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Research Article

Experimental Investigation of Internal Aerogel Insulation Towards Low/Zero Carbon Buildings: A Comprehensive Thermal Analysis for a UK Building

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Abstract: Buildings are responsible for about 40% of total energy consumption in the UK. Decisive measures are taken to mitigate building-oriented energy consumption figures and greenhouse gas emissions. Energy-efficient retrofitting of buildings is such an attempt to both reduce energy consumed in the building sector and make them adaptive to the latest low/zero carbon building requirements. Thermal superinsulation is now more than a necessity towards low/zero emission buildings, and in this respect, it is of vital importance to reinforce building envelopes with thermal superinsulation materials like aerogel at optimum insulation thickness for thermally comfortable indoor environments with a cost-effective energy-saving strategy. Therefore, in this research, a traditional 1930s house in the UK has been internally retrofitted with a specially designed aerogel blanket and a complete and thorough co-heating test methodology has been applied to the whole house. Heat loss coefficient (HLC) and overall heat transfer coefficient (U-value) of each room and building element have been determined at pre and post-retrofit cases, respectively. The results have revealed that the HLC of the test bedroom has been reduced from 17.15 to 6.29 W/K after aerogel insulation. These findings have been achieved to reveal the changes in resistance value and heat transfer coefficient. Thermal bridging effects in the test bedroom have also been resolved after aerogel retrofit, which is verified through thermal camera images.

Keywords: thermal superinsulation, low/zero carbon buildings, aerogel retrofit, co-heating test, heat loss coefficient, U-value

1. Introduction

Presently, the majority of nations are actively working to meet their responsibilities, as the recognition of the imminent threat of climate change arising from elevated levels of greenhouse gas emissions and the combustion of fossil fuels. These committed countries signed the Paris Agreement in 2015 [1] in order to keep the global temperature rise below 2 °C as per the pre-industrial era so as to mitigate this effect. To maintain that limited temperature, a shift away

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from non-renewable energy sources and a heightened reliance on renewable energy sources is imperative. Yet, when examining specific sectors, such as the construction industry in the United Kingdom, which accounted for about 19% of greenhouse gas emissions and roughly 40% of energy consumption in 2016 [2], it becomes essential to conduct research aimed at lowering energy expenses in buildings. Therefore, the UK has been the first major economy to aim for net zero carbon emissions by 2050 and pass legislation to that effect [3]. Making people aware of the use of low-carbon energy sources in buildings and increasing energy efficiency can both reduce greenhouse gas emissions and help reduce energy costs by minimising heat loss [2]. After the mission awareness of the countries, the carbon emission rate of buildings in the UK decreased by 30% in between 2009 and 2019. Following the UK Climate Change Act report released in December 2020, the mean yearly reduction in UK emissions must become at least 21 $MtCO_2e$ in order to reach the net zero goal. The necessity of buildings with net zero carbon emissions has revealed the need to build them with highly efficient heating systems, renewable, airtight controlled ventilation, and high standards of insulation. In addition, no new dwellings to be built by 2025 will be allowed to be connected to the gas network [4]. Considering the total heat loss of a dwelling, it is known that 20-30% of it is due to thermal bridging [5], and up to 50% is due to air infiltration [6]. Therefore, several studies have been conducted in the UK to interpret built-in fabric performance [7].

An experimental method for defining the 'as-built' heat loss coefficient (HLC) of a building is known as the co-heating test; this is determined by plotting the daily heat input toward the daily temperature difference between indoor and outdoor of buildings. The method of the co-heating test is to heat the building in such a way that the temperature differences across the overall thermal envelope must be at least 10 °C on average [8]. There is a disadvantage of using the co-heating test method since the dwelling must be vacant during the monitoring period, hence, potentially making testing extremely expensive. In addition to this, the test is done with the sealing of intended vents and also the use of fans in order to mix the air. This method leads to an estimate, where a performance gap between the actual and applied value may exist [9]. The co-heating test has been mostly improved and enforced in northern European countries, where low external temperatures and the high number of cloudy days during the winter season, allow for the method to be of greater accuracy [10]. There are some studies of researchers who have worked with the co-heating test method. For instance, Alexander et al. [11] and Parker et al. [12] have applied the co-heating test to confront the estimated and real thermal performance of the dwellings and the performance of insulation pre and post-reinforcement. In this study, three structures are evaluated. These are the modern building stock of the 1900s, the new building stock with good application in accordance with 2010 standards, and the building stock with the best application in 2012 standards are discussed as shown in Table 1 below.

Table 1. Envelope specifications for the case study [11]

Case	1990	2010	2012	Ph
U-value in Wall (W/m^2K)	0.45	0.3	0.15	0.1
U-value in Roof (W/m^2K)	0.25	0.2	0.13	0.14
Ground Floor U-value (W/m^2K) **	0	0	0	0
Glazing U-value (W/m^2K)	3	2	0.8	0.8
Target HLC (W/K)	162	110	61	33

**Ground floor treated as adiabatic

Cuce et al. [13] have applied a study at the University of Nottingham, England, employing the co-heating test method to evaluate the thermal performance of their designed windows. The primary objective is to present a compelling alternative to contemporary windows characterised by very low thermal resistance. The windows they developed include vacuum tube windows, thermally insulated solar glass, and solar pool windows. Results from the co-heating test reveal that the vacuum tube windows exhibit the lowest U value at 0.4 W/m^{2}K. Remarkably, this technology demonstrates significantly higher thermal resistance, offering five times better insulation than commonly encountered double-glazed windows. In a different investigation, Cuce [14] carries out a practical experiment in April 2016 within an actual residential setting in Nottingham, UK. The study involves subjecting two variations of window sashes to a dynamic co-heating test. One window sash is insulated from the inside using a specific covering, while the other remains untreated. The U value obtained from the window sash with interior insulation and an airtight cover demonstrates a 33% improvement in resistance compared to the data collected from the untreated window sash. Wingfield et al. [15] have tried to reduce the U-value of a residential building known as the EPS08 prototype by using conventional insulation materials. Samuel et al. [16] have performed a co-heating test on heavyweight (brick-insulation-block) and lightweight (cladding-insulation-plaster) structures in accordance with the UK Building Code of 2010. As a result of what has been done here, it has been observed for heat loss that more accurate and reliable results are obtained in the light structure than in the heavy structure by using the co-heating test. In a study done by E. Lambie and D. Saelens [17], a significant decrease in the U-value of a structure at the pre and post-reinforcement has been shown. They first determined the U-values of the building's windows and glass doors, roof, walls, etc., in the pre-reinforcement. Then, as a result of the technologies used with post-reinforcement, these values have been determined again, and compared with the data of pre-retrofit. Before the reinforcement, the U-value of windows and glass doors have been found to be 2.3 W/m^{2}K, whereas it was reduced to 1 W/m^{2}K at post-retrofit. Additionally, the rear facade had a value of 1.13 W/m^{2}K at the pre-retrofit, whilst it was reduced to 0.12 W/m^{2}K at the post-retrofit. As a result of these values, it is understood that while the maximum improvement is observed at 89.4% for the rear facade, the lowest improvement rate is seen for windows and glass doors at 56.6%. Existing low-carbon building requirements are met on rear facade walls but still appear to be insufficient for windows. Table 2 below contains the data for this study.

Table 2. Target U-values of the pre and post-retrofit building envelope [17]

Building Component	Pre-Retrofit	U-value (W/m^{2}K)	Post-Retrofit	U-value (W/m^{2}K)	Key Findings
Windows and glass doors	Double glazing PVC frame (DG-PVCF)	2.3	Triple glazing PVC frame	1	56.6% reduction in heat losses is achieved with a retrofit
Roof window	-	-	(DG-PVCF)	1.16	-
Front facade	Uninsulated cavity wall (UCW)	1.13	UCW – 12 cm PUR	0.23	79.7% decrease in the U-value is obtained
Rear facade	UCW	1.13	Prefabricated insulated component (PIC)	0.12	There is an improvement of 89.4% after reinforcement
Rear facade extension	UCW	1.45	PIC	0.24	With the use of PIC, an enhancement of 83.5% is acquired
Pitched roof	Wooden frame + 8 cm mineral wool	0.68	Wooden frame with 25 cm mineral wool	0.17	75% reduction in U-value is achieved by thickening the mineral wool wood frame
Flat roof extension	Wooden frame without insulation	1.98	PIC	0.21	Mitigation of 89.4% is obtained by isolating the area after reinforcement
Floor on the ground (Main building)	Uninsulated concrete slab (UCS)	0.57	UCS	0.57	-
Floor on the ground (extension)	UCS	0.57	PIC	0.19	67% benefit is reached by switching from UCS to PIC
Floor above Cellar	UCS	0.75	Concrete slab + 8 cm PUR	0.28	63% reduction is achieved in energy losses

Cuce and Cuce [18] present a research project wherein they replace a 1930s house with a 20 mm thick aerogel thermal superinsulation material on one side of the test chamber. Subsequently, they measure the heat flow in the partition wall of the insulated facade using the co-heating test method. According to the study's findings, the heat flow in the partition wall of the uninsulated facade is 0.66 W/m^2, whereas after the insulation is applied, this value increases to 5.86 W/m^2. As a result, it is deduced that aerogel replacement significantly enhances building insulation performance. This effectiveness is attributed to the prevention of heat penetration through the insulated area, redirecting it towards partition walls as the path of least resistance. In a study by Uriarte et al. [19], they try to find out the HLC values of an office structure that is still in use pre and post-retrofitting. The house from the 1970s is chosen. It is constructed with precast concrete panels without an air gap and three types of windows (Wooden frame and single glazed window, aluminium frame (without heat cutter) and double pane windows, aluminium frame (heat insulated) and double-glazed window) in pre-retrofitting. After retrofitting, the insulated facade is reinforced by adding vacuum-insulated panels inside an air-conditioned facade. Some of the windows have been modified with a reversible window type and others with a high-performance window that can change according to different solar behaviour. As a result of the study, while the HLC value is 5.18 kW/K in pre-retrofitting, it decreases to 3.74 kW/K in post-retrofitting. When looking at these values proportionally, this situation is recorded as 28%.

