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CHARACTERIZATION OF AEROGEL BASED THERMAL INSULATION BLANKETS, ECONOMICS, AND APPLICATIONS FOR DOMESTIC WATER HEATERS

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ABSTRACT

One of the main ways to improve the performance of thermal systems is using better thermal insulation. Recent developments of high performance thermal insulation introduced thermal insulation blankets for low and moderately high temperature applications. One of the leading insulation technologies are aerogel based insulation blankets. Before studying the performance of thermal systems insulated with these materials, it is important to characterize these blankets under conditions similar to the operating conditions. In this study, thermal conductivity measurement experiments are conducted on Low Temperature High Performance Insulation (LTHPI) and High Temperature High Performance Insulation (HTHPI) blankets and their results were discussed. Tests also conducted are scanning-electron-microscope (SEM) imaging to better understand the nano-structure and thermal conductivity test.

Results in this paper show SEM images for Aspen®'s Spaceloft® and Pyrogel® XT-E blankets, and X-ray imaging showing the components inside the blankets' aerogel to be Silicon, Oxygen, and Carbon. Thermal conductivity measurements were conducted for both LTHPI and LTHPI insulation materials. The thermal conductivity results confirm the results mentioned in the literature, showing that the thermal conductivity is 0.0159 W / (m.K) for LTHPI and 0.0188 W / (m.K) for HTHPI at 25 ºC. It can be said that the tested blankets show a promising performance in thermal systems. This paper also demonstrates a comparison of utilizing high performance thermal insulation with current industry practice in domestic water heaters, and a discussion on its economic impacts for individual and national levels. This discussion shows that a minimum of 3.7 billion USA dollars can be saved annually by adjusting regulations to enforce water heater manufacturers to use HPI in their products.

Keywords: *Thermal Conductivity, Aerogel Thermal Insulation Blankets, Domestic Water Heaters, Economics of Aerogel Insulation, Aerogel Blankets Characterization, Scanning-Electron-Microscopy of Aerogel Blankets*

INTRODUCTION

Domestic water heaters are an essential component in households. Water heating takes between 15% and 40% of energy consumed in the residential sector internationally [1]. As mentioned in one of the reports published by Ernest Orlando Lawrence Berkley National Laboratory [2], nearly two billion therms are consumed annually by residential water heaters in California, 90% of which are fueled by natural gas [2]. The US department of energy have changed the minimum energy factor (EF) requirements and raised the bar for water heaters manufacturers to provide high quality and high performance products as of April 16th, 2016 as shown in Table (1) [1]. This indicates the seriousness in providing the highest efficiency domestic water heating systems and the need to improve thermal insulation.

One of the methods used to improve the efficiency of water heaters is using baffles. Baffles are obstacles put in the way of fluids to increase turbulence, and residence time of flue gases to enhance heat transfer to water [3] and [4]. Sedeh and Khodadadi [3] and Tanbour and Rahmani, [4] to [9], studied the performance of gas-fired storage water heaters improved by simple/novel designs of baffles inside the water tank. The studies were conducted numerically and experimentally. These studies reported a decrease in fuel consumption of 1.674% for one design and 4.95% for another design under steady-state thermal efficiency test conditions. The importance of these studies is that it summarizes a good amount of information regarding gas-fired domestic water heaters, especially operating conditions. These studies also aim to increase the efficiency of water heaters, which is one of the goals of this paper. Tajwar et. al. [10] have studied the improvement of traditional gas-fired storage water heaters having thermal and combustion efficiencies of 35% and 67.4%, respectively, they achieved it by using baffles in the fume hood with different shapes. They experimentally showed that the best baffle shape, the barbed razor wire baffle, increased the thermal and

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combustion efficiencies to be 67.4% and 88%, respectively. Similarly, this study is important because of its experimental results that can be used to validate performance calculations in this paper.

Another important piece of literature is the one in the report published by Ernest Orlando Lawrence Berkley National Laboratory [2]. The report discusses the different models used to describe the performance of different domestic water heaters. The discussion is followed by experimental testing. The importance of this study is in the amount of numerical and experimental information that can be used in water heaters' performance simulations [2]. A review on water heating systems was published by Ibrahim et al. [11], showing one thorough discussion on gas water heaters, their advantages and disadvantages, and improvements done to them.

From the previous selection of literature, it is concluded that increasing the efficiency of domestic water heaters is an individual and a national concern. This is justified by economic and environmental aspects. The first is achieved by decreasing waste heat, heaters' sizes, and amount of fuel used, all of which can shorten payback periods of water heaters. The second is achieved by decreasing emissions to the environment by decreasing fuel consumed.

Table 1 Energy factor standards as assigned by the US Department of Energy

Product Class	Storage Volume (Gallons)	Energy Factor as of Jan 20th, 2004	Energy Factor as of April 16th, 2016
Gas-fired storage water heaters	$20 \le \forall \le 100$	$EF = 0.67 - 0.0019\forall$	$EF = \begin{cases} 0.6750 - 0.00150\forall;\ \forall \le 55 \\ 0.8012 - 0.00078\forall;\ \forall \ge 55 \end{cases}$
Oil-fired storage water heaters	$\forall \le 50$	$EF = 0.59 - 0.0019\forall$	$EF = 0.68 - 0.0019\forall$
Electric storage water heaters	$20 \le \forall \le 120$	$EF = 0.97 - 0.00132\forall$	$EF = \begin{cases} 0.960 - 0.00030\forall;\ \forall \le 55 \\ 2.057 - 0.00113\forall;\ \forall \ge 55 \end{cases}$
Instantaneous gas-fired water heaters	$\forall \le 2$	$EF = 0.62 - 0.0019\forall$	$EF = 0.82 - 0.0019\forall$
Instantaneous electric water heaters	$\forall \le 2$	$E = 0.93 - 0.00132\forall$	$EF = 0.93 - 0.00132\forall$

One of the ways to improve the performance of water heaters is using better insulation. So far, common materials used in the thermal systems' industry are predominantly polyurethane, fiberglass and ceramic insulation. Research on coming up with better thermal insulation has been conducted in the open literature, and aerogel insulation has been one of the leading materials. Aerogel insulation blanket products have low thermal conductivity and are relatively thin, inexpensive, and very easy to handle and to install compared to more common materials in the industry. In this study, the researchers are aiming to use aerogel insulation blankets as an improvement for domestic water heaters, which are commonly used thermal systems in households. Studying the main properties considered for the use in water heaters is an essential step. The properties are thermal conductivity and thermal stability at higher temperatures. As highlighted earlier, many domestic thermal systems such as gas-fired water heaters are under stringent regulatory requirements to increase efficiency.

