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Thermal energy storage with super insulating materials: a parametrical analysis

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Abstract

The adoption of super-insulating materials could dramatically reduce the energy losses in thermal energy storage (TES). In this paper, these materials were tested and compared with the traditional materials adopted in TES. The reduction of system performance caused by thermal bridging effect was considered using FEM analysis. Afterwards, parametrical analysis of the most influencing variables that affect super insulated TES tanks was carried out, to investigate effective benefits and drawbacks due to the adoption of these materials. Possible future applications and outlooks were discussed.

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Keywords: Thermal Energy Storage; Storage net volume; Super Insulation Material; Vacuum Insulation Panel; Aerogel Based Products.

1. Introduction

Over the last few decades, Thermal Energy Storage (TES) has played an important role in the reduction of the energy consumption and CO_2 emissions of the conventional energy systems. The research in this field is also rising because of the need to increase the percentage of renewable energy technologies use and mainly the solar thermal energy [1]. The need of TES is arising from the mismatch of the energy production and the energy demand. The stored energy is used to cover this mismatch.

In the literature, the following three types of TES are mainly studied:

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- Sensible heat storage, where the heat is stored by increasing the storage temperature;
- Latent heat storage, where the energy is stored by the phase change of the medium, from solid to liquid or liquid to gas. Phase Change Materials (PCMs) are mostly used as storage medium in latent heat storage systems [2,3]
- Thermochemical storage, where the energy storage is connected to thermochemical reactions [4].

The sensible heat storage is a conventional technology for domestic use, while the latent heat storage with Phase Change Materials (PCMs) is becoming a wide studied technology during the last few years. TES systems are used mainly for short-term storage, such as domestic hot water storage and HVAC systems [5]. However, thermal storage can be also used for long-term storage. Storage tanks used in buildings have also various sizes. There are small and medium sized storage tanks, which are used mostly for short term storage, and large for long term storage.

A significant aspect in TES systems - especially for the small and medium sized storage tanks - is the insulation of the storage tanks. Generally, the storage tanks are insulated by conventional building insulation materials such as polyurethane foam, mineral wool, etc. The insulation reduces the heat losses from the tank. However, it is difficult to get high insulation factor using the conventional materials due to their high thermal conductivity and insulation thickness in comparison with the limited diameter of the tank. Therefore, advanced insulation materials are a promising insulation technology for the storage tanks. The Super Insulating Materials (SIMs), such as Vacuum Insulation Panels (VIPs) and Aerogel Based Products (ABPs), [6], have a 5 - 10 times lower thermal conductivity compared to the traditional insulating materials. [7,8,9]. This makes these materials suitable also for the insulation of the TES. With the use of the advanced insulation materials, the insulation thickness can be dramatically reduced in comparison with the conventional materials. Recent studies on the possible application of VIPs in thermal energy storage were carried out by Fuchs et al. [10,11].

Taking into consideration the operating conditions of TES, the maximum of their effectiveness is a balance between its cost and practicality. On the one hand, SIMs, such as VIP and ABP, provide the lowest thermal conductivity and hence the highest performance of TES. On the other hand, VIP and ABP are the most expensive insulating materials and they have some drawbacks. The main drawbacks of the VIPs are limited range of sizes, restricted flexibility, vacuum degradation, risk of damage and thermal bridge effects [12,13]. In turn, ABP loses its properties when moistened and must be protected by a waterproof envelope. Nevertheless, there are several areas where application of SIMs promises to be the most beneficial. The SIMs are apparent choice for the cases when inner volume of isolable compartment, mass and dimensions characteristics of TES are the main values for consumer. Application of this technology can also be found in sectors different than buildings, such as the vehicle sector, where high performance TESs are required [14].

In this paper a critical analysis of the possible applications of SIMs in TES was carried out. The thermal conductivity of both traditional insulating materials and SIMs applied in TES was experimentally measured and compared. The VIP thermal bridge effect was simulated using a numerical energy balance method to obtain the equivalent thermal conductivity of the insulating layer. Furthermore, a traditional cylindrical TES was taken into account, using parametrical dimensional values. The critical diameter of insulation was calculated and parametrical analysis was carried out to evaluate the possible advantages/disadvantages due to the VIP adoption in TES.