Thermal superinsulation represents a phenomenon characterized by significantly superior insulation properties and exceptionally low airtightness when compared to other insulation materials. Conventional insulators currently available do not possess a thermal conductivity as minimal as that observed in aerogel thermal superinsulation. On the other hand, since it is high cost, the usage areas of such materials are restricted. In this experiment, a 1930s 2-storey Victorian house is used. The aim is to look at the effect on the U-value of the building envelope in its pure form and after with the aerogel thermal superinsulation added inside to the exterior facing walls. Next, answers are sought to questions such as the effect of using this material on the cost of the house and whether it is appropriate to use. According to the literature review conducted for the retrofit of buildings, none of the studies carried out so far have tried to look at the before and after effects of adding aerogel thermal superinsulation. Additionally, future projections clearly reveal that more than reinforcement with conventional building elements will be required. Hence, extra resistive materials are in demand, and researchers need justified co-heating test results and validated data on how to use them in the field. In this sense, the present research is one of the rare studies in which the dynamic behaviour of a house is determined from a thermal superinsulation application during a co-heating test period in actual dynamic conditions in a given winter season, and this is a pioneering study in meeting the demand for validated data.

2. Methodology

2.1 *Co-heating test*

The co-heating test is a reliable method to determine the heat loss (both fabric and background ventilation) with a unit of W/K, which can be applied to an unoccupied dwelling [20]. Though it does not have an international standard [21], countries especially the UK, have been conducting research since the late 1970s [22]. Recently, most co-heating tests in the UK utilise the entire household heat loss method developed by Leeds Beckett University [20]. In the co-heating test, an attempt should be made to keep the interior temperature at around 25 °C for a long time to heat an unused dwelling. To do this, electrical resistance point heaters are used. After the internal temperature reaches equilibrium, it should be tested for approximately 1-3 weeks [20]. For the accuracy of the test to be even better, the differences between the internal and external temperatures of the unoccupied house should be as high as possible. Therefore, generally, the winter condition is preferable for this type of test [23]. The co-heating test can solely be used to measure the loss of heat through the shell of a building [24]. The heat loss through the building envelope is solved by linear regression analysis, and the following simple formulas can be used to calculate this loss.

$$Q_{elect} + Q_{sol} = Q_{loss} \tag{1}$$

$$Q_{elect} + R \times S = H \times \left(T_i - T_e\right) \tag{2}$$

$$Q_{elect} = H \times \Delta T - R \times S \quad (3)$$

The Solar Aperture, R, is able to be obtained either by statistical methods from regressing co-heating data or by numerical calculations, and it is in units of m^2 [25]. In determining the value of R data obtained by statistical means is taken into account of being much more precise and coherent, as it eliminates the uncertainties in building and numerical estimation [26]. Q_{elect} represents the electrical heat inlet, which is in units of W. Q_{sol} indicates the solar heat gains, which is its unit of W, while Q_{loss} shows the net heating flow out of the building, in units of W. S is the incident solar radiation, which is in units of W/m^2. T_i represents the internal temperature (°C), whilst T_e is the external temperature (°C), and ΔT is obtained by subtracting the outside temperature from the inside temperature. H represents the heat loss coefficient, which is in units of W/K.

2.2 *Overview of the experimentation*

The testing in the model house project is split into two distinct parts, which were taken place over the 2012/2013 heating season. The first part of the testing involves the retrofitting of the box bedroom with new internal wall insulation, known as an aerogel blanket. Aerogel is not a novel material and has been used in many other areas, such as refrigeration and transport. The aerogel insulation has a very low thermal conductivity compared to conventional building insulation materials, but also has a higher cost (currently). The advantage of using this material is that a smaller thickness of material is used to achieve a similar resistance to conventional insulation materials. Hence, when used as an internal retrofitting measure, less floor space is taken up. Due to this lower thickness, it may also be the case that there may be installation technique benefits compared to other materials and systems. This can only be identified by embarking on an installation process and will form part of the reporting. Aerogel materials have a known thermal conductivity by means of tests performed in laboratory conditions. Therefore, theoretical calculations can be performed to assess the effect of using the material within a building. However, the in-situ reality is generally different from theoretical values due to the fixing methods and inhomogeneous structures. It is also the case that unintended consequences can arise from such installations, where condensation risks could be an example. The testing will therefore, investigate the heat loss performance of the aforementioned test room before the retrofitting and also afterward. In addition to a whole room heat loss, individual temperatures will be assessed at various points around the room and also underneath the insulation at the original wall surface. Heat flux measurements will also be taken to assess the heat flow through the wall surface. This is especially important in wall areas, which are near to thermal bridges within the structure (where building structural elements penetrate the insulation layer). Humidity sensors will also be located behind the insulation at the original wall surface, to monitor any potential for a build-up of moisture due to interstitial condensation.

The second part of the testing is in relation to the obscure glazing, i.e. bathroom, toilet, pantry and front door windows. A novel design of evacuated glass tubes sandwiched between double-glazed panels is considered to have high heat insulation characteristics. Due to the vacuum tubes creating a distorted view through the windows, it is considered that this technology is only applicable to windows with obscure glazing. The in-situ tests will consist of temperature measurements and heat flux measurements to investigate any differences between the current double-glazed argon-filled units and the new vacuum tube panels. A panel will also be tested in laboratory conditions inside an environment chamber where temperatures on either side of the glazing can be accurately controlled.

Thermal imaging will also be used on both the insulation retrofit testing and the vacuum tube in situ glazing tests. This will provide valuable images of the effect of the insulation and window technologies. As the installation of the new materials is part of a research project, it will be necessary to document the installation process, as this is equally as important in terms of new knowledge as the quantifiable performance testing. This document sets out the testing plan for this phase of the project, including the test timeline. It must be noted that due to the fact that the outlined tests are dependent upon an internal and external temperature difference, it may be necessary to change the testing dates and periods due to the vagaries of the weather. Therefore, any dates are indicative to provide an understanding of the minimum time scales required.

2.3 *Test details*

The testing is separated into two components; initial testing (prior to retrofit) and final testing (post-retrofit). Initial testing is to provide baseline data for the heat loss performance of the bedroom. This is achieved in two parts:

1. A full house co-heating test is set up, which maintains a constant internal house temperature of circa 25 °C. The full co-heating test methodology is based upon the protocol as defined by Leeds Metropolitan University, Centre for the Built Environment. This test, however, will not include the air tightness testing component. Each room will have an electric heater to supply the required heat to the room to maintain the temperature. Heat loss from the bedroom will be via the external walls and the ceiling. Heat loss/gain through the internal walls will be minimised or eliminated due to the balance of temperature within the building. The co-heating test will be performed over a ten-day period. As the whole house will be maintained at a specific temperature, the data from the testing will measure the whole house heat loss, i.e. whole house co-heat. Specifically, data will be analysed to investigate the heat loss from the test bedroom. The parameters that will be measured in the experimental study are given below:

• Energy input to all heaters.

• Trend system to monitor all room parameters (continuous monitoring). Temperature measurements are checked to ensure a steady temperature profile across all rooms. Relative Humidity data is analysed to identify any changes in building moisture content, etc.

• Outside air temperature and relative humidity logged. (Other weather parameters; wind direction, wind speed and rainfall).

• Detailed monitoring of the test bedroom walls with heat flux sensors and thermocouples.

• Thermal Imaging of the building taken and specifically test bedroom location. (This test will be dependent upon ambient air temperature and weather conditions. It may be the case that a highly elevated internal temperature is required due to warm outside air temperature. This may therefore be carried out at the end of the co-heat test.)

2. Independently of the co-heat test, heat flux and temperature measurements will be taken up to the point of the retrofitting of the insulation. This will provide a valuable data set which can be cross analysed with weather data, in order to assess the heat loss performance of the room under various weather conditions. In other words, that will enable us to investigate the effect of variations in wind and solar irradiance upon the external wall of the test bedroom. Heat flux sensors will be affixed to the walls by means of thermal paste between the sensor and wall and masking tape to secure them. T-type thermocouples are to be affixed to the wall with reflective tape next to the heat flux sensor. Figure 1 provides details of the sensing locations. Hukseflux heat flux sensors and T-Type thermocouples are utilised in the experimental study. The internal view of the test bedroom is shown in Figure 2. The weather station is located on the roof of the house. West west-facing pyranometer is mounted on the external side of the centre of the internal wall.