The idea of using silica aerogels in thermal insulation have been studied by many researchers. He and Xie [12], have summarized the thermal conductivity models describing different aerogel insulation materials. They have discussed various factors affecting the thermal conductivity of aerogel insulation materials, and the main properties important for the industry. Table (2) shows the aerogel material properties considered in different applications, Hrubesh [13], Cohen [14], Zou [15], He and Xie [12], and Goutierre [16], have been working on a research project that aims to make an aerogel thermal insulation with a thermal conductivity lower than 9 mW/mK, and that is mechanically robust to be used in the industry. They have been working on different aspects: Aerogel synthesis, testing, structural reinforcement, and insulation design for different purposes.

Cuce et al. [17] gave a comprehensive review on the use of aerogel insulation materials in different building applications. Based on their review, we list some points concluded about using aerogels in buildings that are related to this study:

Best indoor thermal comfort can be achieved corresponding to slimmer constructions and high insulation performance. It can reduce thermal losses to the ambient by 90% with very slim insulation. It shows promising performance compared to other conventional insulation materials. It has slimmer constructions (50% less than polyurethane, and 70% less than glass wool).

Many researchers have discussed properties, merits, and disadvantages of aerogel based insulation. Bardy, Mollendorf, and Pandergast [18], have studied prototypes of aerogel blankets under applied hydrostatic pressure up to 1.2 MPa. During compression, an increase of 46% in the thermal conductivity has been observed for the product-line blanket and 13% for the prototype at that pressure. After recovery, the thermal resistance of the product-line blanket decreased by 64%, and by 1% for the prototype blanket. The importance of that study lies in knowing the effect of stressing the aerogel blankets during installation on its thermal performance. Bardy et.al. [18]. Oh, Kim, and Kim [19], have prepared and characterized ultra-porous aerogel blankets at ambient pressure. They have done different tests to determine the properties of their blankets including SEM imaging and thermal insulation performance. Coffman et al. [20], have published an article showing their aerogel characterization results. They have obtained the thermal conductivities of Aspen® aerogel blankets at different temperatures and vacuum pressures. They have also determined other properties like water vapor sorption and compressive resistance. The importance of that study lies in knowing the thermal conductivity variation with temperature and the maximum operating temperature for Aspen®'s blankets, which can be used to compare with this study's results. Coffman et.al. [20] and Wei et.al. [21], have synthesized and characterized a transparent hydrophobic aerogel with low thermal conductivity. They have experimentally studied different properties including thermal conductivity, water contact angle as a measure of hydrophobicity, Young's modulus of bending, and thermal stability or thermal gravimetric analysis (TGA). Even though they have studied aerogels but not aerogel blankets, their article is important because of the variety of tests and the measurement of hydrophobicity of aerogels.

Table 2 General properties of aerogel materials considered in different applications

Properties	**Features**
Thermal	Best insulation solid, High temperature, Lightweight
Density, Porosity	Lightest synthetic solid, Homogeneous, High specific surface area, Multiple compositions
Optical	Low reflective index solid, Transparent, Multiple compositions
Acoustic	Lowest sound speed
Mechanical	Elastic and light weight
Electrical	Lowest dielectric constant, High dielectric strength, High surface area

It can be concluded that using high performance insulation materials in certain components and thermal systems is a promising move to improve performance and meet new high standards of efficiency and environmental gains discussed earlier, and possibly making an impact on a national level were high performance insulation is added to the picture through new set of codes and regulations.

Based on the literature search, this work can be considered a verification study in insulation characterization, and the first to tie experimental characterization to increasing water heaters' efficiency as a common domestic application. The objectives are:

- To determine and discuss the main properties of the acquired LTHPI and HTHPI aerogel blankets needed in insulating domestic appliances. These properties are thermal conductivity, and thermal stability, and then discuss their merits and disadvantages.
- To study the performance of water heaters insulated with (HPI), and compare the results with the performance of water heaters insulated with Polyurethane (PUR).
- To discuss the economic impacts of replacing commonly used insulation (like PUR) with (HPI) in water heaters for individuals and on a national level.

Aspen® is one of the main supplier of aerogel based insulation blankets available commercially. They have reported the general methods used to manufacture their products in several patents [22], [23] and [24], to summarize: the blanket is produced by making the aerogel interstitially within the batting fibers. The precursor is impregnated into the fibers, then it is supercritically dried to form the aerogel within the fibers. Resulting in having a fibrous blanket containing aerogel particles inside. According to the material safety data sheet (MSDS) documents attached with the acquired samples, the compositions are as listed in Table (3) [25] and [26].

Table 3 Components of high performance insulation blankets and their compositions as reported in the manufacturer's MSDS

LTHPI	%	HTHPI	%
Synthetic Amorphous Silica	40-50%	Synthetic Amorphous Silica	30-40%
Methylsilylated Silica	10-20%	Methylsilylated Silica	10-20%
Polyethylene Terephthalate	10-20%	Fibrous Glass (textile grade)	40-50%
Fibrous Glass (textile grade)	10-20%	Iron Oxide (iron (III) oxide)	1-10%
Magnesium Oxide	0-5%	Aluminum Trihydrate	1-5%
Synthetic Graphite	0-5%	Other components	Balance

CHARACTERIZATION

Scanning Electron Microscopy (SEM): *Imaging:* Firstly, a scanning electron microscopy is done to better understand the structure of these insulation blankets and how the different components are arranged. The images were taken by an SEM (Hitachi 3400 N-II), (Central Michigan University) [27], with an accelerating voltage of 5 kV, a current of 30 mA, and a distance of 8mm. Fig. 1 shows images of LTHPI aerogel insulation blankets. In image (a) and (b), it is noticed that aerogel particles are attached to polystyrene fibers from the outside; this explains the dustiness of those blankets while handling them. Image (b) shows the shape of the pores in aerogel particles, and the pore size can be estimated from the image to be between 100 and 500 nm. Those images can also be explained by the manufacturing process used, which includes supercritical drying of the blankets after soaking them with the solution; that explains why aerogel chunks are located between the fibers rather than inside them.

Figure 2 shows SEM images for HTHPI’s structure. Similar to LTHPI, it is a blanket made of fiberglass impregnated with silica aerogel. Since fiberglass is used instead of polyethylene, the blanket is more resistant to bending, and more stable at high temperatures, as will be discussed in the next section. Images (a, b, c) show the fibers attached to them some silica aerogel, again, and similar to LTHPI, this explains the dustiness of these blankets, and the attachment is explained by the same manufacturing process. It is clear from the SEM images that aerogel impregnated blankets experience a fair homogeneity when it comes to aerogel penetration and distribution through the fibers. The SEM scanning images also emphasize the irregularity in aerogel crystals’ size and shape. This irregularity makes the case for suggesting experimental characterization opposite to modeling of the nano-structure of aerogel blankets.

