thread in tension, which keeps the two plates from touching each other. The pillars never touch the other surface and only if the Kevlar breaks or gets loose, are they supposed to touch the other plates in order to keep them separated.

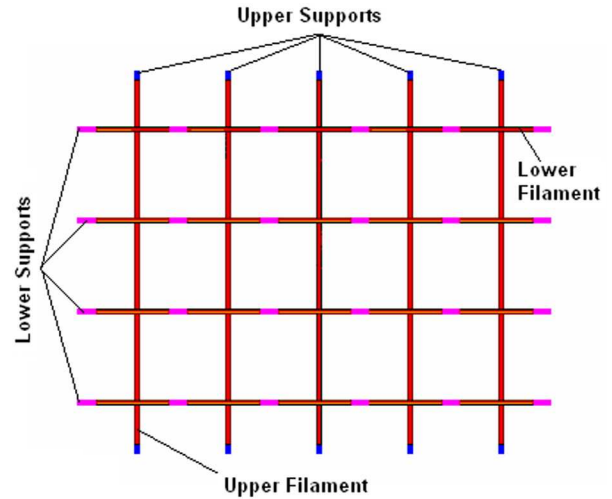


FIG. 3: Top view of the 3D design.

Methods and Materials

The first step in starting the project was to design the prototype using AutoCAD. The two plates of the VIP, the pillars that attach to the Kevlar, the holes for the pillars, the hole for the vacuum pump, and the small holes to tie the Kevlar thread were designed. Figure 4 shows the AutoCAD drawing clearly labeling each part of the drawing.

The top plate has a hole to connect the vacuum pump. The rectangular holes in the two plates hold the pillars in place. Kevlar thread is placed in the small cut on top of each pillar. The thread is tied down at the ends through the small circular tie down holes. The corners of the plates are rounded to minimize the stress on the bag during testing.

The next objective was to cut acrylic using the CO₂ laser in the lab. The laser is automatic and is operated through AutoCAD. The drawing for the VIP prototype was sent to the laser and the acrylic was placed on the cutting bed. A test run is done that shows the position

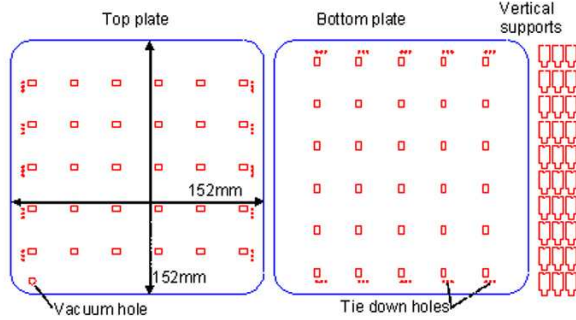


FIG. 4: TopAutoCAD drawing for the VIP prototype.

where the laser will cut and so the acrylic can be moved and re-positioned accordingly. Once everything is set, the laser cut the acrylic according to the prototype drawing. A picture of the CO₂ laser is shown below in Figure 5. Table I shows the cutting parameters for the three dif-



FIG. 5: CO₂ laser by Universal Laser Systems, Inc..

ferent acrylic thicknesses that were used in building the prototypes.

Once the prototype was designed and cut using AutoCAD and the laser respectively, the final goal was to assemble all the parts together. To accomplish this goal the pillars were glued in the rectangular holes on the two plates using Devcon Plastic Welder,² which is a tough structural adhesive. It is resistant to composite polyesters, fiberglass wood, concrete, ceramic, metal and many other surfaces. Next, the Kevlar needed to be positioned on top of the pillars and tied in the holes at the end. However, the thread needed to be as firm as

Thickness (in inches)	Power	Speed	Ppi	Lens
0.06	35	3	1000	Normal 2"
0.06	25	3	1000	High Power Density 2"
0.125	45	3	1000	Normal 2"
0.125	40	3	1000	High Power Density 2"
0.185	60	3	1000	High Power Density 2"

TABLE I: Cutting Parameters for Acrylic

possible for the testing. To make that possible, weights needed to be attached at both ends of the Kevlar to make it stretched. The weights were made by filling plastic zip-lock bags with 500mL of water and were tied to the thread. Once the Kevlar was in place and firm, Devcon² plastic welder was used in the tie down holes and on the pillars to keep the thread in place. Once the glue dried, weights were cut from the plates and the prototype was ready to be tested.