South facing pyranometer is located on the external side of the center of the internal wall (i.e. equidistant between the window frame and west wall, and from ceiling to floor from internal measurements). The data collated from the heat flux sensors will be used to calculate a heat loss map of the external wall area. This will then provide a calculation of the total heat loss against internal-external temperature difference and will then be cross-compared to the co-heat total heat loss analysis. The purpose of this testing is to investigate the effect of the internal insulation retrofit upon the heat flux through the wall structure. Therefore, before any testing is carried out and to ensure that the readings from the heat flux sensors are not un-uniformly skewed by incident solar radiation, the windows will be blacked out by use of reflective vinyl adhered to the glass (or similar). This will ensure that any heat passing through the fabric from inside to outside will originate from within the building. Final testing is post-retrofitting of the aerogel internal insulation. This will also be done in two parts, as with the initial testing. The performance of the insulation will be investigated by cross-comparison of before and after data. The diagram in Figure 3 illustrates the areas which will be internally insulated with the aerogel blanket.

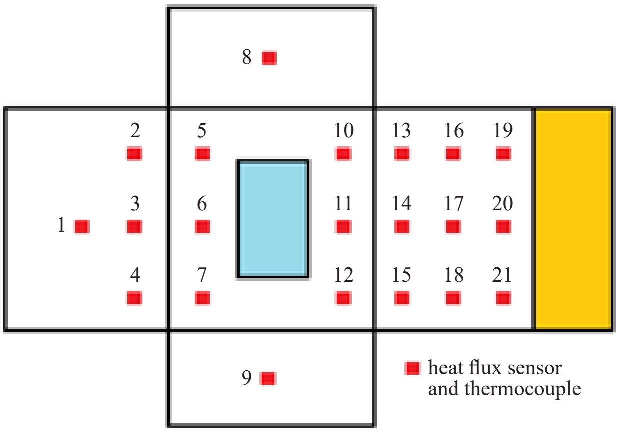

Figure 1. Heat flux sensor and thermocouple locations

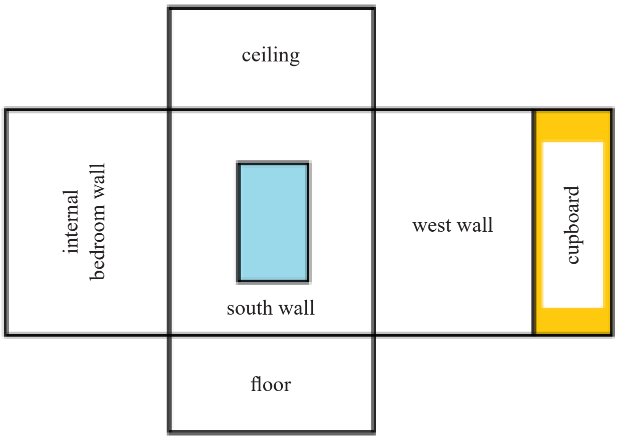

Figure 2. Detailed of the test bedroom from the interior

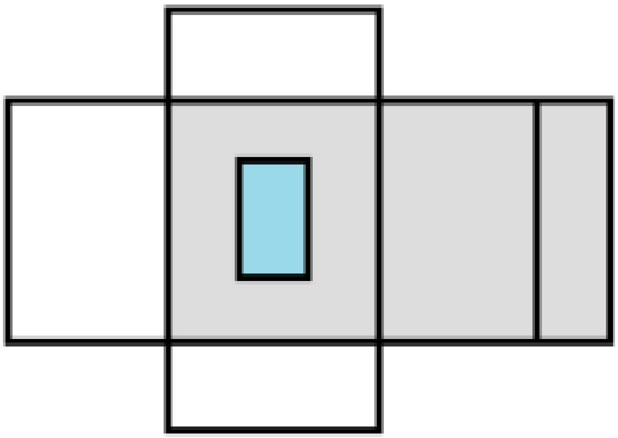

Figure 3. The walls of the test bedroom which are internally insulated with aerogel blanket

Other testing involves specific investigations of certain areas, such as heat loss at thermal bridge junctions and analysis of humidity sensors. It is also possible that other areas of investigation are identified as the initial and final testing proceeds. There are certain parts of the building structure, which have an impact upon the heat loss through the wall. These areas tend to be thermal bridges where a building element penetrates the insulation layer. An area of interest is the internal separating wall between the bedrooms. This wall will have direct contact with the structural external wall both before and after the insulation retrofit. This is an area of interest to assess any impact of the insulation on the heat flux of this wall. Similarly, the floor and ceiling junctions will also have a thermal bridging effect and will be an area of interest. In addition to the direct comparison of pre and post-retrofit heat flux data, a number of additional thermocouples will be located on the wall before the insulation is retrofitted. This will provide information with regard to the temperature of the wall-insulation interface. There are five locations which coincide with the locations of the humidity sensors. Humidity sensors will be placed within the structure between the insulation and the internal wall surface. These will be used to assess any potential for interstitial moisture build-up. The results from the co-heat test will be analysed in terms of the energy required to maintain the set point internal temperature versus the temperature difference between the internal and external environments. More specifically the test bedroom will be analysed in individual detail. This testing will provide a heat loss parameter for the whole house and the individual bedroom. This is the baseline data for comparison to the data gained from the co-heating test after the insulation retrofit. In addition to this primary analysis, further interrogation of the data will be performed to investigate the effect of varying weather conditions upon the test bedroom.

Thermal imaging of the exterior will provide a thermal map of the outside of the bedroom. This will provide details of where the excessive heat loss areas exist, potentially highlighting current thermal bridge elements. Interior thermal imaging will be used, which may provide details of cold spots within the interior. Data will have been collated from the array of heat flux sensors and thermocouples. This data will be used to analyse the agreement between the co-heat whole room heat loss and that reported using heat flux through the exterior walls. Differences between the two values will be investigated to determine the source of the variance. The results from the final co-heat test will be used to cross-compare with those results derived from the initial testing. This should indicate how the increase in the wall's thermal resistance has reduced the fabric heat loss. Again, this is going to be compared to the results from the heat flow sensors. The performance of the insulation in situ will then be analysed against the theoretical performance (U-value) of the insulation-wall combination. The heat flux sensor data will be analysed to assess any differences in heat loss throughout the structure. This may indicate specific areas of increased heat loss, i.e. in the location of thermal bridges. This can be cross-compared to any thermal bridge effects identified in the initial testing. The use of post-retrofit thermal imaging will provide a thermal map, which can be compared to that produced in the initial testing. This will be able to provide a visual assessment of any potential benefit and may highlight how thermal bridging becomes proportionately more significant as a heat loss mechanism. Temperature and potential heat flux data collected from the wall-insulation interface will also be analysed to understand the temperature gradient across the insulation. This will be compared to theoretical calculations of the material's thermal resistance. If performed, the data from the heat flux sensor within the wall at the wall-insulation interface will be compared to the comparable surface-located heat flux sensor. This analysis could provide an indication of the error within the surface flux measurements. Finally, once the beneficial effect of the aerogel has been understood from the testing, the result of this will be used to assess the effect upon the whole house heat loss by application to the IES model of the house. This will be used to assess energy and CO_2 savings.

As shown in Figure 4, it is simply illustrated for a better understanding of the experiment.

It involves an increase in heat of the inside dwelling electrically, using resistance heaters, to an average internal temperature (usually 25 °C) over a specific test period, generally between 1 to 3 weeks. By determining the electrical energy which is used to keep the average internal temperature constant each day, the heat transfer to the dwelling per day is found. The HLC of the dwelling is then determined by plotting the daily heat transfer against the daily temperature difference between the indoor and the outdoor of the place (ΔT). The corresponding slope of the plot yields the HLC in W/K. In order to obtain an adequate value of ΔT (generally 10 °C or more), the co-heating tests should be carried out in the winter months, usually between October/November and March/April. A photograph from the co-heating test of the test bedroom is given in Figure 5.

