energies

MDPI

Article

Seasonal Solar Thermal Energy Sand-Bed Storage in a Region with Extended Freezing Periods: Part I Experimental Investigation

Getu Hailu [1,*], Philip Hayes [1] and Mark Masteller [2]

1 Department of Mechanical Engineering, University of Alaska Anchorage, 3211 Providence Drive, ECB 301K, Anchorage, AK 99508, USA; pmhayes@alaska.edu
2 Bristol Bay Campus, University of Alaska Fairbanks, P.O. Box 1070, Dillingham, AK 99576, USA; mamasteller@alaska.edu
* Correspondence: ghailu@alaska.edu

Received: 22 October 2017; Accepted: 10 November 2017; Published: 15 November 2017

Abstract: We present the first experimental study of sand-bed thermal energy storage conducted in a region with extended freezing period. The study was carried out on a home situated in Palmer, Alaska, 61.6° N, and 149.1° W. The home is equipped with evacuated tube solar thermal collectors that are connected to a seasonal sand-bed solar thermal energy storage system. Fourteen weeks of data was collected from a period of 28 January 2017 through 7 May 2017. Results suggest that seasonal sand-bed solar thermal storage systems are an excellent option for storing heat for climates in regions with long periods of freezing temperatures. The present study shows a proof of concept of a sand-bed seasonal solar thermal storage that needs additional controls for residential heating application. The system could also be used to provide heat for unoccupied spaces such as garages and greenhouses.

Keywords: thermal energy storage; sand-bed; cold region; solar energy

---

1. Introduction

Energy demand and usage is expected to change significantly as a result of changing weather patterns, affecting heating/cooling and electricity demands. In the U.S., the buildings sector accounts for 41% of the primary energy use [1], hence it is very likely that this sector will be highly impacted by climate change and associated weather patterns. In cold regions like Alaska, sea level rise, permafrost melting, intense and more frequent extreme weather events, increased wind speeds and ocean storms will all negatively impact energy infrastructure, in the form of reduced efficiency of thermal plants, cooling constraints on thermal plants, and increased stress on transmission and distribution systems. Electricity generation from hydro, wind and other renewable and biofuel production will also be affected. For example, according to International Energy Agency (IEA) estimates, 1 °C of temperature warming will reduce the available summer electricity generation capacity up to 16% by the 2040s in the United States alone [2].

Distributed energy generation through renewable energy (RE) sources provide growing price competitiveness, long-term certainty and energy security [3]. RE sources are local thus providing security of supply, helping a nation reduce its dependence on imported sources. Renewable Energy Systems-based technologies have the potential to mitigate the effects of climate change through the use of energy storage, and distributed and dispersed energy generation. RE systems for space heating/cooling, such as photovoltaic-thermal (PVT) systems, building integrated photovoltaics/thermal (BIPV/T) systems, seasonal thermal storage systems (STSS) and heat pumps are very attractive and have great potential to mitigate impacts associated with changing weather patterns to a great extent and make substantial contributions towards GHG emission reduction [4].

In the building sector, solar energy has been used for space heating/cooling and electricity production. As solar energy is intermittent and there is a mismatch between the supply and demand periods there is a need for heat storage so that the excess heat produced during the peak soar irradiation can be stored for use during peak demand periods. Sensible heat storage, which is achieved by changing the temperature of the storage material without changing its phase, is one of the most widely used techniques for thermal energy storage methods. It is simple and least expensive [5,6]. Another attractive feature of sensible heat storage systems is that charging and discharging operations can be completely reversible for unlimited number of cycles, i.e., over the life span of the storage [7]. In addition, the use of simple materials such as rocks, which are readily available in many areas (including remote areas), makes sensible heat storage long-lasting, safe and relatively easy to install.

Because of their applicability in residential, industrial and commercial settings, sensible heat storage systems have been studied extensively. A review paper by Pinel et al. [6] indicates that large-scale seasonal storage systems have been constructed in Switzerland, Denmark, Finland, France, The Netherlands, the United States, Turkey, Korea, Germany and Canada.

American Society for Heating Refrigerating and Air-conditioning Engineers (ASHRAE) provides guidance on solar thermal designs indicating that each system must be individually engineered. One important item of note is that ASHRAE Applications Handbook cautions engineers that an active solar thermal system is not suitable in climates with long periods of freezing temperatures [8].

Thermal energy storage systems have been utilized in normally unoccupied buildings and power plants. One example demonstrated by M.K. Ghosal et al. [9] is a greenhouse where it was shown that solar thermal energy storage systems outperform utilizing the near constant temperature of the ground for heating applications. Concentrated Solar Power (CSPT) thermal storage has also shown great promise in offsetting the diurnal nature of solar availability. Bruch et al. [10] showed that a rock-bed filled with high-temperature oil could be used to store a large amount of heat for CSP plants.

D. Phueakphum and K. Fuenkajorn 2010 [11] reported that a passive system was designed for a rural Thailand application. The system uses an opaque surface to allow heating of a rock bed and air naturally transfers heat to the living space through convection. While the system achieved the goal of adding heat to the space during cold evenings, it did increase the interior temperature to near 35 °C during the day, which is beyond the comfort level.