X-Ray Photoelectron Spectroscopy: An X-ray photoelectron spectroscopy was done on an aerogel piece to show the materials inside the aerogel using the same microscope. Fig. 3 shows the results of the X-ray scan. Fig. 3.a shows three points analyzed in an aerogel piece inside the LTHPI sample. Fig. 3.b-d show the results of the X-ray scan, indicating the existence of Silicon, Oxygen, and Carbon.

THERMAL CONDUCTIVITY

Thermal conductivity apparatus: The experiments discussed throughout this paper exclude radiative heat transfer. The rational for excluding radiative heat transfer is due to careful insulation of the test specimens during all experiments. This is explained in the components of the characterization experimental set-up. The insulation was designed to make the external temperature of insulation (Figure 4.a and 4.b) very close to room temperature where the radiative heat transfer can be neglected. Thermal conductivity is measured using an apparatus assembled specifically to allow measurements according the ASTM standard C518 [28]; Fig. 4 shows a pictorial and a CAD drawing of the apparatus. The apparatus contains a (6” by 6”) high temperature resistance heater (23.31Ω, Maximum power of 590W) placed under the sample, samples have been cut to have the same shape and size of the heater, and a heat sink made of aluminum has been placed on the top of the sample. J-type thermocouples (Omega TJ36-CAXL), Omega Engineering Inc. [29], are placed on the top and bottom of the sample (8 on the top and 8 on the bottom) to accurately measure the temperature difference across the faces of the sample. Two heat flux sensors (acquired from ITI-Model A-HT-4 Thermal Flux Meter), International Thermal Instruments Company Inc. [30], with internal K-type thermocouples have been placed on the top and bottom of the sample to measure the heat flux through the insulation. All sensors are connected to a data acquisition device (National Instruments NI 9213) [31], and connected to a computer. Fig.4 shows an exploded view of the apparatus. The set-up was insulated using high temperature industrial ceramic blanket insulation. A computer fan is used to improve heat transfer from the finned surface as shown in Fig.4, (a). Fig.5 shows a schematic drawing and a flow chart of the assembled apparatus. The thermal conductivity is calculated using Fourier law of conduction expressed in Eqn. (1) under steady state conditions, knowing the temperatures across the sample, the area, the thickness, and the power generated by the heater.

$$q = kA\frac{\Delta T}{t} \tag{1}$$

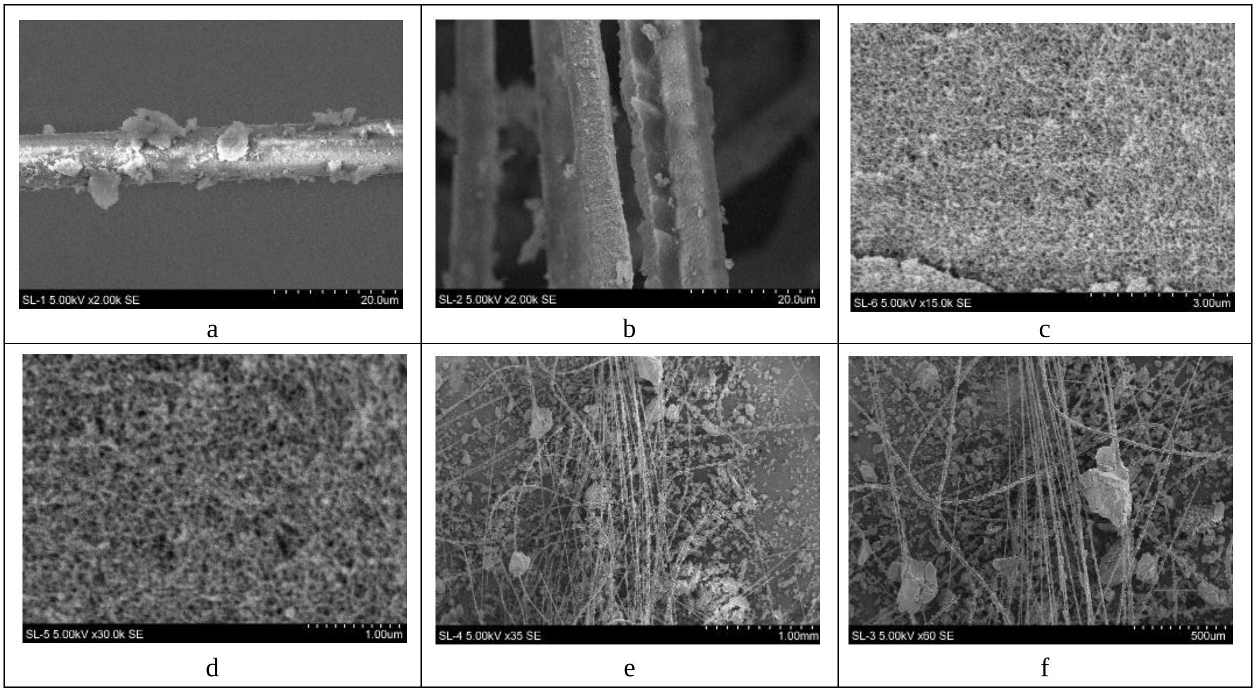
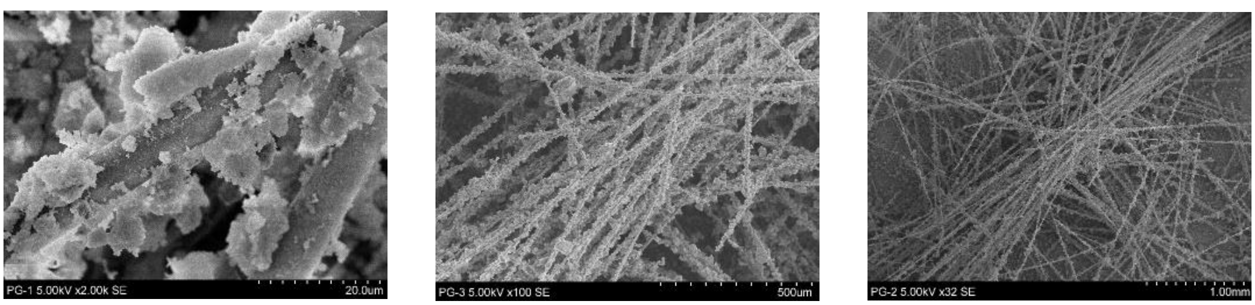