2. Methodology

2.1. Thermal conductivity measurement of different insulating materials

Expanded polystyrene (EPS), mineral wool and polyurethane foam (PU) represent the most common materials that are used in TES, while Vacuum Insulation Panels and Aerogel Based Products are innovative Super Insulating Materials (SIMs). Experimental measurements were performed on each of these materials to directly estimate their thermal conductivity. A single sample guarded heat flow meter device (Lasercomp FOX600) was used, according to UNI - EN 12667 (2001) international standard [15]. The instrument was designed and realized in accordance with ASTMC518-91 Standard [16] and was calibrated with calibration reference samples “1450b NIST SRM” and EPS sample (high accuracy expanded polystyrene). To avoid the moisture influence all the samples were dried up to constant mass in a ventilated oven for 48 h and 60 °C (except for VIP). Moreover, in order to minimize the measurement uncertainty for heat fluxes and temperature-difference, the tests were carried out with a mean temperature of 25°C and a temperature difference between the plates about 20 °C.

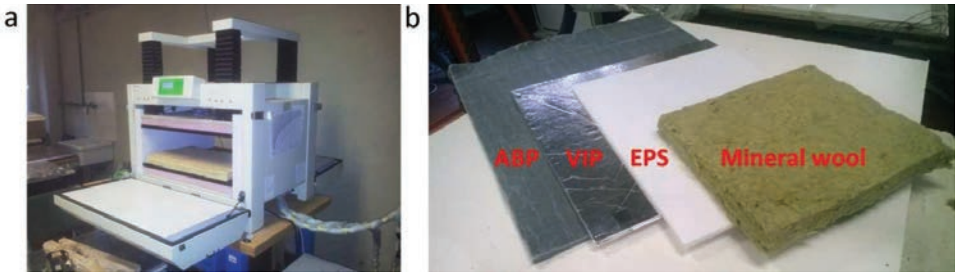

Fig. 1. (a) Guarded heat flow meter apparatus; (b) experimental samples.

2.2. The effective thermal conductivity of Vacuum Insulation Panels

In storage tanks, TES insulating layers present some junction lines causing thermal bridging effects. For traditional insulating materials (PU, EPS or Mineral Wool), these effects could be neglected because of their relatively high thermal conductivities. Differently, in case of SIMs (ABP and VIP) the thermal bridge effects could become more influent on the overall insulating performance, due to the decrease of thermal conductivity of the materials [13]. However, the fibrous conformation of the ABPs reduces the heat losses through the junction sections and the thermal bridge effects could be not considered also in this case. Instead, the characteristic panel edge shapes of VIPs cause not negligible thermal bridging effects.

For this reason, the effective thermal conductivity of VIPs insulating layers should be evaluated to assess the influence of thermal bridges on the overall thermal conductivity. This phenomenon was evaluated through a 2D energy balance method, in accordance to UNI EN ISO 10211:2008 [17]. The numerical analysis was performed with Physibel BISCO software, following the same calculation methodology adopted in [12]. From BISCO heat flux output, the thermal bridge linear thermal transmittances (ψ [W/mK]) could be calculated in accordance with UNI EN ISO 14683:2008 [18]. The distance between panels was kept equal to 2mm (the minimum value found in [13]). The thermal bridge length is a function of the number of panels used in the envelope layer. Considering constant 1m^2 VIPs, the number of panels depends only on TES dimensions and the thermal bridges can be evaluated as it is shown in Fig. 2(b). The effects of external TES envelope and internal surface resistance (*Ri* [m^{2}K/W]) were neglected: only the external surface resistance was considered (Re = 0.13 m^{2}K/W).

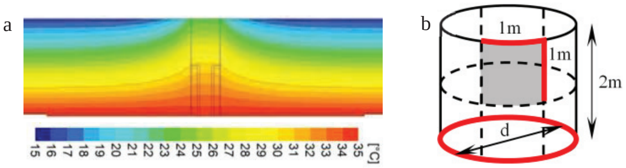

Fig. 2. (a) 2D FEM: output isothermal profiles; (b) TES subdivision with VIPs and individuation of thermal bridges (red lines).

Once it is known the linear thermal transmittance of VIPs joint, it's possible to calculate the effective thermal conductivity of TES insulating layer through Equation (1):

$$\lambda_{eff} = \left(\frac{H_{tr}}{\quad} - \frac{\quad}{he} \right). \qquad (1)$$

Where: A is the external surface of TES [m^2], $1/he$ is the external surface resistance [m^{2}K/W], s is the insulating layer thickness (s=10 mm, typical commercial thickness), and H_{tr} is the heat transmission coefficient [W/K] evaluated with Equation (2):

$$H_{tr} = U \cdot A + \psi \cdot l = \frac{1}{\frac{s}{\lambda_{cop}} + \frac{}{he}} \cdot A + \psi \cdot l \tag{2}$$

Where λ_{cop} [W/m^{2}K] is the VIP thermal conductivity without thermal bridges [13] and l is the thermal bridges overall length [m] equal to the number of panels which compose the envelope layer multiplied for VIP emi-perimeter and summed to the lower enclosure (Fig. 2(b) - red lines).