An active solar thermal residential design simulation was conducted by Sweet and McLeskey [12], which showed a significant reduction in fossil fuel consumption for a single residence dwelling in Richmond, Virginia. Sweet and McLeskey simulated flat plate solar collectors by varying the home size as well as the sand-bed size. The sand-bed thermal storage took almost five years to reach a seasonal equilibrium and become “fully charged”. Their research also showed that an improperly sized thermal storage system could lead to negligible heating results. Too small of a storage system would not effectively store enough heat for seasonal use, and too large of a storage system would never obtain a warm enough sensible heating temperature.

The use of local available storage materials such as gravel or silica sand is a key for cost effectiveness [13]. One of the primary advantages of dry sand-bed thermal storage systems is their ability to reach high temperatures and therefore provide a higher energy quality, which is important for commercial systems. Sand-beds can also be easily integrated into the design of the structure or facilities siting, for example, the foundation or parking lot. L.T. Terziotte et al. [14] modeled a thermal energy storage system utilizing a sand-bed for a large university complex for the Virginia Commonwealth University, a relatively warm climate compared to Alaska, and predicted as much as 91% of heating needs could be provided by the thermal storage system.

Literature review shows that there is a significant gap in research for solar thermal energy storage systems for residential applications in regions with extended periods of freezing temperature like Alaska. This study is conducted on the premise that sand-bed seasonal solar thermal energy systems are a feasible means to effectively reduce the space heating costs of a residential home in cold regions like Alaska. This paper reports results experimental study of sand-bed seasonal thermal energy storage conducted on a residential home in Palmer, Alaska.

2. Experimental Home Description

A two-story house located in Palmer, Alaska was used for this experiment. The lower floor of the house consists of a normally unoccupied garage and storage space with the upper floor consisting of 54 m^2 (581 ft^2) living space. The home is designed to be Net Zero Energy home, where electricity is fed to the utility grid during high solar production months and supplied from the utility grid during low solar production month. High efficiency, non-traditional construction techniques were used for the construction of the home. The walls are designed as arctic walls [15] where there is no direct thermal path from the interior side of the wall to the exterior wall, and insulated with densely packed cellulose with permeable membranes in lieu of a traditional vapor barrier. The home is placed with each face pointed in a true cardinal direction with the solar PV panels and solar thermal arrays on the south side (Figure 1). The walls and roof are insulated with densely packed cellulose giving an aggregated thermal resistance of RSI-10.6 (US R-60) for the wall and RSI-15.9 (US R-90) for the roof.

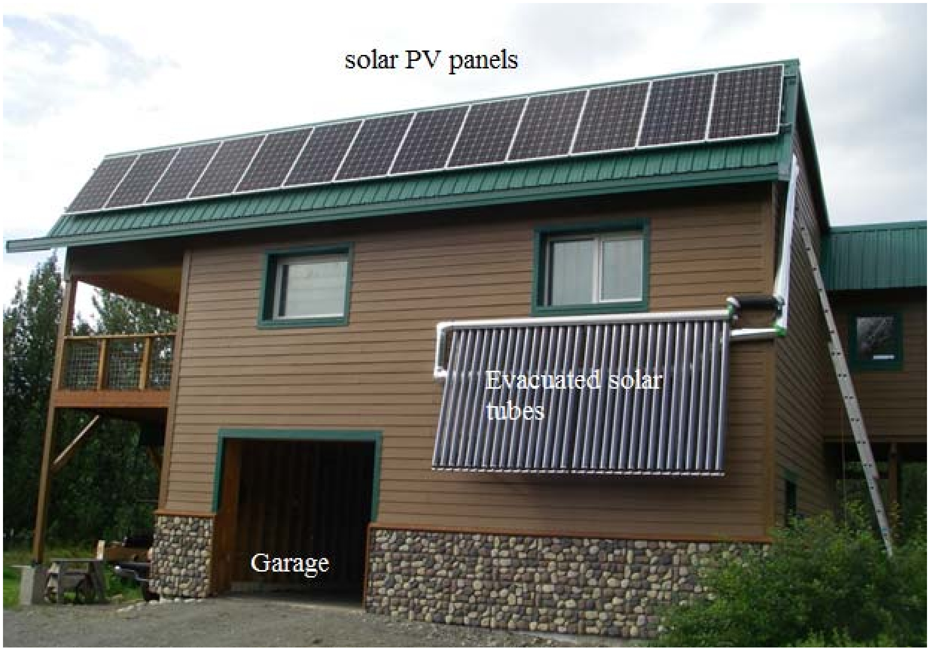

Figure 1. The experimental home in Palmer, Alaska.

The lower floor is composed of the garage and storage space with the sand-bed thermal energy storage underneath. Floor trusses between the garage and living space are also intended to be insulated at a later date to reduce the thermal link between the living space and garage.

The Solar PV panels (SolarWorld, Sunmodule Plus SW 285-290, Hillsboro, OR, USA) are 285-watt panels in an array of 13 panels with a combined rated power of 3.705 kW mounted at a 60° angle on the roof. Solar PV panels feed into a power inverter (a SolarEdge SE5000A-US (5000 watt capacity)) and then onto the two-way meter connecting to Matanuska Electric Association, Inc. (MEA) power grid located in Eagle River, AK, USA. Evacuated solar tubes (Sunda Solar, Beijing, China, part Sunda Seido 5-16) with two collector arrays are placed in series at a tilt angle of 75° on the southern wall. The test data from Solartechnik [16] shows a rated efficiency curve based on a flowrate of 300 L/h and solar irradiance of 800 W/m^2, shown in Figure 2.