Results and Calculations

The next step was to test the prototype in vacuum. First, a small hole was made in a zip-lock bag using a drill. Next, after placing the prototype in the bag, it was sealed using a double-wire heat press. Figure 6 shows the picture of the prototype just before the vacuum pump was attached. Finally, the vacuum pump was connected to the bag through the hole that was drilled and observations were made. During the summer research program,



FIG. 6: Prototype of a Vacuum Insulation Panel.

a total of eight prototypes were created. Detailed description along with the results for all the prototypes are provided in Table II.

Thickness (in inches)	Thread Diameter (in inches)	Pillar Support	Acrylic Wall	Results
0.125	0.038	No	No	Failure
0.125	0.038	No	No	The two panels were too close, thread got little loose.
0.18	0.038	No	No	Pillar height was increased and the model was a great success.
0.18	0.025	No	No	Thinner Kevlar thread was used in this prototype but it became loose in the vacuum.
0.06	0.038	No	No	Thread would not stay on top of the pillars. Prototype needed improvements.
0.06	0.038	No	Yes	Bag ripped, pillars and acrylic wall broke.
0.06	0.038	Yes	Yes	Bag ripped causing pillars to break, but the wall was made thicker and therefore, it stayed firm.
0.06 & 0.125	0.038	Yes	Yes	The wall was made longer in length.

TABLE II: Results for Prototypes

During testing, all prototypes had one common result. The zip-lock bag was getting sucked in the space between the two VIPs. The most recent prototypes were designed to prevent this from happening, but the models failed during testing. This is where the REU program is concluded. However, once this problem is figured out, the future plans will be to make a larger prototype to test the thermal efficiency of the VIP. Figure 7 below shows the initial design of the new prototype.

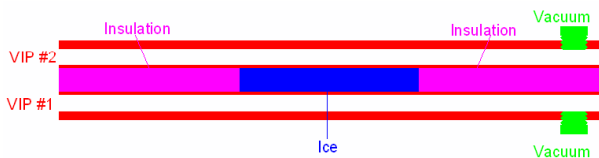


FIG. 7: Prototype design to test thermal efficiency of VIP.

The two insulation panels in the new design will be 12 in × 12 in while the block of ice will be 4 in × 4 in. The insulation material will be Styrofoam and it will be 0.5 in thick. The objective of this prototype is to determine the amount of time it takes for the ice to completely melt in a vacuum. The longer it takes for the ice to melt, the more efficient the vacuum insulation panel is. The theoretical calculations for this prototype were completed and are shown below.

Theoretical calculations were done to determine the amount of heat loss due to blackbody radiation and thermal conduction in a block of ice insulated by a vacuum insulation panel. The equation below is used.

$$Q = \epsilon\sigma A(T_2^4 - T_1^4) \quad (1)$$

In this equation, Q is the amount of heat transferred, ϵ is the emissivity of the material (acrylic), σ is Stefan's constant with a constant value of $5.6703 \times 10^{-8} \frac{W}{m^2 K^4}$, A is the area of the ice, T_1 is the temperature inside the VIP and T_2 is the temperature of the surroundings or the room temperature.

$$\begin{aligned} \epsilon_{acrylic} &= 0.94 \\ A_{ice} &= \pi * (2in)^2 \\ &= 8.11 * 10^{-3} m^2 \\ T_1 &= 273K \\ T_2 &= 300K \\ Q &= 1.10W \end{aligned}$$

However, since there two insulation panels surround the block of ice, the heat loss due to blackbody radiation (Q_{BB}) doubles. Therefore,

$$Q_{BB} = 2 * Q = 2.20 W \quad (2)$$

After determining the radiation heat transfer, the next step was to calculate heat transfer to the edges of the VIP due to conduction. For this calculation, the temperature equation in cylindrical coordinates is required.