Figure 1. SEM images for the LTHPI blanket



a b c

Figure 2 SEM images for HTHPI blanket

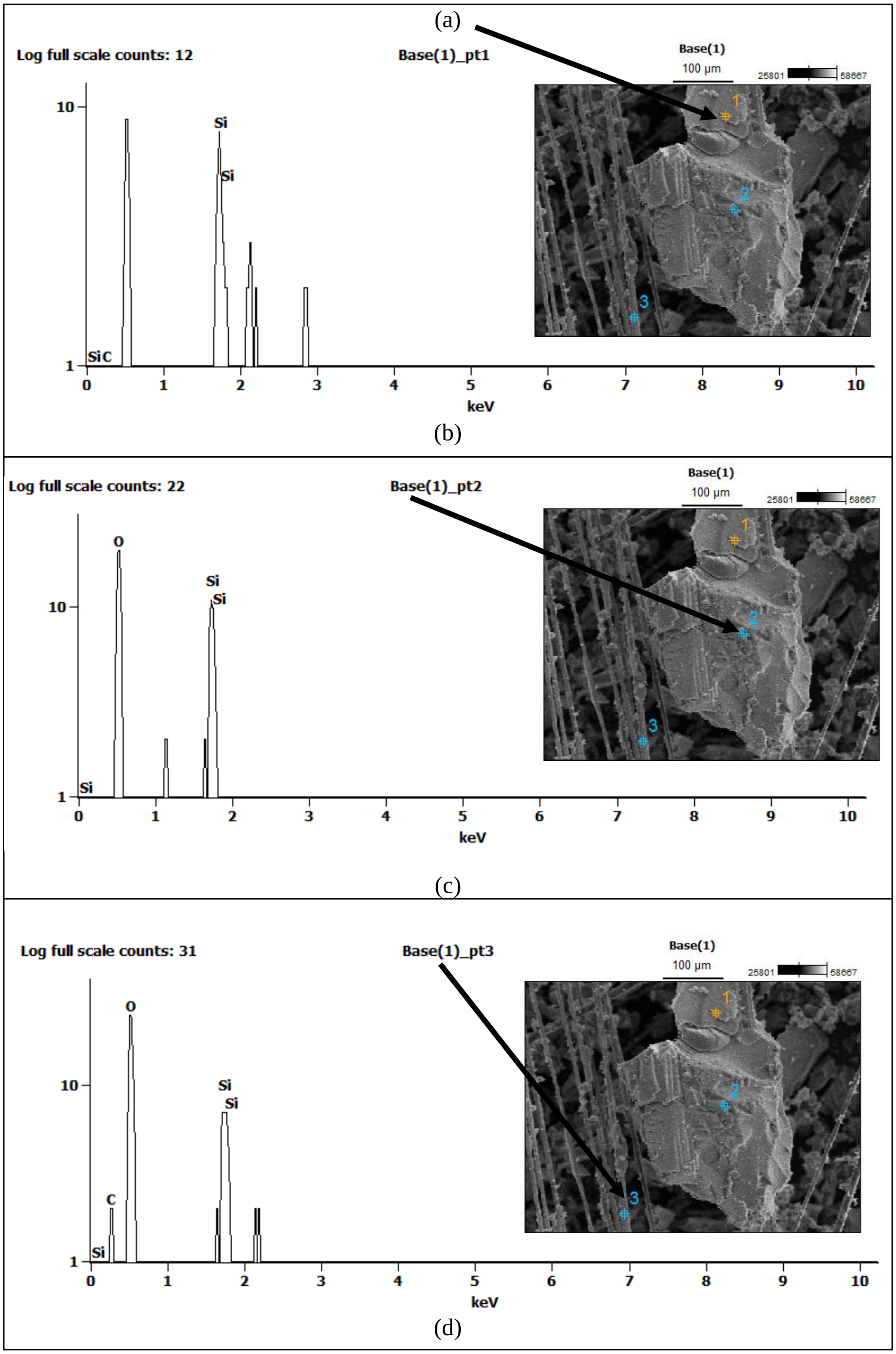
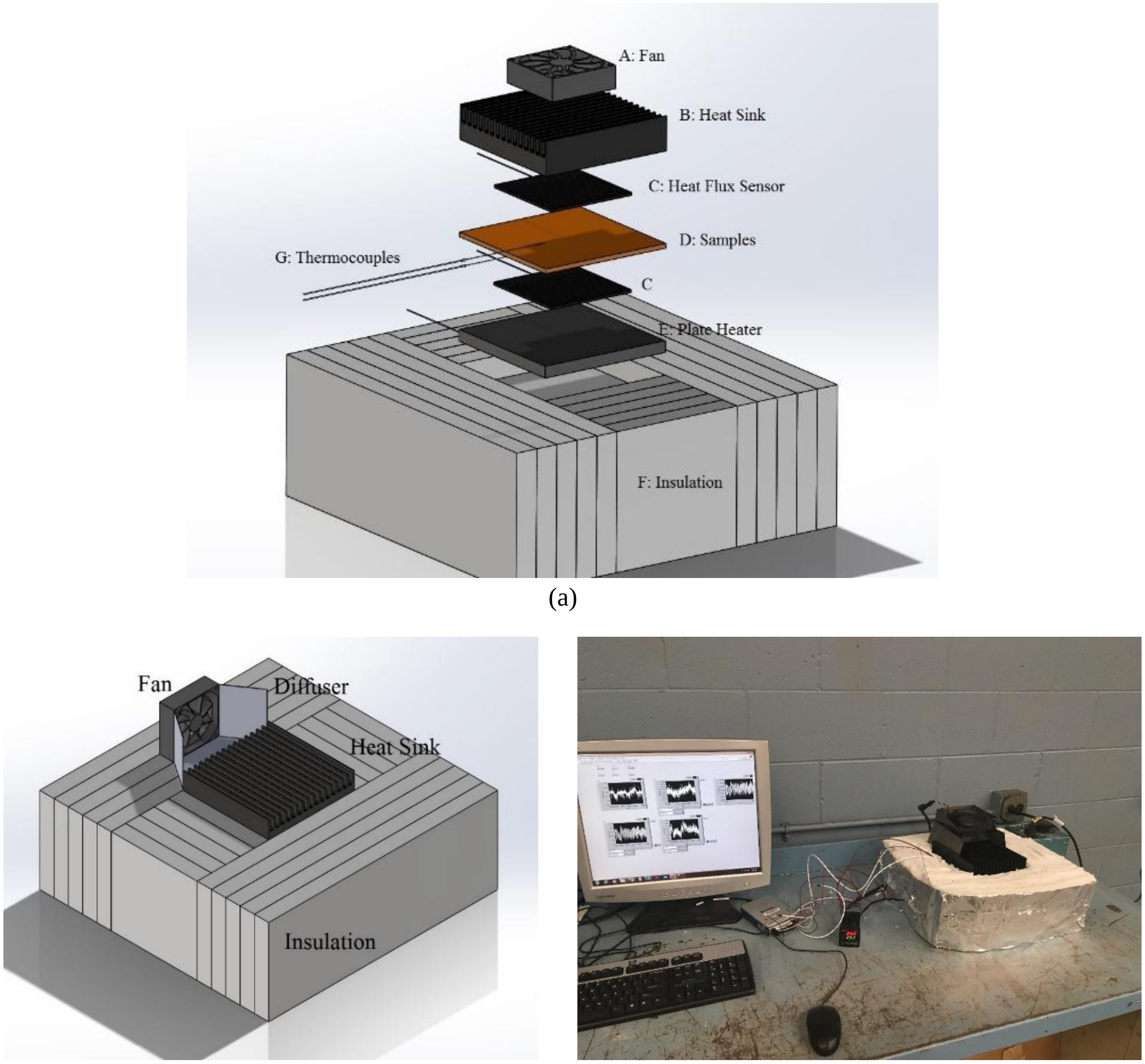