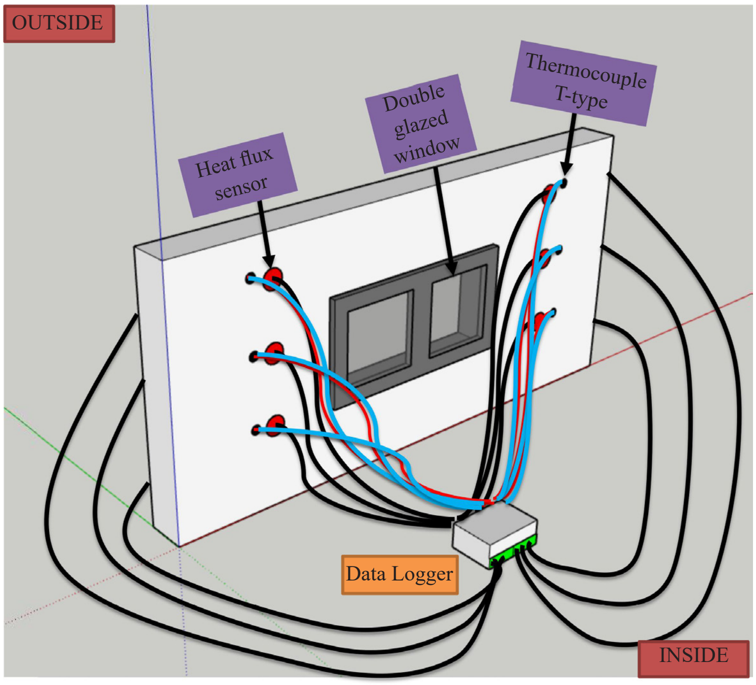

Figure 4. Simply experimental setup demonstration

Figure 5. A photograph from test bedroom as it is being prepared for the co-heating test

2.4 *Uncertainty analysis*

According to Coleman and Steele [27], the total uncertainty for *n* independent variables:

$$W_Q = \left[\left(\frac{\partial Q}{\partial X_1} \times W_1\right)^2 + \left(\frac{\partial Q}{\partial X_2} \times W_2\right)^2 + \left(\frac{\partial Q}{\partial X_n} \times W_n\right)\right]^{1/2} \tag{4}$$

where, Q is the dimension to be measured, X is the variable affecting the measurement, and W is the uncertainty of the independent variable.

In the case observed during the uncertainty analysis:

$$T_i = 25\ °C$$

$$T_e = 11.5\ °C$$

$$Q = U \times A \times \Delta T = 240 \qquad (W)$$

$$H_{loss} = Q/(\Delta T) \qquad (W/K)$$

$$\Delta T = 13.5$$

$$\frac{\partial H_{loss}}{\partial Q} = \frac{1}{\Delta T} = \frac{1}{13.5} = 0.074$$

$$\frac{\partial H_{loss}}{\partial T} = -\frac{Q}{\Delta T^2} = \frac{240}{13.5^2} = -1.317$$

Uncertainty of thermocouples: 0.25
Uncertainty of heat flux = 0.03

$$W_H = \left[\left(\frac{\partial H_{loss}}{\partial Q} \times 0.03\right)^2 + \left(\frac{\partial H_{loss}}{\partial T} \times 0.25\right)^2\right]^{1/2}$$

$$W_H = \left[(0.074 \times 0.03)^2 + (-1.317 \times 0.25)^2\right]^{1/2}$$

$$W_H = 0.329$$

$$H = \frac{Q}{\Delta T} = \frac{240}{13.5} = 17.777$$

$$\frac{W_H}{H} = \frac{0.329}{17.777} \times 100 = 1.85\%$$

The overall uncertainty is calculated as 1.85%.

3. Results and discussion

3.1 *Co-heating test results for the pre-retrofit case*

Graphs in Figure 6 show the actual data from the co-heating test application, through regression analysis before and after the test bedroom is closed. The 'Power' placed on the y-axis indicates the energy consumed/given per unit of time in this relevant temperature difference in order to keep the test bedroom at that temperature. Frankly, it is a waste of energy because energy is spent as much as the energy lost. With the slope to be taken from this graph, the heat loss coefficient (W/K) values can be easily found at any desired temperature difference.

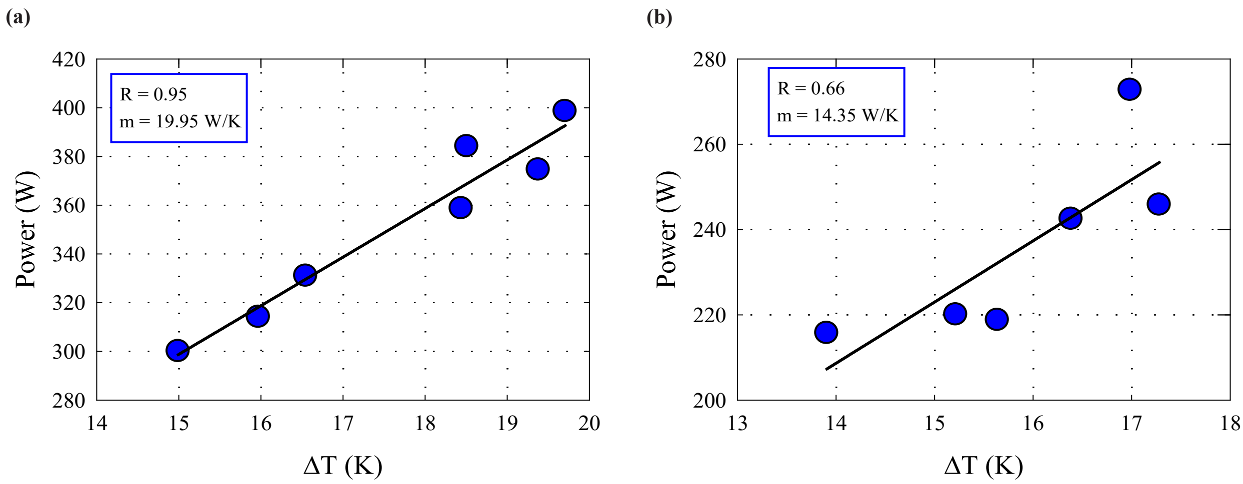

Figure 6. a) Co-heating test for the test bedroom through regression analysis before the test bedroom door was closed, b) Co-heating test for the test bedroom through regression analysis after the bedroom was closed

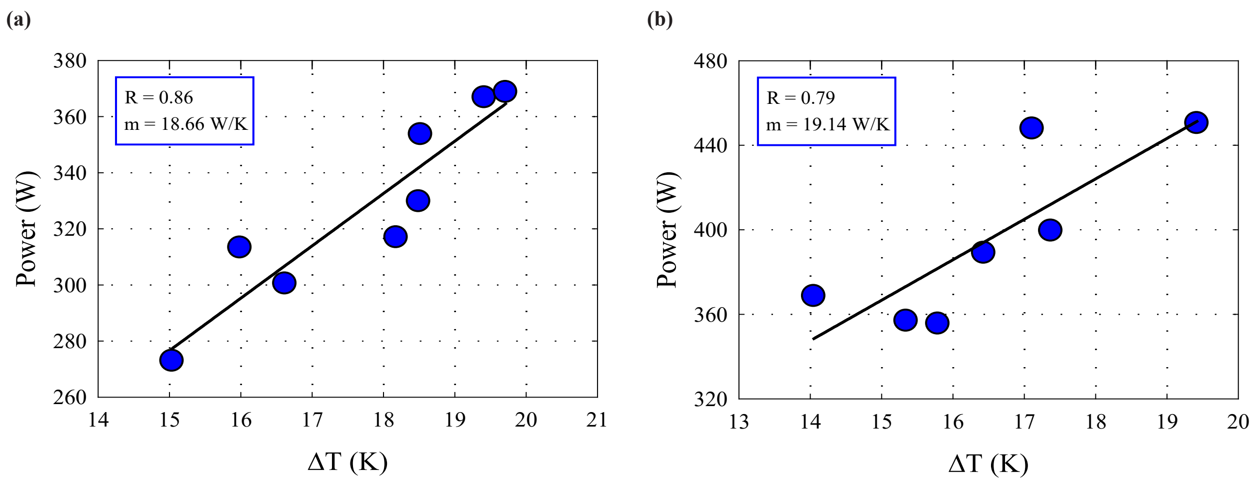

Figure 7. a) Co-heating test for the back bedroom through regression analysis before the test bedroom door was closed, b) Co-heating test for the back bedroom through regression analysis after the test bedroom door was closed

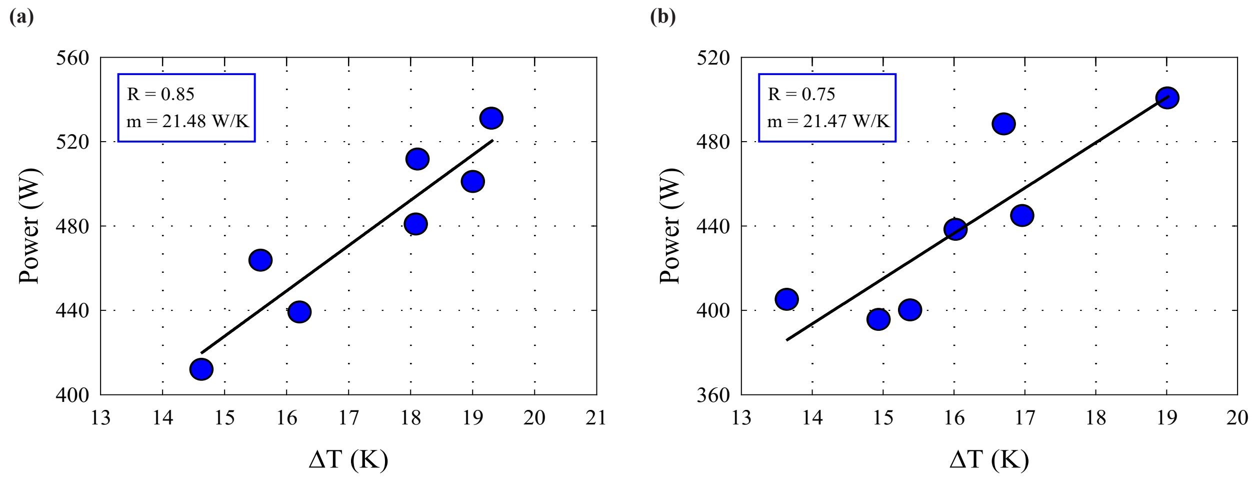

Figure 8. a) Co-heating test for the dining room through regression analysis before the test bedroom door was closed, b) Co-heating test for the dining room through regression analysis after the test bedroom door was closed