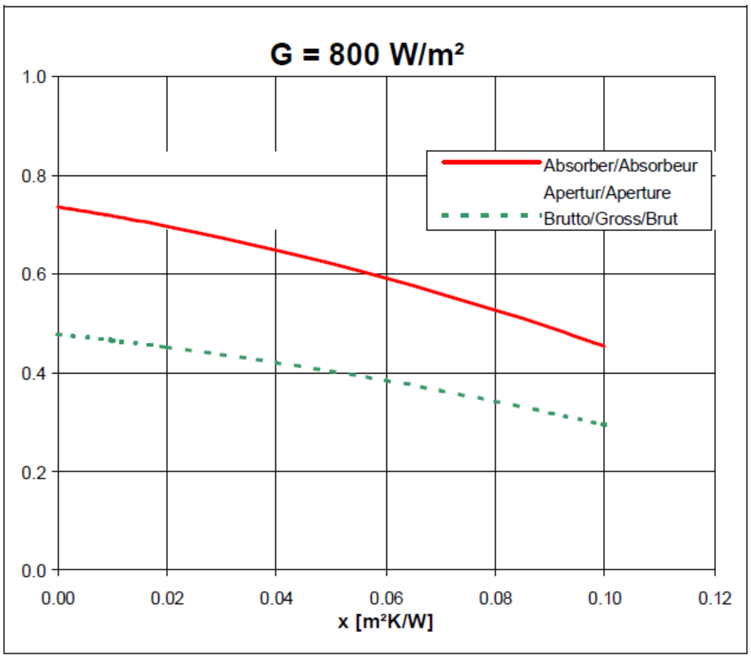

Figure 2. Sunda Seido 5-16 efficiency curve, image from Solartechnik [16].

The efficiency curves for the Sunda Seido 5-16 are shown in Equations (1)–(3).
Absorber:

$$\eta(x) = 0.736 - 1.78x - 0.0130Gx^2 \tag{1}$$

Gross:

$$\eta(x) = 0.478 - 1.16x - 0.0084Gx^2 \tag{2}$$

$$x = \frac{T_m - T_{amb}}{G} \tag{3}$$

where

T_m—mean fluid temperature (K)
T_{amb}—ambient temperature (K)
η—efficiency
G—irradiance (W/m^2)

Solar collectors heat a water-glycol solution that, during normal operation, passes through a heat exchanger to heat the domestic hot water tank. When the domestic hot water tank is not calling for heat the excess heat is sent to the sand-bed under the garage floor for heating. A schematic of the evacuated tube solar collectors and the thermal storage is show in Figure 3. Figure 4 gives solar radiation for Anchorage, Alaska for the duration of the experiment.

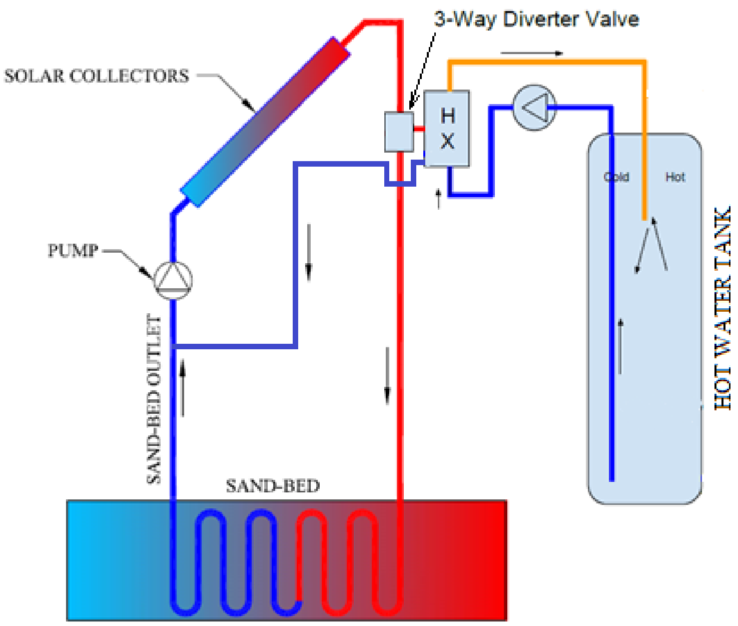

Figure 3. Schematic of the evacuated tube solar collectors and the thermal storage.