Figure 3 X-ray photoelectron spectroscopy of a piece of aerogel in LTHPI sample showing the elements count at three different points. (a) Aerogel piece in LTHPI) (b) Elements count at the first point (c) Elements count at the second point (d) Elements count at the third point



(b) (c)

Figure 4.CAD drawing showing the thermal conductivity measurement apparatus (a) CAD drawing showing the apparatus from the outside (b) an exploded view of the apparatus' components. (c) a bird eye view photo of the assembly

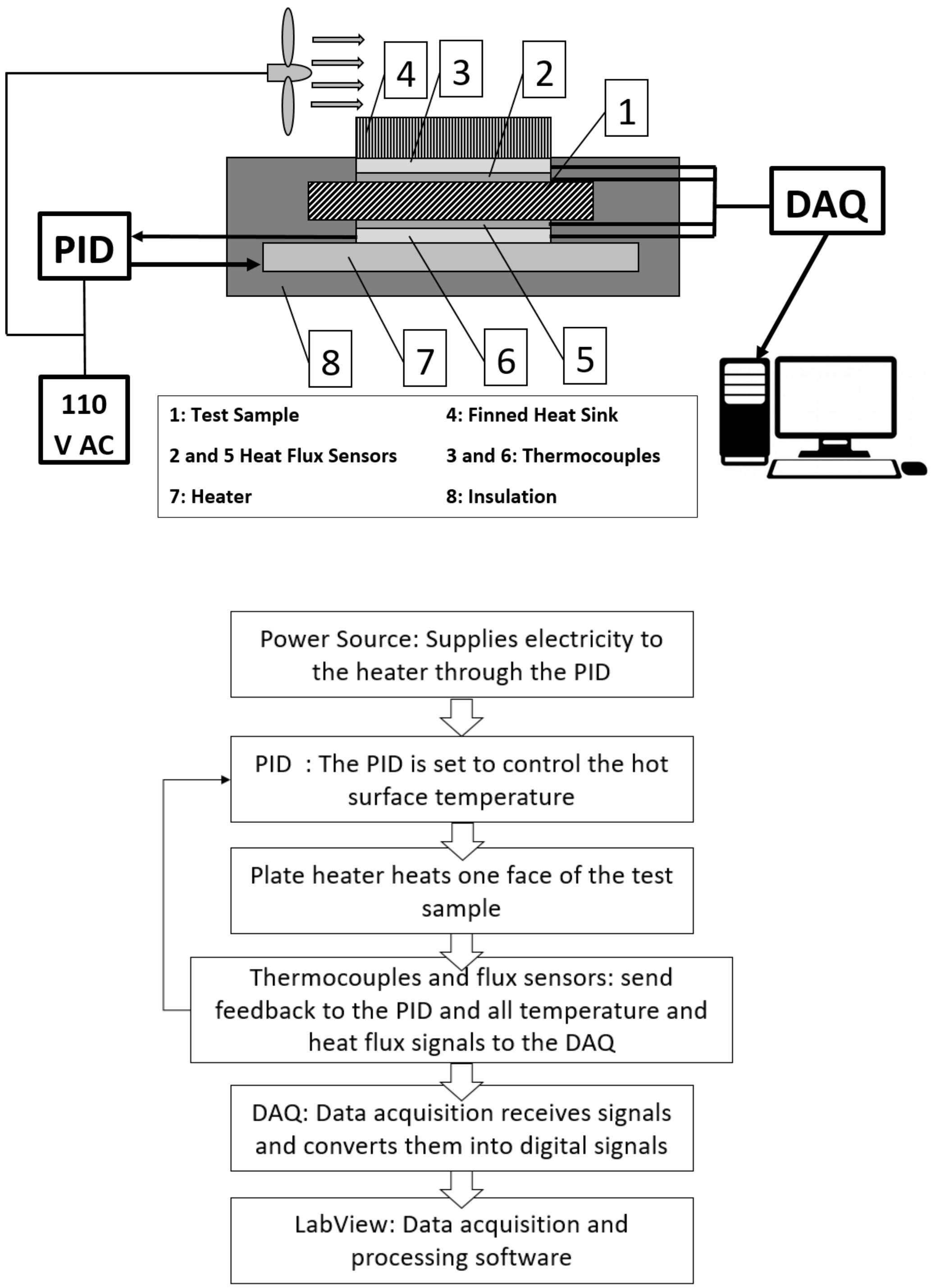


Figure 5 A schematic figure and a flow chart describing the data acquisition process