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) = 0 \quad (3)$$

The solution to the above differential equation is in the form $T = a + (b * \ln r)$. The particular solution that was obtained for the above equation is shown below

$$T(r) = T_{out} + \frac{(T_{in} - T_{out}) \ln r / r_{out}}{\ln r / r_{out}} \quad (4)$$

Before going any further, this equation needs to be verified. In order to do that, initial conditions must be established. The inner temperature is the temperature of the ice, which is freezing point or 273 K. The outer temperature is the room temperature, which is at 300 K. The inner and outer radii are for the ice and acrylic sheet respectively. The value of inner radius is 2 inches, while

the outer radius has a value of 6 inches. In order to verify the equation, the temperature must be calculated using the inner and outer radii for the variable r .

$$T(r = r_{out}) = T_{out} + \frac{(T_{in} - T_{out}) \ln 1}{\ln r/r_{out}} \quad (5)$$

$$T(r = r_{out}) = T_{out} = 300K \quad (6)$$

Similarly,

$$T(r = r_{in}) = T_{out} + T_{out} + \frac{(T_{in} - T_{out}) \ln r/r_{out}}{\ln r/r_{out}} \quad (7)$$

$$T(r = r_{in}) = T_{out} + T_{in} - T_{out} = T_{in} = 273 K \quad (8)$$

Since the temperatures obtained from the equation were similar to the actual boundary conditions, it can be concluded that the equation is indeed correct and can be used for the calculations.

The equation for conduction heat transfer in cylindrical coordinates is:

$$Q_{edge} = \kappa A \frac{\partial T}{\partial r} \quad (9)$$

$$\frac{\partial T}{\partial r} = \frac{T_{in} - T_{out}}{\ln r/r_{out}} \frac{1}{r} = \frac{-27}{\ln 2/6} \frac{1}{r} \quad (10)$$

$$Q_{edge} = \kappa 2\pi r t \frac{-27}{\ln 2/6} \frac{1}{r} \quad (11)$$

Therefore,

$$Q_{edge} = 2\pi \kappa t \frac{-27 K}{\ln 2/6} \quad (12)$$

Q_{edge} is the heat loss to the edges of the VIP, κ is the thermal conductivity of acrylic measured in $\frac{W}{m \cdot K}$, A is the area of the surface, and t is the thickness of acrylic. Furthermore, since there are two acrylic sheets in the insulation panel, the amount of heat transferred will be twice as much. Therefore, the new conduction heat transfer equation for a VIP is:

$$Q_{edge} = 4\pi \kappa t \frac{-27 K}{\ln 2/6} \quad (13)$$

The above equation was then used to calculate the heat loss to the edges of the VIP based on the thickness of the acrylic. The acrylic used in this research had thicknesses of 0.060", 0.125" and 0.180" and its thermal conductivity at room temperature was 0.20 $\frac{W}{m \cdot K}$. The heat loss to the edges is calculated below.

Thickness = 0.06" = 1.524 * 10⁻³ m

$$Q_{0.06} = 4\pi \kappa t \frac{-27 K}{\ln 2/6} = 9.41 * 10^{-2} W \quad (14)$$

Thickness = 0.125" = 3.175 * 10⁻³ m

$$Q_{0.125} = 4\pi \kappa t \frac{-27 K}{\ln 2/6} = 1.96 * 10^{-1} W \quad (15)$$

Thickness = 0.18" = 4.572 * 10⁻³ m

$$Q_{0.18} = 4\pi \kappa t \frac{-27 K}{\ln 2/6} = 2.82 * 10^{-1} W \quad (16)$$

Additionally, the same equation was also used to determine the heat loss through the Styrofoam placed on each side of the ice to decrease the melting of the ice. The calculation below shows the theoretical heat loss.

$$Q_{Styro} = 4\pi \kappa t \frac{-27 K}{\ln 2/6} \quad (17)$$

Q_{Styro} is the amount of heat loss from the ice, t represents the thickness of the Styrofoam, and κ is its thermal conductivity, which is 0.025 $\frac{W}{m \cdot K}$.