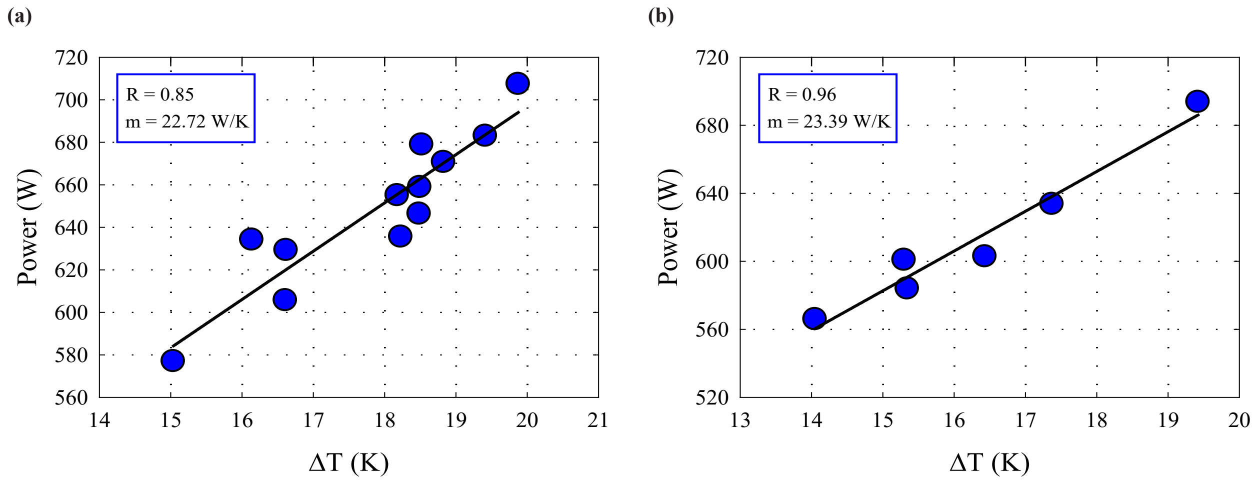

Figure 9. a) Co-heating test for the front bedroom through regression analysis before the test bedroom door was closed, b) Co-heating test for the front bedroom through regression analysis after the test bedroom door was closed

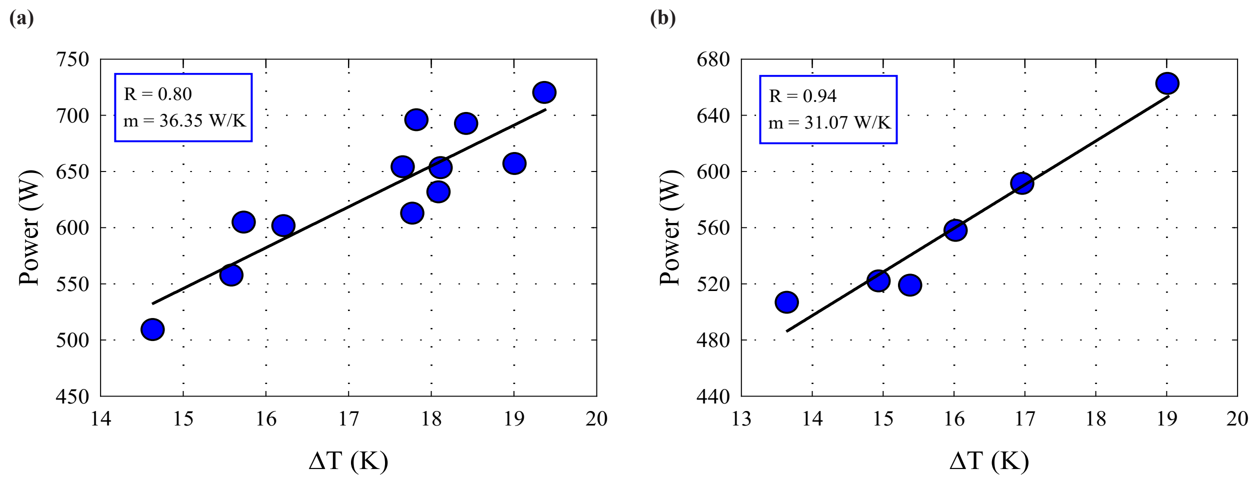

Figure 10. a) Co-heating test for the hall bedroom through regression analysis before the hall bedroom door was closed, b) Co-heating test for the hall bedroom through regression analysis after the hall bedroom door was closed

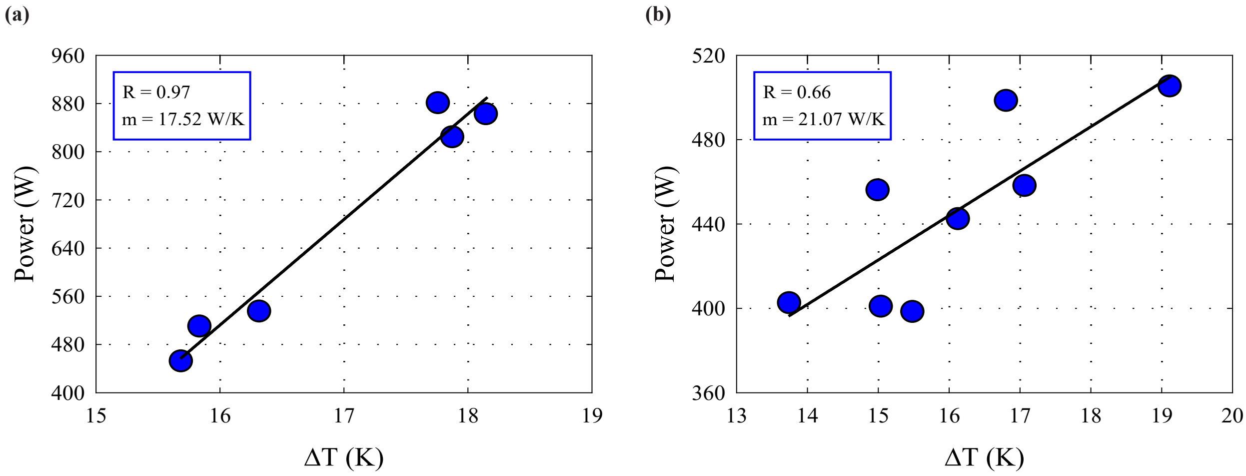

Figure 11. a) Co-heating test for the kitchen through regression analysis before the test bedroom door was closed, b) Co-heating test for the kitchen through regression analysis after the test bedroom door was closed

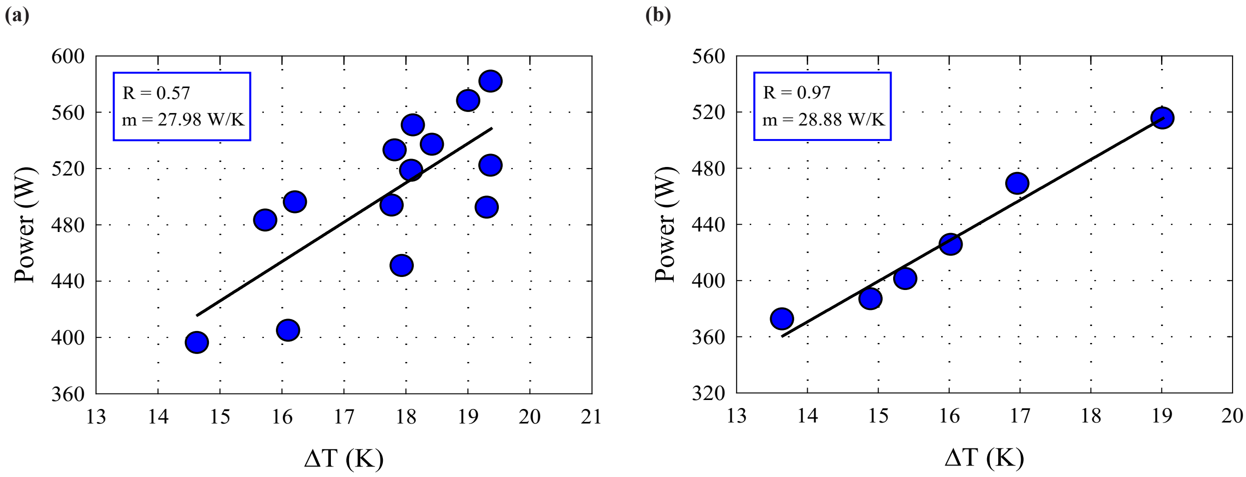

Figure 12. a) Co-heating test for the lounge through regression analysis before the test bedroom door was closed, b) Co-heating test for the lounge through regression analysis after the test bedroom door was closed

In this section, co-heating test results for the pre-retrofit case are presented. For each part of the test house, the heat loss coefficients are calculated as illustrated in Figures 6-12. The tests started on the 13th of December 2012. On the 30th of December 2012, the door of the test bedroom was closed to investigate its influence on the heat loss coefficient of the test bedroom. As a consequence of this, the results for the pre-retrofit case are given in three forms: heat loss coefficients before the test bedroom door was closed, heat loss coefficients after the test bedroom door was closed, and overall heat loss coefficients, as shown in Table 3. The results indicate that the overall heat loss coefficient of the whole house is approximately 162 W/K for the pre-retrofit case. The hall is found to be the place where the maximum heat loss occurs. This is because the hall space has two large windows, and it is dominated by the convective flows of air. On the other hand, the minimum heat loss is observed in the test bedroom with an overall heat loss coefficient of around 17 W/K.