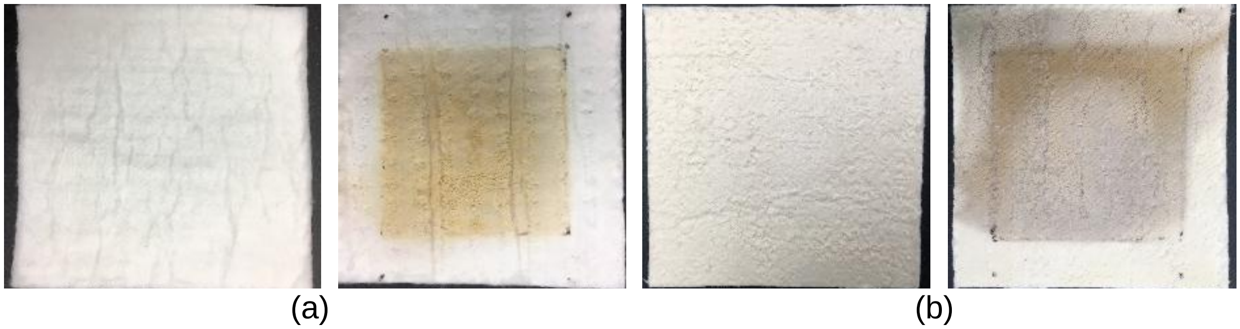


Figure 6. Samples used for thermal conductivity testing: (a) LTHPI (b) HTHPI

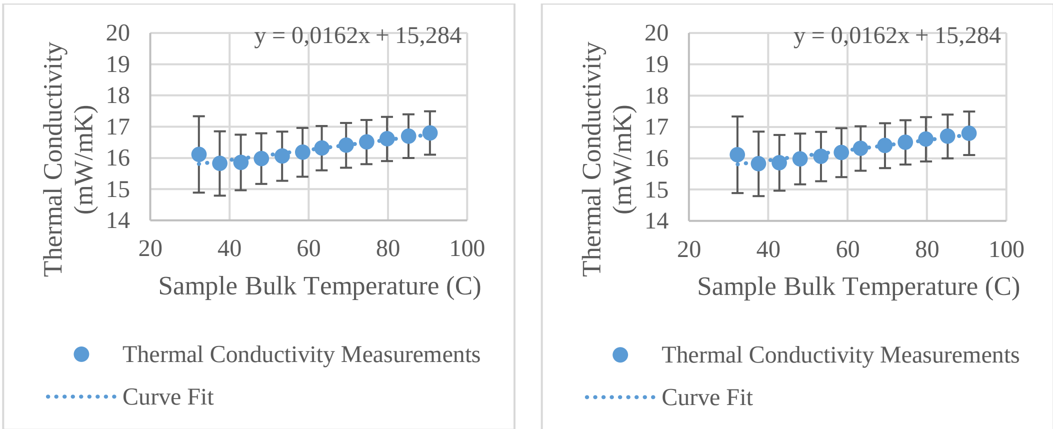
TESTING RESULTS AND OBSERVATIONS

The apparatus contains a (6" by 6") heater, hence, the samples have the same size. Fig. 6 shows two samples before and after using them in in the apparatus. The first observation is that the LTHPI sample has a bright white color, whereas the HTHPI sample has an off white a little yellowish color. The photos also show a slight change in color that indicates a change in insulation properties.

A thermal conductivity curve is obtained for both LTHPI and HTHPI samples. Five samples of each are tested at room temperature (with thickness of 5mm). Table (4) shows the recorded room temperature ranges for all samples. It is noted that all samples were tested under very close conditions.

Table 4. Ambient temperature during testing each sample

Sample Number	Room Temperature Range (ºC)
LTHPI 1	(25.4-28.1)
LTHPI 2	(25.1-27.9)
HTHPI 1	(25.1-27.2)
HTHPI 2	(24.9-27.7)



(a) (b)

Figure 7. Thermal conductivity vs. temperature (a) LTHPI (b) HTHPI

Fig. 7 shows thermal conductivity curves for LTHPI and HTHPI for a forward (heating) test. The curves show that the thermal conductivities obtained are consistent with manufacturer's claims and results found in reference [21].

Statistical and Error Analysis

For each of the reported results, the sample size was n = 5. The mean and standard deviations of the collected temperature data for each temperature measurement are given as follow:

$$\bar{T} = \frac{\sum T_i}{n} \tag{2}$$

n : is the number of tested blanket samples. The standard deviation for temperatures are calculated as:

$$S_T = \sqrt{\frac{\sum (T_i - \bar{T})^2}{n-1}} \tag{3}$$

And the standard deviation of the temperature means is given as:

$$S_{\bar{T}} = \frac{S_T}{\sqrt{n}} \tag{4}$$

Then the temperature data are reported as:

$$T = \bar{T} \pm t_{(4,95\%)} S_{\bar{T}} \tag{5}$$

It should be noticed that $t_{(4,95\%)}$ is the t-distribution value for 5 samples and confidence level of 95% equals to 2.2770.

Similarly, the standard random errors for the other variables (heat flux, thickness, and area) are found and listed.

$$q = \bar{q} \pm t_{(4,95\%)} S_{\bar{q}} \tag{6.a}$$

$$t = \bar{t} \pm t_{(4,95\%)} S_{\bar{t}} \tag{6.b}$$

$$A = \bar{A} \pm t_{(4,95\%)} S_{\bar{A}} \tag{6.c}$$

Finally, the resulted thermal conductivity values are reported as:

$$k = \bar{k} \pm u_k \tag{7.a}$$

$$u_k = \sqrt{\left(t_{(4,95\%)} S_{\bar{T}}\right)^2 + \left(t_{(4,95\%)} S_{\bar{q}}\right)^2 + \left(t_{(4,95\%)} S_{\bar{A}}\right)^2 + \left(t_{(4,95\%)} S_t\right)^2 + {u_c}^2} \tag{7. b}$$

u_c: Is the calibration uncertainty.

HEAT LOSSES FROM WATER HEATERS

Many water heater manufacturers supply the US market with gas-fired water heaters. They provide many different models and designs with various capacities starting with 40,000 BTU/hr to 100,000 BTU/hr. Water heaters market is a competitive market, manufacturers are always competing to provide good products with low cost, which makes it a challenging task to find a low-cost improvement to increase the energy factor of water heaters. Furthermore, water heater manufacturers are required to meet the Department of Energy regulations and the Canadian Standards Association (CSA) standards for water heaters. This makes using HPI in water heaters a very reasonable consideration to improve water heaters.

Fig. 8 shows a pictorial and a schematic diagram of a typical gas-fired water heater. It shows the main parts relevant to the calculations of this study. Simple calculation was done to compare the insulation performance of currently used Polyurethane and LTHPI blankets in water heaters.