Thickness of Styrofoam = 0.5" = 1.27 * 10⁻² m

$$Q_{Styro} = 4\pi \kappa t \frac{-27 K}{\ln 2/6} = 9.81 * 10^{-2} W \quad (18)$$

The final step was to calculate the time it would take for the ice to melt theoretically. The following equation is used.

$$\tau = \frac{\Delta_{fus} H \rho_{ice} V_{ice}}{Q_{BB} + Q_{therm}} \quad (19)$$

τ is the time it takes for the ice to melt, $\Delta_{fus} H$ is the enthalpy of fusion or also known as heat of fusion, ρ_{ice} is the density, V_{ice} is the volume, Q_{BB} is the heat loss due to blackbody radiation, and Q_{therm} is the heat loss due to thermal conduction. The calculation is shown below.

$$\begin{aligned} Q_{BB} + Q_{therm} &= Q_{BB} + Q_{0.06} + Q_{0.18} + Q_{Styro} \\ &= 2.2 W + (0.04705 + 0.141 + 0.0981) W \\ &= 2.486 W = 2.486 \frac{J}{s} \end{aligned}$$

$$\begin{aligned} V_{ice} &= \pi * \frac{(2 in)^2 * 0.5 in * (2.54 cm)^3}{1 in^3} \\ &= 102.96 cm^3 \end{aligned}$$

$$\begin{aligned} \tau &= \frac{334.88 J/g * 0.931 g/cm^3 * 102.96 cm^3}{2.483 J/s} \\ &= 1.29 * 10^4 s = 3.58 hrs \end{aligned}$$

According to the calculations, it should take 3.58 hrs for the ice to completely melt under the ideal conditions. However, since the model has not been built, the experimental data has not yet been acquired.

Discussion

The results were very conclusive from the tests and it was determined that the Kevlar can indeed keep the two plates of the insulation panel apart. Before the testing was completed, a list of possible failures was made. It

was assumed that once the vacuum pump was turned on the Kevlar thread could break, the Devcon Plastic Welder could fail causing the thread to get very loose, which would make the pillars touch the opposite surface, the plastic bag could tear by getting sucked into the sides of the insulation panel, the pillars could break or fall, and the acrylic surface could crack. However, once the testing was finished and observations were made, many of these assumptions were proved to be wrong.

The vacuum pump used for the testing was a diaphragm pump that has the capability of creating a vacuum of maximum 710 *torr*. During testing, the vacuum created by the pump was approximately 660 *torr*. It was a small pump and the initial tests were done to determine the strength of the Kevlar and whether the design was realistic. To test the future prototypes for energy efficiency, a 2-stage vacuum pump will be used that has the potential to create a vacuum of approximately $4 * 10^{-2}$ *torr*. The ideal conditions, however, would require a vacuum with the ability to reach 10^{-3} *torr*.

Conclusion

The objective this summer was to study and understand the concepts of Vacuum Insulation Panels. The

goal was to design and create prototypes that would be tested to determine whether this technology would be useful in the future and if it would even work. After conducting the necessary tests on the small prototypes, it can be concluded that this is a very useful concept and would indeed prevent heat transfer and save energy in residential and commercial buildings.

Acknowledgements

National Science Foundation (NSF), Research Experiences for Undergraduates (REU) and the Department of Defense (DoD) ASSURE (Awards to Stimulate and Support Undergraduate Research Experiences) programs provided the funding for this great learning experience, specifically the NSF EEC 0453432 grant. Thanks to the University of Illinois at Chicago REU site Novel Materials and Processing in Chemical and Biomedical Engineering, the UIC program director Dr. Christos Takoudis, co-director Dr. Andreas Linninger for being a great mentor and presenting this wonderful opportunity. Also, thanks to Tatjana Dankovic who helped me with the use of the laser, and Rebecca Carlton of Illinois Wesleyan University who started this project in the summer of 2006 as part of the REU program.

¹ F. P. Incropera, P. Dewitt, T. Bergman, and A. Lavine, *Introduction to Heat Transfer* (John Wiley & Sons, New York, 2006).

² www.devcon.com.