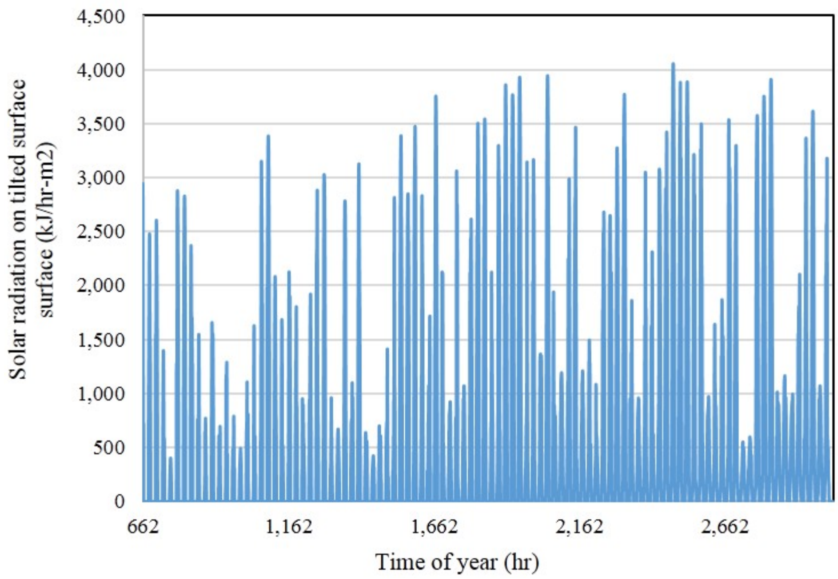

Figure 4. Solar radiation for Anchorage, Alaska for the duration of the experiment.

During this experiment the solar thermal controls were set to 100% heat demand to be sent to the sand-bed.

The garage floor consists of a 6.502 m (21′−4″) by 8.331 m (27′−4″), 10.2 cm (4″)-thick concrete slab, with one vehicle door and one man door as shown in Figure 5.

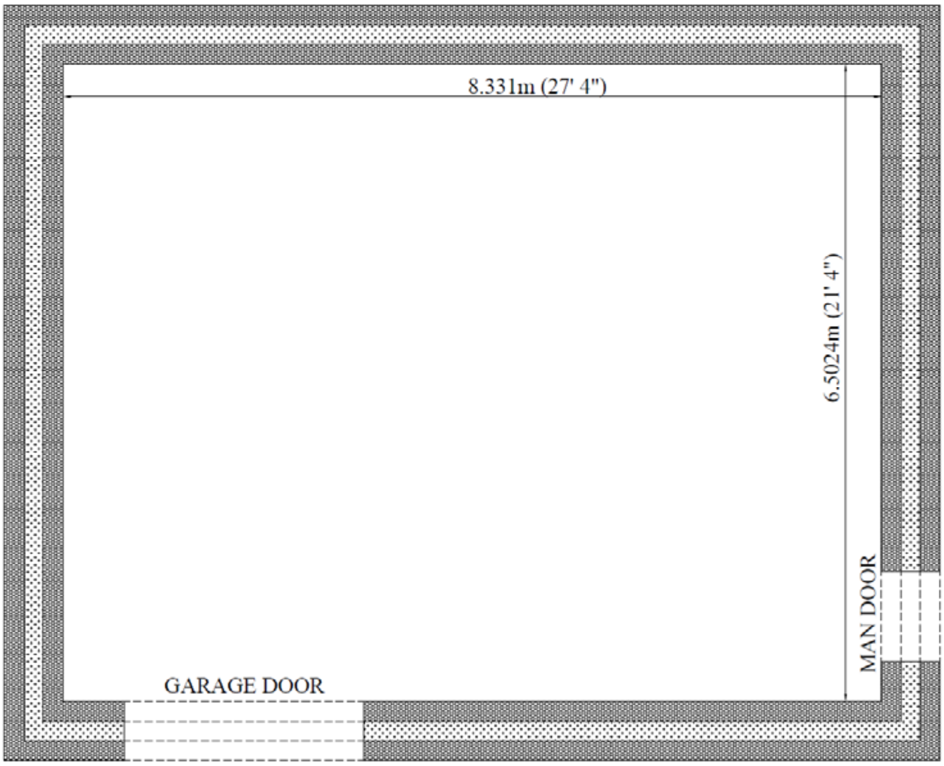

Figure 5. Lower floor layout of the home.

Underneath the concrete slab is the solar thermal storage, which contains 29.7 cm (11″) of fine sand and 38.1 cm (15″) of pit-run gravel as seen in Figure 6a.