As previously mentioned, another goal of the project is the retrofitting of the standard Argon-filled double-glazed windows of the research house with novel vacuum tube windows. In this respect, it is required to determine the thermal characteristics of the existing double-glazed windows in the pre-retrofit case. Since the vacuum tubes cause a distorted view through the windows, it is considered that this technology is only applicable to windows with obscure glazing. Therefore, the windows of the bathroom, toilet, pantry and front door are selected for the retrofitting. The windows used in the testing are of different sizes, as shown in Table 4.

Table 3. Co-heating test results of the whole house: Heat loss coefficient [W/K] for each place

	Before the test room door was closed	After the test room door was closed	Overall
Test Bedroom	19.98	14.35	17.15
Back Bedroom	18.66	19.14	18.90
Dining Room	21.48	21.47	21.48
Front Bedroom	22.72	23.39	23.06
Hall	36.35	31.07	33.71
Kitchen	17.52	21.07	19.30
Lounge	27.98	28.88	28.43
Whole House	164.66	159.37	162.02

Table 4. Dimensions of the windows that will be analysed for retrofitting

	Width [mm]	High [mm]
Utility/Panty window	19.95	14.35
Bathroom window	18.66	19.14
Toilet window	21.48	21.47
Front door window	22.72	23.39
Adjoining window	36.35	31.07

Figure 13. Visual representation depicting the current windows of the research house

The existing windows of the research house illustrated in Figure 13 are the standard Argon-filled double-glazed windows. Only the windows with obscure glazing are investigated in this study. The co-heating test procedure is also applied to the aforementioned windows, and the heat loss coefficient of each window is determined, as shown in Figure 14.

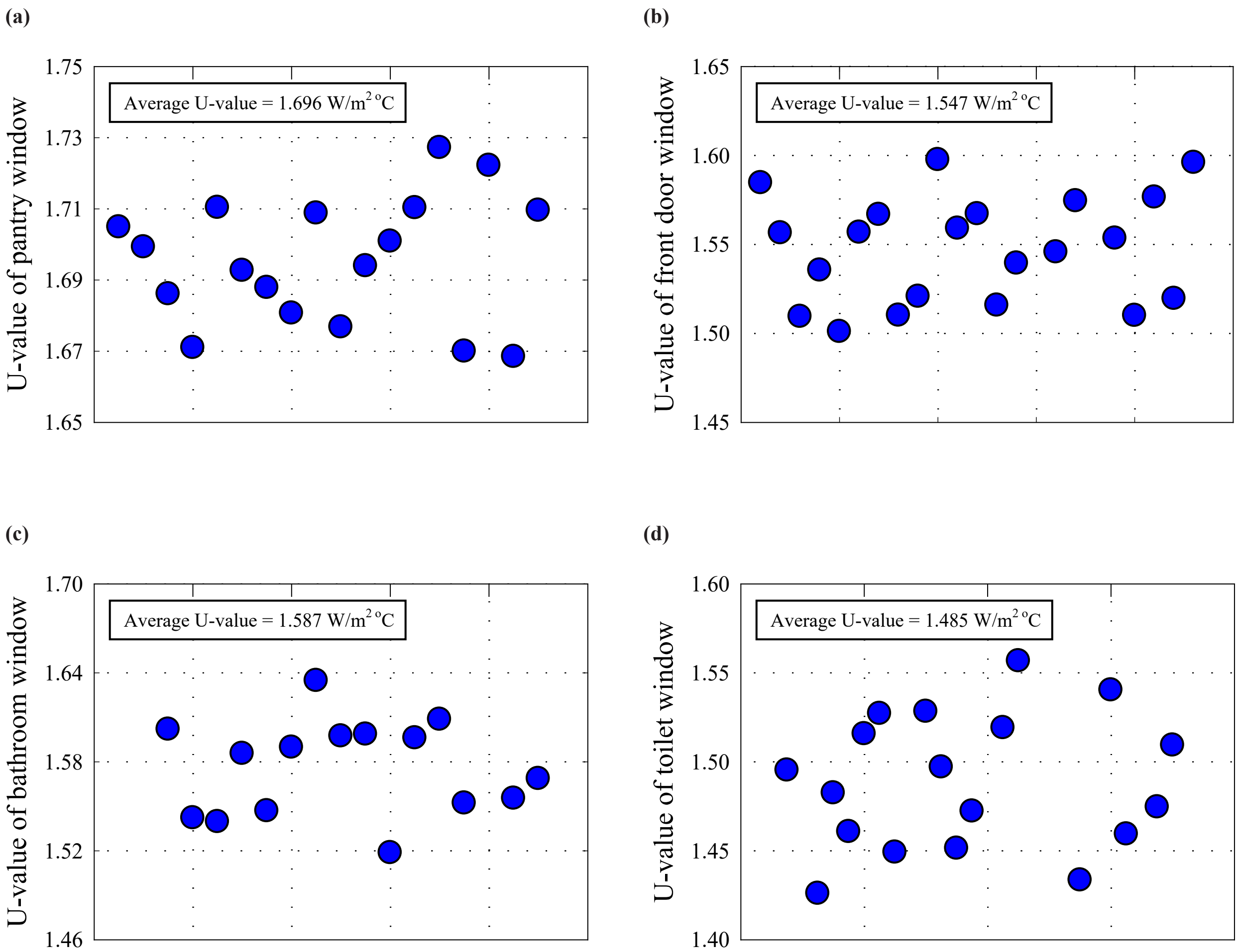

Figure 14. a) Heat loss coefficient of the pantry window at the pre-retrofit case, b) Heat loss coefficient of the front door window at the pre-retrofit case, c) Heat loss coefficient of the bathroom window at the pre-retrofit case, d) Heat loss coefficient of the toilet window at the pre-retrofit case

3.2 *Co-heating test results for the post-retrofit case*

Co-heating test results for the post-retrofit case are illustrated in Figures 15-21. Whole house co-heating test results are given in Figure 22 (a). The hall is found to be the place where the maximum heat loss occurs. The heat loss coefficient of the hall is around 38 W/K in the post-retrofit case. After aerogel retrofitting, the minimum heat loss is observed in the test bedroom with a heat loss coefficient of about 6 W/K.

Figure 22 (b) shows the comparison of the co-heating test results in the pre and post-retrofit case. As it is understood from the results that the heat loss coefficients of the spaces and the whole house are very similar except for the test bedroom. The heat loss coefficient of the entire house is found to be 162.02 W/K and 161.52 W/K at the pre and post-retrofit, respectively. This is because of that the insulated area is negligible compared to the total heat transfer surface area of the test house.

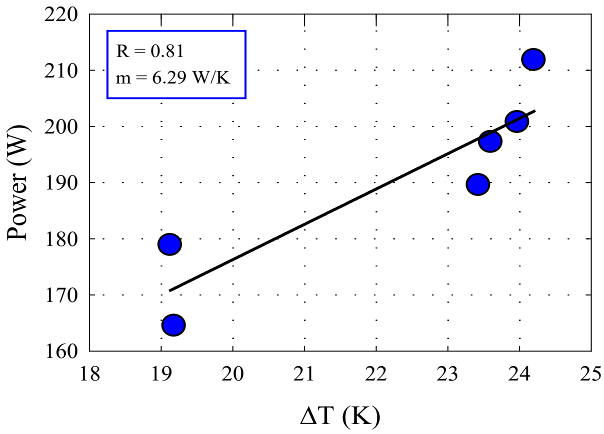

Figure 15. Co-heating test for the test bedroom through regression analysis at the post-retrofitting

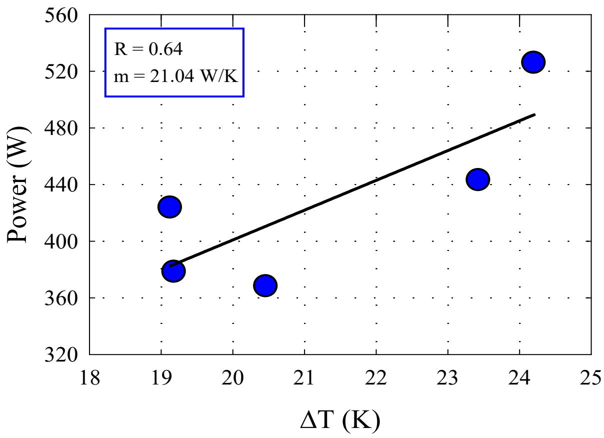

Figure 16. Co-heating test for the back bedroom through regression analysis at the post-retrofitting