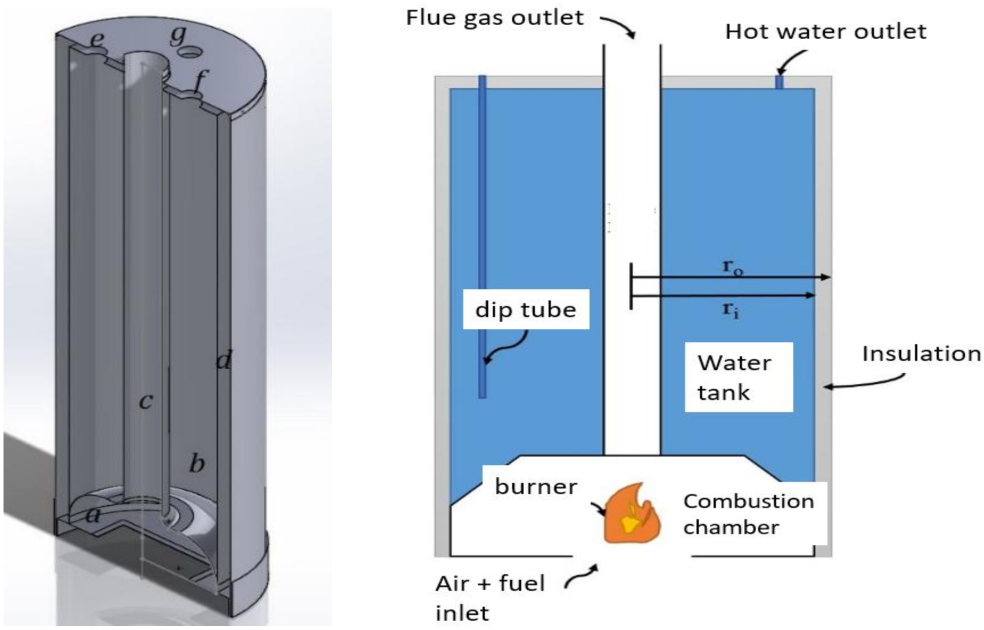


Figure 8 A typical residential gas-fired water heater: Left: a pictorial CAD showing the combustion chamber (a), the water tank (b), the flue tube (c), the insulation cavity (d), the dip tube opening (e), the water exit opening (f), and the thermocouple opening (g). Right: A schematic showing the gas-fired water heater.

The calculations were done based on the following assumptions:

- Steady state conditions.
- Natural convection on the outer wall.
- Negligible steel thermal resistance (representing thin steel skin of the water heater).
- A one dimensional temperature distribution across inner wall thickness.

Fig. 9 shows a thermal resistance network representing the thermal insulation wrapping the heater.

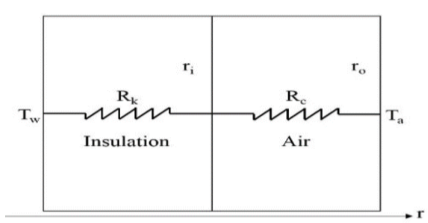


Figure 9 Thermal resistance representation of the water heater insulation

The system heat loss is calculated using Eqn. (8):

$$q_l{}' = \frac{T_w - T_a}{R_{eq}} \tag{8}$$

$q_l{}'$: is the heat per unit length, (T_w) is the water temperature, (T_a) is the ambient temperature, and (R_{eq}) is the equivalent thermal resistance per unit length given as:

$$R_{eq} = \frac{\ln r_o/r_i}{2\pi k} + \frac{1}{h_a(2\pi r_o)} \tag{9}$$

Finally, energy savings can be given as:

$$S\% = \frac{q_l{}'|_{PUR} - q_l{}'|_{HPI}}{q_l{}'|_{HPI}} \times 100\% \tag{10}$$

Where $S\%$ is the energy savings percentage, $q_l{}'|_{PUR}$ is the heat transfer per unit length using polyurethane insulation and $q_l{}'|_{HPI}$ is the heat transfer per unit length using high performance insulation. Table (5) shows the input parameters of the calculations, values have been chosen based on commercial water heaters and normal operating conditions. Results of the calculations have shown a decrease in heat losses of about 29.64561%. This shows that LTHPI is a better insulation for water heaters than Polyurethane and shows a promising advantage to the water heaters industry.

Table 5. Water Heater Parameters

Parameter	Value (Unit)	Parameter	Value (Unit)
$\boldsymbol{h_a}$	25 W/m^{2}K	$\boldsymbol{r_i}$	0.19 m
$\boldsymbol{k_{PUR}}$	0.0235 W/mK	$\boldsymbol{r_o}$	0.205 m
$\boldsymbol{k_{HPI}}$	0.0159 W/mK	$\boldsymbol{T_a}$	25 ^{o}C

ECONOMIC ANALYSIS

In this section, a simple payback period analysis and comparison between a case without using HPI in gas-fired water heaters and a case with using HPI. Table (6) shows financial parameters to be used in this analysis.
The analysis is based on the following assumptions:

- The replacement of PUR with HPI is considered an investment, where the value of the initial cost is the difference in price.
- No operation and maintenance costs for both insulations.
- Energy savings are based on showers alone, no other activity have been taken into consideration.
- Water heater dimensions discussed in the previous section are to be used in this analysis.

For HPI, one (5 mm thickness) layer of HTHPI and two (5 mm thickness) layers of LTHPI are used. Two cases are demonstrated:

Case1: Where an individual replaces insulation, where less than 24.17 ft^2 are needed.

Case 2: Where a mass producer is purchasing HPI with quantities larger than 169.17 ft^2.

Annual savings (revenues) are calculated based on the formula:

$$Annual\ Savings\ (\$) = Operation\ Time \times Power\ Rating \times (1 - Energy\ Factor) \times Energy\ Cost \times (0.2965) \tag{11}$$

Table 6. Parameters used in the single water heater analysis

Parameter	Value (Unit)
LTHPI (5 mm thick) Price (Area under 24.17 ft^2)	5.72 ($\$/ft^2$)
LTHPI (5 mm thick) Price (Area over 169.17 ft^2)	3.79 ($\$/ft^2$)
HTHPI (5 mm thick) Price (Area under 24.17 ft^2)	5.79 ($\$/ft^2$)
HTHPI (5 mm thick) Price (Area over 169.17 ft^2)	3.73 ($\$/ft^2$)
PUR cost	20-24 ($/kg)
PUR density	32 (kg/m^3)
Area of Insulation	1 (m^2) or 10.7639 (ft^2)
Interest rate	10%
Gas Cost	0.022963 ($/kWh)
Heater power rating	40000 (BTU/hr)
Energy factor	0.675
Average shower time	8.2 (min/person/day)
Number of people in each household	2.54 (person/household)

The time value of money based on a given interest rate is calculated by the following discrete compounding formula:

$$F = P\frac{1}{(1+i)^N} \tag{12}$$

Where: P is the present value of investment, F is the future value of investment, i is the annual interest rate and N is the number of years. The calculated values for the initial investment are $168.3 for case 1 and $104.6 for case 2, and the values for the saving revenue is $29.97/yr. Table 7 shows the cash flow for replacing PUR with HPI as an investment with 10% interest rate. It can be noticed that the payback period for the investment is 8 years for an individual replacing the water heater insulation, and 4 years for a mass producer (taking into consideration shower use only).