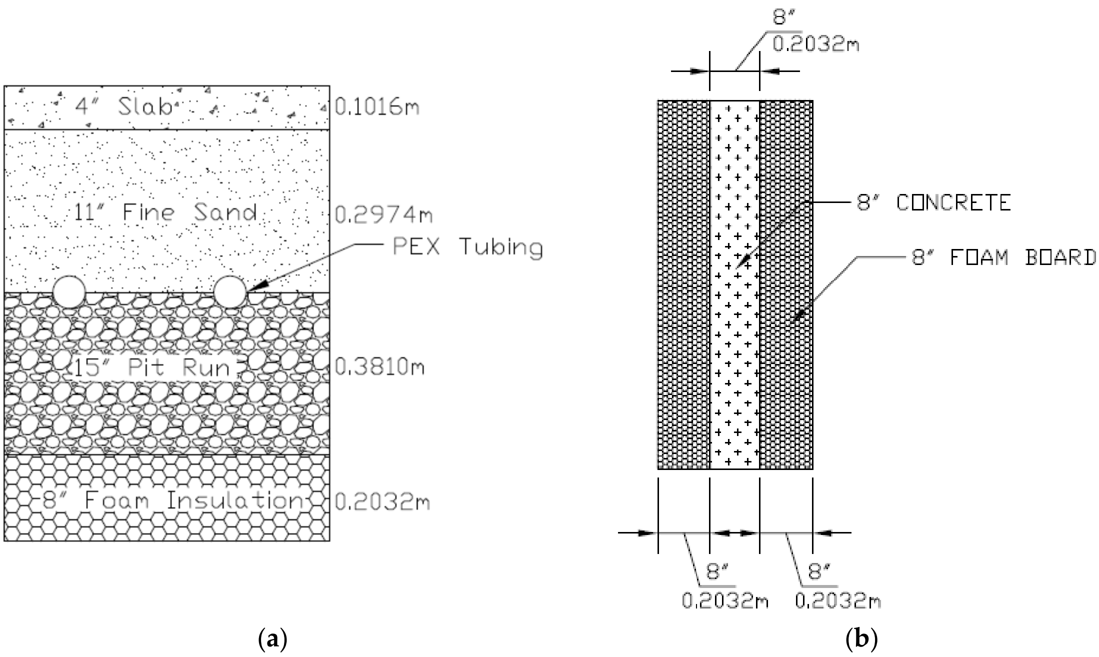

Figure 6. (**a**) Profile of solar thermal storage; (**b**) foundation wall cross-section.

Underneath the sand-bed is 20 cm (8″)-thick polystyrene foam resulting in a thermal resistance value of RSI-5.64 (US R-32) insulation barrier between the sand-bed and ground. The four sides of the sand-bed are insulated with 0.2 m (8″) of polystyrene foam board on both sides of a 0.2 m (8″) poured concrete foundation wall for a total of 0.4 m (16″) of insulating foam as shown in Figure 6b. A total of 91.4 m (300 ft) cross-linked polyethylene (PEX) tubing was installed in two loops in the sand-bed tubing as shown in Figure 7.

Figure 7. Cross-linked polyethylene (PEX) heat loop installation in progress.

3. Instrumentation and Data Collection

Temperature and flow rate data were collected from 28 January to 7 May 2017. Six Caleffi resistive temperature detectors (RTDs) (FKP6 pt1000 RTDs, Caleffi North America Inc., Milwaukee, WI, USA), were embedded in the sand-bed as shown in Figure 8. A Caleffi DL3 data logger was used to capture the temperature data from the RTDs in the sand-bed inlet and outlet. The same data logger was used to capture flow rate data that was measured using a Caleffi V40 rotary pulse flow meter. The pump when activated by the controller averaged 3.06 L/min flowrate, which converts to 186.6 kg/h of the glycol mixture through the sand-bed. Using a refractometer the glycol-water mixture was found to be 43% glycol by volume.

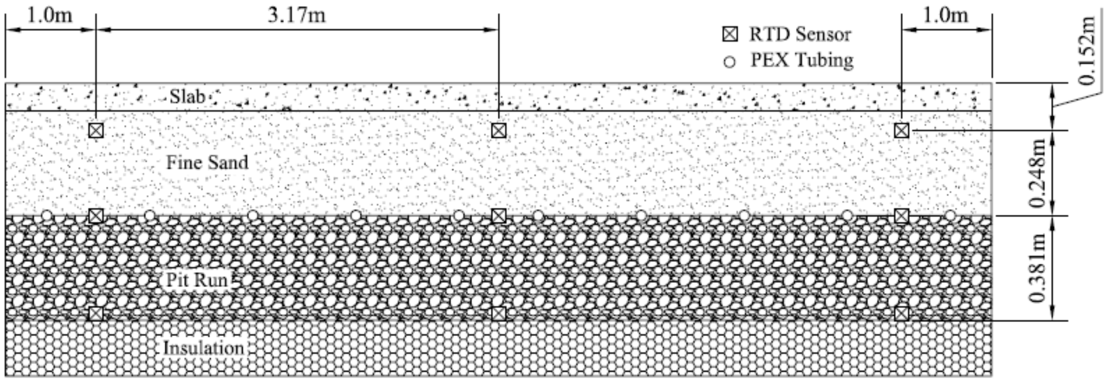

Figure 8. Resistive temperature detectors (RTD) locations in sand-bed.

In addition to RTDs, type K thermocouples (selected for their wide temperature range application) were used for this research (part number EXPP-K-24-100, Omega Engineering, Inc., Bridgeport, NJ, USA), with an accuracy of ±2.2 °C or 0.75%. These thermocouples were embedded in two places into the sand-bed and an additional four thermocouples were embedded into the surface of the garage floor, shown in Figure 9, to monitor the temperature profile of the sand-bed. Thermocouple temperatures were recorded using Lascar EL-USB-TC data loggers (Lascar Electronics Inc., Erie, PA, USA) with a resolution of 0.5 °C and an accuracy of ±1 °C. Outside and Garage ambient temperature were measured and recorded using Lascar EL-USB-2 data loggers with a resolution of 0.5 °C and an accuracy of ±0.55 °C. Both devices (EL-USB-TC and EL-USB-2) are designed to have the data-logging interval set by the user and read via USB connection by a PC using software provided by Lascar Electronics.