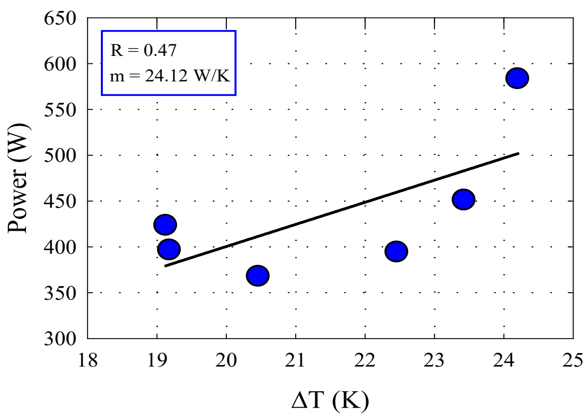

Figure 17. Co-heating test for the dining room through regression analysis at the post-retrofitting

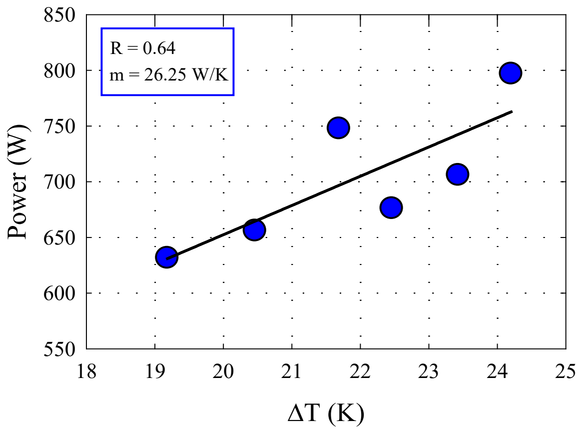

Figure 18. Co-heating test for the front bedroom through regression analysis at the post-retrofitting

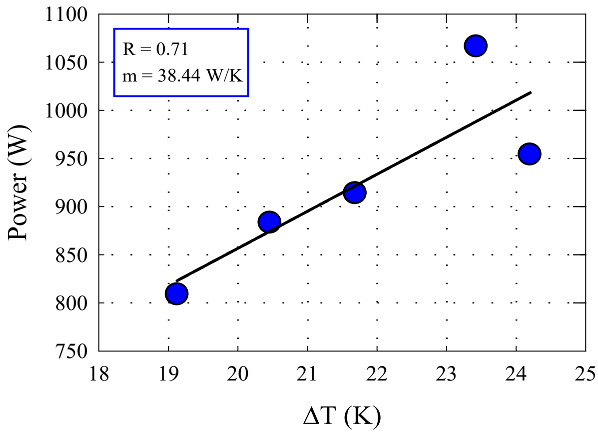

Figure 19. Co-heating test for the hall through regression analysis at the post-retrofitting

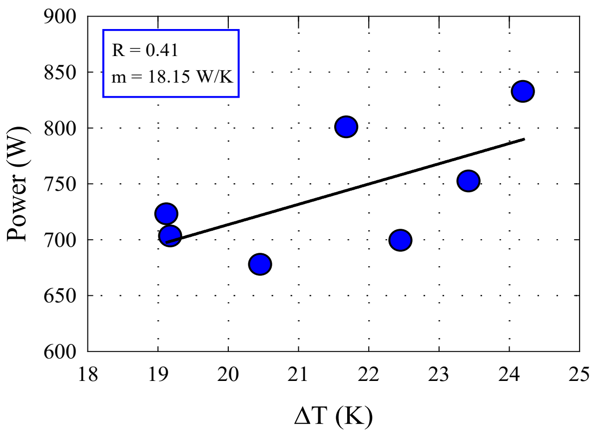

Figure 20. Co-heating test for the kitchen through regression analysis at the post-retrofitting

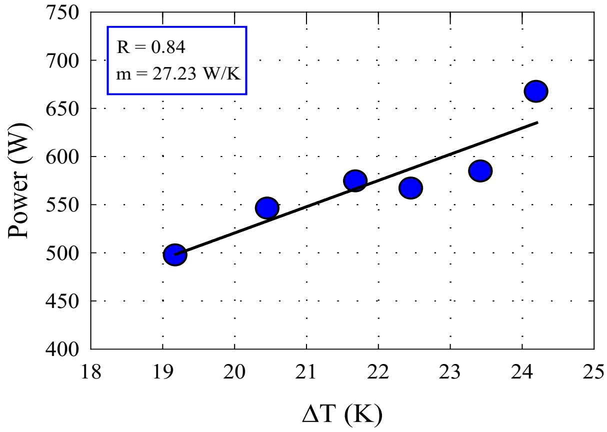

Figure 21. Co-heating test for the lounge through regression analysis at the post-retrofitting

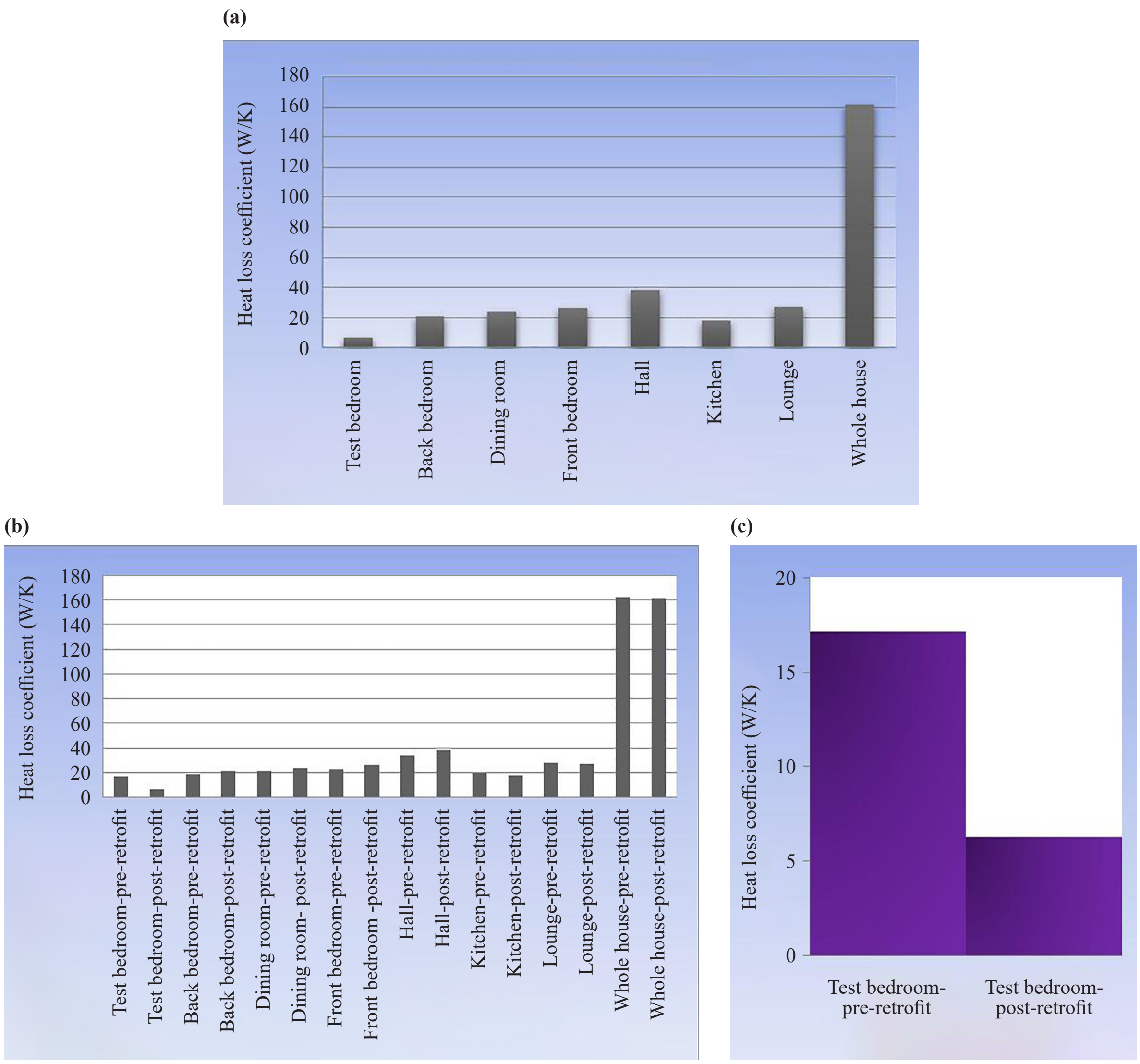

Figure 22. a) Co-heating test for the whole house at the post-retrofitting, b) Comparison of the co-heating test results at the pre and post-retrofitting, c) Heat loss coefficient of test bedroom at the pre and post-retrofit

Figure 22 (c) illustrates the decrease in HLC of the test bedroom after reinforcement. Before internal aerogel insulation, the HLC of the test bedroom is 17.15 W/K, while it is 6.29 W/K in the post-retrofit case. In this respect, energy loss is mitigated by about 63% via only 20 mm thick thermal superinsulation.