Table 7. Cash flow table for both individual and mass producer scenarios

Year	Case 1 ($)	Case 2 ($)
0	-168.338	-104.6157
1	27.24545	27.24545
2	24.7686	24.7686
3	22.5169	22.5169
4	20.46991	20.46991
5	18.60901	**18.60901**
6	16.91728	16.91728
7	15.37935	15.37935
8	13.98123	13.98123
9	**12.71021**	12.71021

A conclusion can be made that replacing PUR with HPI for water heaters is a fine and acceptable investment if mass production is involved in the process, the payback period will be less taking into consideration further activities like dishwashing and laundry. Also, taking into consideration that the price of such insulation material will decrease in the future and become more available, and it can be said that special contracts with water heater manufacturers can make the replacement initial cost further less. Therefore, a recommendation can be made: replacing PUR with HPI in water heaters is a feasible investment in a mass production scenario.

To expand this simple calculation on a national level, the US has a number of households of about 124 million households according to The Statistic Portal (2016) [32], having saved at least $29.97/year for each household, that shows an annual saving of 3.7 billion dollars in the US.

CONCLUSIONS

This paper presents tests conducted on aerogel based insulation blankets. The aim is to study the blankets' structure and thermal conductivity. HPI blankets have been acquired to be experimentally studied. The first part was studying the structure of aerogel insulation blankets, this has been done by SEM imaging the blankets and observe the shape and interaction between the different components. X-ray analysis was done to show components exist in aerogel inside the blankets (Silicon, Oxygen, and Carbon were found). For thermal conductivity, curves were recorded for both heating and cooling cycles. The thermal conductivity results were found to be in agreement with results reported in the literature from major manufacturers. Thermal conductivity of LTHPI at 25C was found to be 0.0159W/mK, and the thermal conductivity of HTHPI was found to be 0.0188 W/ (m.K) at 25 ºC.

Simple heat loss calculations on using LTHPI in water heaters have shown a significant decrease in heat losses of 29.65%. This shows a promising improvement in the performance of water heaters. A simple economic calculation have shown that replacing PUR with HPI in water heaters is feasible in mass production scenarios, and annual savings of minimum of 3.7 billion dollars can be obtained on the USA national level.

Based on the results of this work, it can be concluded that the tested blankets show a promising performance in thermal systems and domestic applications, and are suitable to be used as an insulation for domestic water heaters industry. The following are two recommendations based on this study:

- Commercially available HPI shows a promising insulation performance in water heaters. Having regulations to make water heaters manufacturers consider HPI in water heaters is highly recommended.
- More studies and experiments for HPI in water heaters environments are encouraged. Studies include the effect of combustion induced vibrations and interaction with water and humid air on HPI are recommended. Furthermore, the effect of using HPI in water heater on the energy factor can also be studied.

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NOMENCLATURE

$\boldsymbol{A}$	Sample area (m^2)
$\bar{\boldsymbol{A}}$	Mean of sample areas (m^2)
$\boldsymbol{F}$	Future worth of money ($)
$\boldsymbol{i}$	Interest Rate (%)
$\boldsymbol{k}$	Thermal Conductivity (W/mºC)
$\bar{\boldsymbol{k}}$	Mean thermal Conductivity (W/mºC)
$\boldsymbol{n}$	Number of samples (-)
$\boldsymbol{P}$	Present worth of money ($)
$\boldsymbol{q}$	Heat rate (W)
$\bar{\boldsymbol{q}}$	Mean heat rate (W)
$\boldsymbol{q_l}'$	Heat losses per unit length (W/m)
$\boldsymbol{R_{eq}}$	Equivalent resistance of the insulation gap per unit length (ºC/W)
$\boldsymbol{r_i}$	Inner radius of the insulation gap (m)
$\boldsymbol{r_o}$	Outer radius of the insulation gap (m)
$\boldsymbol{S_q}$	Standard deviation of heat flux (W)
$\boldsymbol{S_{\bar{q}}}$	Standard deviation of means of heat flux (W)

$\boldsymbol{S_T}$ Standard deviation of temperatures (ºC)
$\boldsymbol{DAQ}$ Data Acquisition
$\boldsymbol{DOE}$ Department of energy
$\boldsymbol{HPI}$ High performance insulation
$\boldsymbol{HTHPI}$ High temperature high performance insulation
$\boldsymbol{S_{\bar{T}}}$ Standard deviation of means of temperatures (ºC)
$\boldsymbol{S_t}$ Standard deviation of thicknesses (m)
$\boldsymbol{S_{\bar{t}}}$ Standard deviation of means of thicknesses (m)
$\boldsymbol{S_A}$ Standard deviation of area (m^2)
$\boldsymbol{S_{\bar{A}}}$ Standard deviation of means of area (m^2)
$\boldsymbol{S}\%$ Heat loss decrease percent (%)
$\boldsymbol{T}$ Temperature (ºC)
$\boldsymbol{T_a}$ Ambient temperature (ºC)
$\boldsymbol{T_w}$ Water temperature (ºC)
$\boldsymbol{\bar{T}}$ Mean temperature (ºC)
$\boldsymbol{T}$ Temperature (ºC)
$\boldsymbol{T_a}$ Ambient temperature (ºC)
$\boldsymbol{T_w}$ Water temperature (ºC)
$\boldsymbol{\bar{T}}$ Mean temperature (ºC)
$\boldsymbol{t}$ Sample thickness (m)
$\boldsymbol{\bar{t}}$ Mean thickness (m)
$\boldsymbol{t}_{(\boldsymbol{v},\%)}$ Student t distribution (-)
$\boldsymbol{u_c}$ Calibration error of the apparatus (W/mK)
$\boldsymbol{u_k}$ Uncertainty in thermal conductivity (W/mK)
$\boldsymbol{wt}\%$ Weight loss percentage (%)
$\forall$ Tank volume (m^3)
$LTHPI$ Low temperature high performance insulation
PUR Polyurethane
SEM Scanning electron microscopy
TGA Thermogravimetric analysis

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