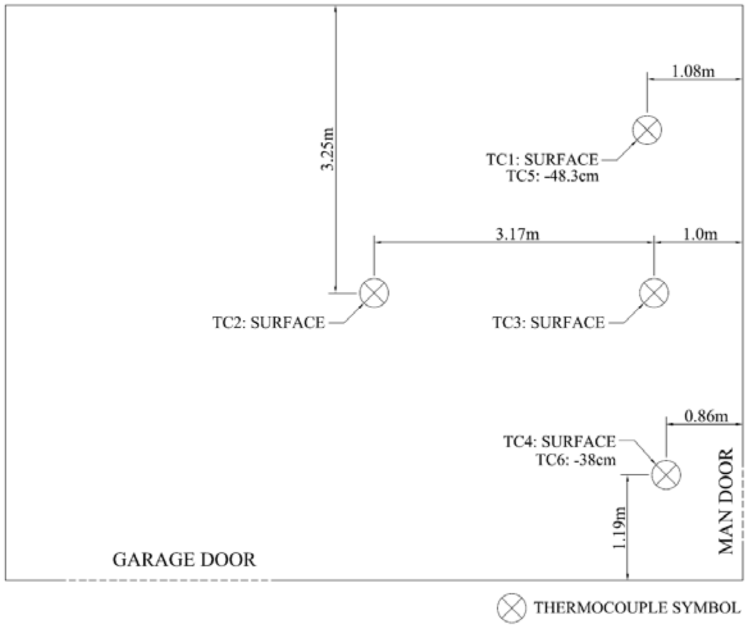

Figure 9. Thermocouple arrangement on sand-bed thermal storage.

Caleffi iSolar Plus solar thermal system controller was used to activate the pump and allow fluid flow from the solar thermal array to the sand-bed on a 5.778 °C (12 °F) temperature difference. The controller was configured for a single zone and all heat from the collector was sent to the sand-bed for the duration of this research.

4. Results and Discussion

Glycol mixture supply and return RTD sensor temperatures were recorded at one-minute intervals by the Caleffi DL3 with results shown in Figure 10. Periods of exceptionally high temperatures are observed prior to March when the pumps' speed controller was being periodically varied to establish a preferred flowrate. Note that the *x*-axis gives the date, month and year of measurement. Besides the initial period where the speed controller was adjusted and the time instance contained no data, the data follows an expected trend with daily high temperature representing the peak solar radiation and daily low periods representing no solar radiation, where the sensors approach ambient temperature.

Ambient conditions for the outside and garage were recorded every 15 min continuously for the 14-week period from 28 January through 7 May. Figure 11 shows both the ambient outside and garage temperatures plotted for the time period.

Figure 11 shows a clear upward trend of the garage ambient temperature even during a cold period in March, which indicates heat was being added to the garage to compensate for environmental heat losses. Average temperatures for the outside and garage over the 14-week period were −3.2 °C and 7.7 °C respectively.

Multiple points in the sand-bed were recorded every 15 min for the duration of the experiment. Figure 12 shows each sensor's recorded temperature.

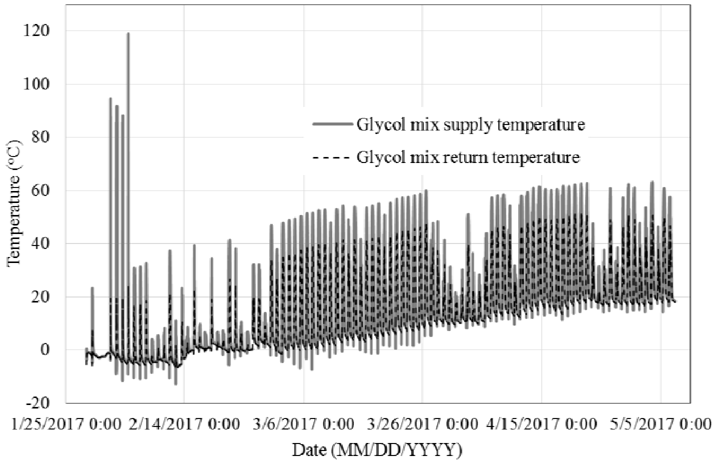

Figure 10. RTD measured glycol supply and return temperatures.

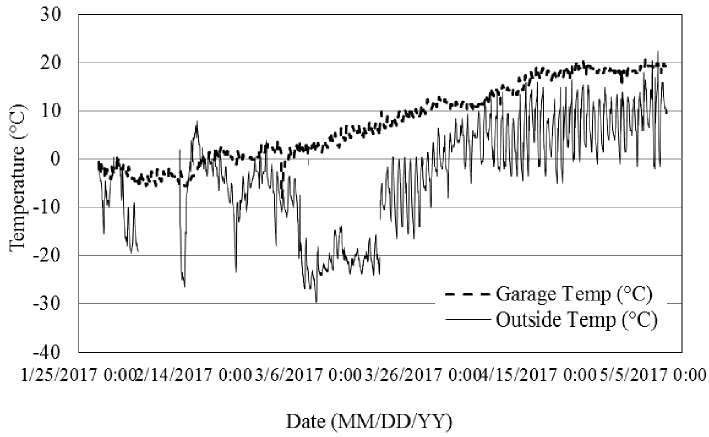

Figure 11. Ambient outside and garage temperature as measured.