3.3 *Thermal imaging results*

Thermal imaging tests are taken when the internal temperature is raised to 35 °C to be able to get the most extraordinary clarity. The first thermal image is to demonstrate the non-uniform cavity insulation. As is clearly seen from Figure 23 (a) there is a great deal of non-uniformity in the cavity insulation, which leads to cold spots on the internal wall surfaces. The images also illustrate the areas of reduced temperature due to the thermal bridging elements and high surface thermal resistances of the wall corners.

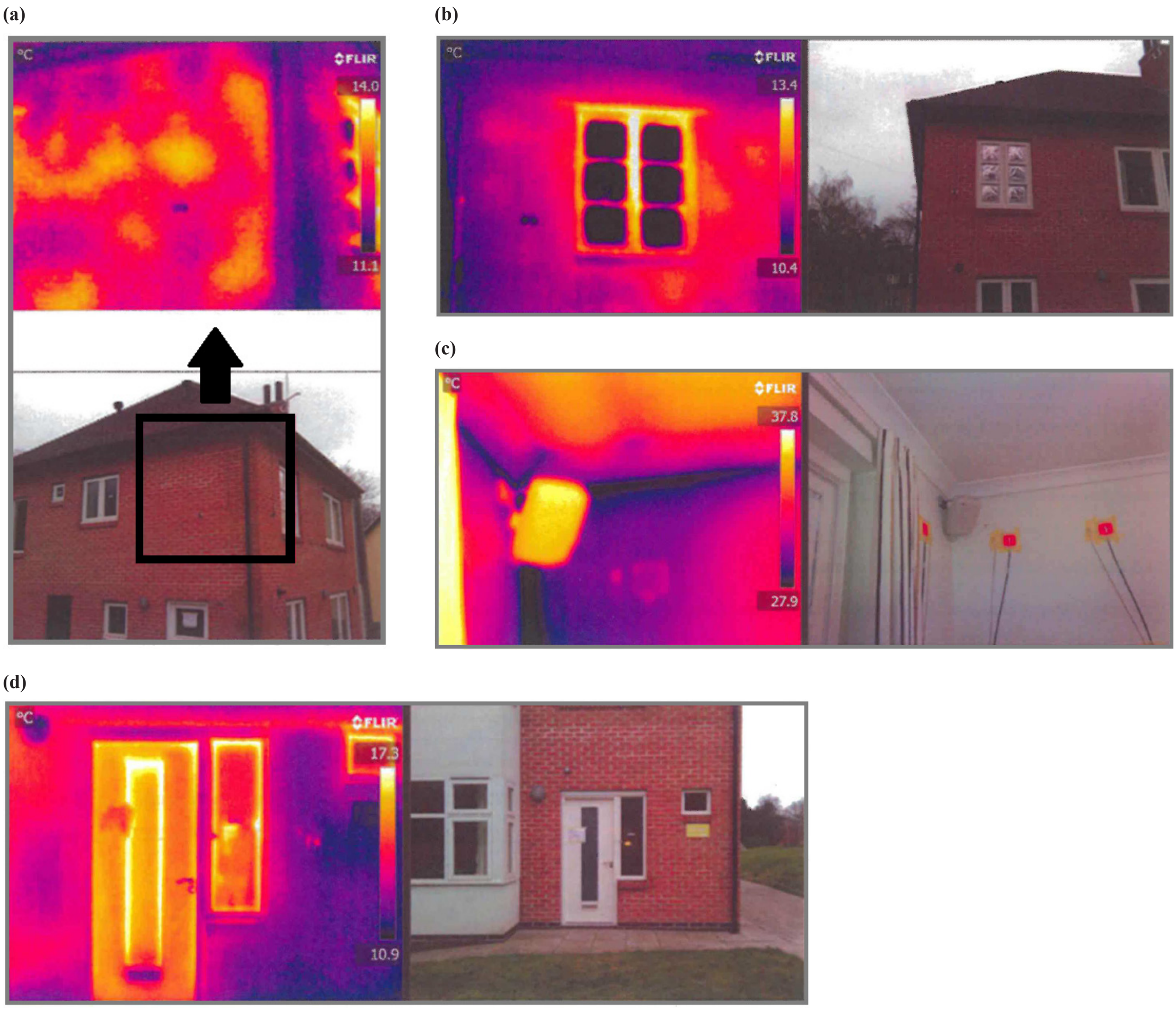

Figure 23. a) Thermal image of west wall, b) Thermal image of south wall, and the window covered with reflective coil, c) Thermal image of the west-south wall ceiling junction, d) Thermal image of the front door and side window panel

The thermal image for the south-facing wall also shows the non-uniform nature of the cavity wall insulation. In the tests, window glass surfaces are covered with reflective coil as illustrated in Figure 23 (b). The soil reflects the atmospheric reflection temperature due to its low emissivity and high reflectance. The areas of the south-facing wall excluding the window are shown in the image to have a minimum temperature of 10.7 °C and a maximum of 12.4 °C.

During the thermal imaging test, the outside ambient temperature is approximately 11 °C to 12 °C. The effect of solar intensity on the wall fabric is insignificant. The wind speed is around 2 m/s, and the relative humidity is approximately 90%.

Figure 23 (a) reports a minimum temperature of 11.4 °C on the west wall and a maximum of 13.3 °C. At first glance, the temperature difference of 2.1 °C may not appear significant. However, this difference accounts for about 10% of the internal and external temperature difference (24 °C), which is not negligible.

Figure 23 (c) clearly indicates the effects of surface resistance at the wall corner junction on the temperature distribution. Due to higher thermal resistance around the corner, a remarkable temperature difference occurs between the junction and the plane area of the wall. Through the thermal image, the maximum temperature is reported as 31.7 °C at the plane area, and the minimum is 27.0 °C at the junction. The reason for the more excellent surface resistance near the corner junction is the effectively trapped air around the corner. The trapped air behaves as a good insulator, and as a consequence of this, less heat from the room air transfers to this area. Therefore, the corner region becomes notably cooler than the plane area.

Figure 23 (d) illustrates the thermal imaging of the front door and the side panel. Most of the door is constructed from timber; hence, the temperature distribution for the front door will be broadly correct. However, it is challenging to say the same things for the window panel since the thermal imaging for that will be a combination of the surface temperature and that of the infrared reflections from the surroundings. Despite this, the thermal imaging results are verifiable. For instance, the temperature of the glass surface in the side panel is approximately 13.8 °C, which is also reported by the thermocouple reading.

The aerogel thermal superinsulation material is a costly reinforcement process. However, there is a consensus that conventional materials may not meet the requirements of 2030-2050s homes because of their poor thermal conductivity range. Therefore, the thermal conductivity of the materials corresponding to these costs should be below 0.01 W/mK, which is the point of the thermal superinsulation materials range. In the future, the increased use of more resistant thermal superinsulation materials will become a necessity rather than a choice, despite the high cost. Its high cost can only be reduced by the increase in usage, that is, by commercialisation. Even if not used purely, hybrid applications can be used with conventional materials.

4. Conclusion

In the present work, the thermal behaviour of a traditional house from the 1930s in the UK is investigated through a co-heating test methodology. One rule in the test house is selected for aerogel-based thermal superinsulation, and the said test room has been reinforced with 20 mm thick of aerogel blanket. HLC and U-value at pre and post-retrofitting of the building are evaluated in detail. Glazed areas of the whole house have also been assessed in terms of thermal insulation performance. The outputs of this research are represented as follows:

• HLC of the whole house is mitigated from 162.02 to 161.52 W/K since the insulated area constitutes a small part of the whole house.

• Whilst the HLC of the test bedroom is 17.15 W/K at pre-retrofit, it is reduced to 6.29 W/K at post-retrofit.

• Therefore, the decrease in energy loss through the test bedroom is calculated proportionally as around 63% with the help of using 20 mm-thick aerogel thermal superinsulation.

• In the study of Lambie and Saelens [28], a reduction of 63% takes place in the U value of 8 cm thick PUR used after reinforcement for the floor above the cellar, whilst a 63% mitigation is observed in this study with a similar rate. The point to be noted here is that while 8 cm thickness is used for reinforcement in one study, 2 cm thickness is used in this study thanks to using aerogel. This yields to slimmer and more aesthetic internal details in the built environment.

• Hence, a more effective resistance field can be created with a smaller thickness with the use of aerogel thermal superinsulation material compared to conventional materials.

• According to the test results, the maximum temperature is seen at the plane field wall of the connection point with 31.7 °C whereas the minimum one is observed at the junction with 27.0 °C.

- The minimum heat loss is viewed in the test bedroom with an overall heat loss coefficient of practically 17 W/K.
- Aerogel can play a crucial aid in overcoming thermal bridging in buildings.

Conflict of interest

The authors declare no competing financial interest.

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