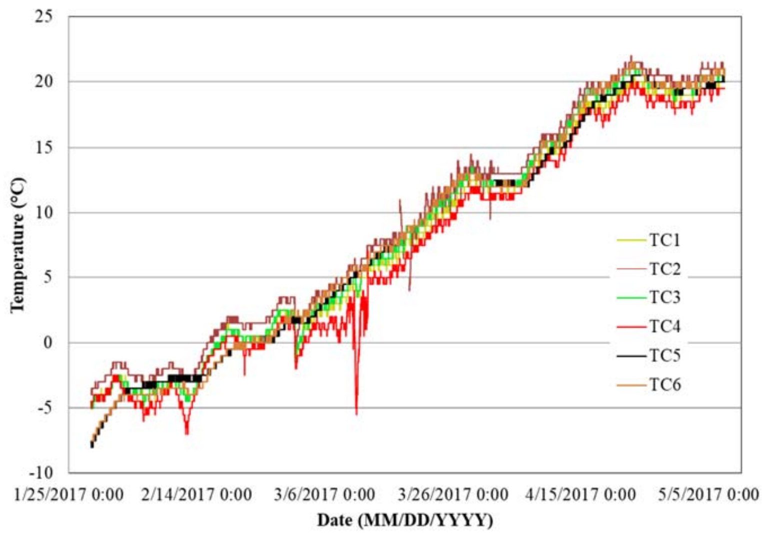

Figure 12. Temperature profile of each sand-bed measurement location.

Thermocouple number 6 (TC6) represents a temperature sensor placed nearest to the garage man door, which explains the greater temperature fluctuations on days where work was performed in the garage during cold days. The core temperature and surface temperature averages are shown in Figure 13. An increase in temperature is observed with little difference with the core and surface temperature.

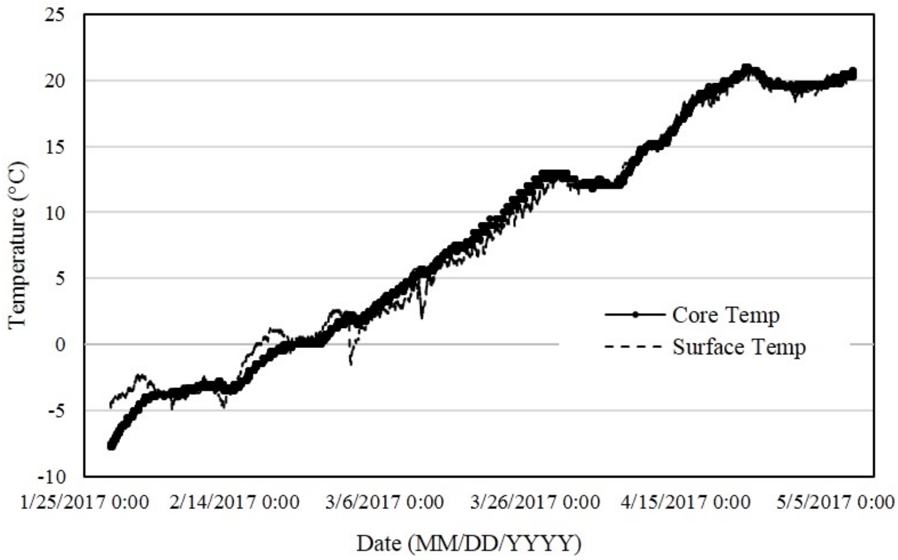

Figure 13. Average sand-bed core temperature and surface temperature.

Figure 14 compares the TRaNsient SYstem Simulation (TRNSYS) simulated temperature of the sand-bed to the measured one. The difference between the maximum measured and simulated temperatures was found to be 15%, while the difference between the average measured and simulated temperatures was 4.7%.

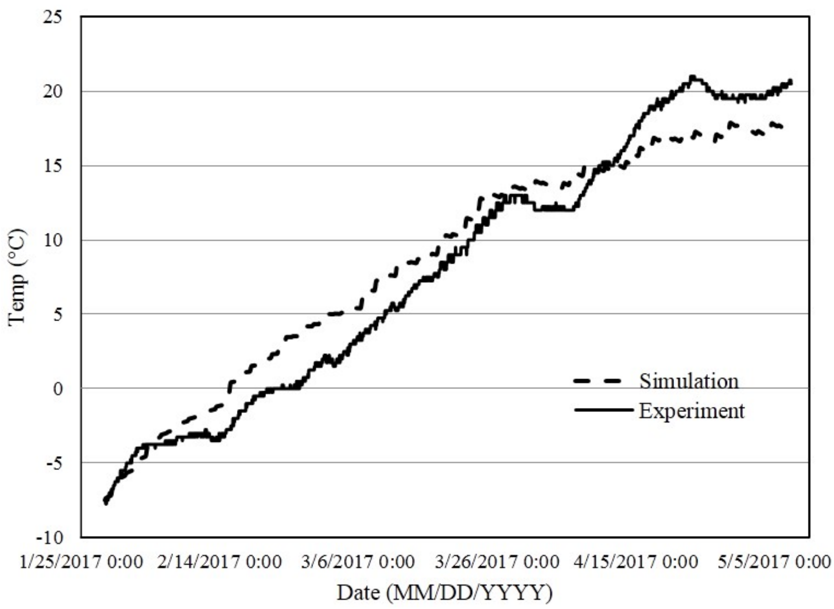

Figure 14. Simulated sand-bed temperature over time.

The sand-bed simulated temperature profile shows less fluctuation than the observed temperature profile, which is likely due to the experimental system being thermally coupled to the garage. The upward trend of the measured temperature compared to the simulated temperature in April thru

May was due to the warmer than average weather experienced in Palmer, Alaska compared to the simulated TMY2 data for Anchorage, Alaska.

5. Conclusions

We presented the first experimental study of sand-bed thermal storage conducted in a region with extended freezing periods. A two-story house located in Palmer, Alaska, 61.6° N, and 149.1° W was built with sand-bed thermal energy storage. The home is equipped with evacuated tube solar thermal collectors, which provided the thermal energy to the sand-bed. A normally unoccupied garage, 6.502 m (21′−4″) by 8.331 m (27′−4″), 10.2 cm (4″) floor was composed of a 10.2 cm (4″)-thick concrete slab, 29.7 cm (11″)-thick fine sand and 38.1 cm (15″) of pit-run gravel. This structure was used as a thermal storage. Fourteen weeks of data were collected from the solar thermal energy sand-bed storage system. TRNSYS simulated temperature of the sand-bed temperature compared very well to the measured one. The difference between the maximum measured and simulated temperatures was found to be 15%, while the difference between the average measured and simulated temperatures was 4.7%. The measured garage and sand-bed temperatures suggest that such types of solar thermal storage systems are viable options for climates in regions with long periods of freezing temperatures despite ASHRAE recommendations [8]. In subsequent papers, we present detailed energy analysis and 5-year simulation results. Monitoring work will continue for several years.

Acknowledgments: The authors would like to thank the ASME Alaska chapter whose funding made this research possible. Their generous donation purchased almost all the sensors and data logging equipment necessary to complete the research.

Author Contributions: Getu Hailu: Thesis Supervisor, paper writing; Philip Hayes; MASc student, all the Thesis work, Mark Masteller: Complete experimental home design and construction.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. National Science and Technology Council Subcommittee on Building Technology. Available online: http://www.bfrl.nist.gov/ (accessed on 21 June 2017).
2. International Energy Agency (IEA). Report on World Energy Outlook. Available online: www.worldenergyoutlook.org/energyclimatemap (accessed on 21 June 2017).
3. Philibert, C. Three Reasons Why Renewable Energy Is So Important to the Power Industry. Available online: http://www.gepowerconversion.com/inspire/three-reasons-why-renewable-energy-so-important-power-industry#sthash.xVoDxO9M.dpuf (accessed on 23 June 2017).
4. Edenhofer, O.; Madruga, R.P.; Sokona, Y. Renewable Energy Sources and Climate Change Mitigation (Special Report of the Intergovernmental Panel on Climate Change). *Clim. Policy* **2012**, *6*. [CrossRef]
5. Tatsidjodoung, P.; Le Pierres, N.; Luo, L. A review of potential materials for thermal energy storage in building applications. *Renew. Sustain. Energy Rev.* **2013**, *18*, 327–349. [CrossRef]
6. Garg, H.P.; Mullick, S.C.; Bhargava, V.K. *Solar Thermal Energy Storage*; Springer: Dordrecht, The Netherlands, 1985; pp. 82–153. ISBN 978-94-009-5301-7.
7. Pinel, P.; Cruickshank, C.A.; Beausoleil-Morrison, I.; Wills, A. A review of available methods for seasonal storage of solar thermal energy in residential applications. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3341–3359. [CrossRef]
8. HVAC Applications. In *ASHRAE Handbook*; 33.16, 33.18; ASHRAE: Atlanta, GA, USA, 2003.
9. Ghosal, M.K.; Tiwari, G.N.; Das, D.K.; Pandy, K.P. Modeling and comparative thermal performance of ground air collector and earth air heat exchanger for heating of greenhouse. *Energy Build.* **2005**, *37*, 613–621. [CrossRef]
10. Bruch, A.; Fourmigue, J.F.; Couturier, R. Experimental and numerical investigation of a pilot-scale thermal oil packed bed thermal storage system for CSP power plant. *Sol. Energy* **2014**, *105*, 116–125. [CrossRef]
11. Phueakphum, D.; Fuenkajorn, K. A rock fills based solar thermal energy storage system for housing. *ScienceAsia* **2010**, *36*, 237–243. [CrossRef]

12. Sweet, M.; McLeskey, J., Jr. Numerical simulation of underground Seasonal Solar Thermal Energy Storage (SSTES) for a single family dwelling using TRNSYS. *Sol. Energy* **2012**, *86*, 289–300. [CrossRef]
13. Schlipf, D.; Schicktanz, P.; Maier, H.; Schneider, G. Using sand and other small grained materials as heat storage medium in a packed bed HTTESS. *Energy Procedia* **2015**, *69*, 1029–1038. [CrossRef]
14. Terziotti, L.T.; Sweet, M.L.; McLeskey, J.T., Jr. Modeling seasonal solar thermal energy storage in a large urban residential building using TRNSYS 16. *Energy Build.* **2012**, *45*, 28–31. [CrossRef]
15. Grunau, B. *Arctic Wall Performance: A Super-Insulated Vapor-Permeable Wall Design in Interior Alaska*; Cold Climate Housing and Research Center: Fairbanks, AK, USA, 2013.
16. Collector Test No. C196. Available online: http://www.sundasolar.com/images/test%20report/SEIDO5-16_SPF%20Test%20report.pdf (accessed on 23 June 2017).