Because of VIPs dimensions were kept constant equal to 1mx1m, the effective thermal conductivity is the same for each diameter considered.

2.3. Influence of insulating materials on TES net volume

Several storage tank technical sheets show that a common material used for TES insulation is PU (layer 5cm thick). The corresponding thermal resistance is equal to 1.92 m^{2}K/W [19]. Setting this resistance as a reference value, different insulating materials were adopted and the necessary thickness was calculated for each material (depending on their thermal conductivity). Afterwards the ΔV and V_{tot} ratio was evaluated: ΔV was determined as the difference between the total volume V_{tot} and the net volume V_n (Equation 3). A parametrical analysis was carried out considering different TES diameters while maintaining constant the TES height.

$$V_n = \pi \cdot \left(r^2 - s\right) \cdot \left(h - 2 \cdot s\right) \tag{3}$$

Where: r is the TES radius [m], s is the thickness of insulation layer [m] and h is the storage height [m].

Moreover a comparison between the PU insulation layer (common TES insulation) was evaluated through the difference between $V_{n,i}$ (insulation material i) and $V_{n,PU}$ (net volume with PU insulation layer), normalized respect to $V_{n,PU}$. For this analysis a fixed thermal resistance of the insulating layer was used (PU 5 cm of thickness) varying only the thickness associated to other insulating materials, which have different thermal conductivities.

2.4. Critical diameter of insulation

Furthermore, to cover maximum factors in defining certain insulation for certain case, it is beneficial keep in mind values of critical diameter of insulation $d_{cr,ins}$ [m]. Obviously, the value of critical diameter depends on the types of insulation materials, their temperature and mean heat emission coefficient:

$$d_{cr,ins} = \frac{2 \cdot \lambda_{ins}}{\alpha} \tag{4}$$

Where: λ_{ins} is the thermal conductivity coefficient of the insulation [W/mK], α is the mean coefficient of heat emission [W/m^{2}K], for natural convection α is between 5 and 10 W/m^{2}K, for the analysis a value of 7.7 W/m^{2}K was considered for the external laminar coefficient according to the standard UNI EN ISO 6946:2007 [20], while also in this care the internal laminar coefficient was neglected.

3. Results and discussion

Results of the analysis were summarised in Table 1, which reports: the fixed thermal resistance value R=1.92m^{2}K/W (corresponding in 5 cm of PU); the experimental results of the thermal conductivities λ of each insulating material; the insulation thickness *s* calculated as the product of the fixed *R*-value and the thermal conductivity λ; the crucial diameter of insulation $d_{cr,ins}$; the total volume V_{tot} and the net volume V_n for different TES diameter *d*.

Table 1. Total volume V_{tot} and net volume V_n for different TES diameter and insulating materials.

					d = 0.4 m		d = 0.6 m		d = 0.8 m		d = 1.0 m		d = 1.2 m		d = 1.4 m	
	R [m^{2}K/W]	λ [W/mK]	s [m]	$d_{cr,ins}$ [mm]	V_{tot} [m^3]	V_n [m^3]	V_{tot} [m^3]	V_n [m^3]	V_{tot} [m^3]	V_n [m^3]	V_{tot} [m^3]	V_n [m^3]	V_{tot} [m^3]	V_n [m^3]	V_{tot} [m^3]	V_n [m^3]
PU	**1.92**	**0.0260**	**0.050**	**6.8**	0.251	0.134	0.565	0.373	1.005	0.731	1.571	1.209	2.262	1.806	3.079	2.522
Mineral Wool		0.0401	0.077	10.4		0.088		0.288		0.605		1.037		1.586		2.250
EPS		0.0345	0.066	9.0		0.105		0.321		0.653		1.104		1.671		2.356
Aerogel		0.0166	0.032	4.3		0.172		0.437		0.824		1.333		1.964		2.716
VIP_{eff}		0.0058	0.011	1.5		0.222		0.519		0.940		1.485		2.155		2.949

The influence of different insulating materials in TES was investigated through the reduction ratio $\Delta V/V_{tot}$ represented in Fig. 3(a) for different TES diameter d.

Moreover Fig. 3(b) shows the variation of V_n, comparing the net volume of TES for each insulating materials with the net volume of the PU insulation $V_{n,PU}$, for different TES diameter *d*.

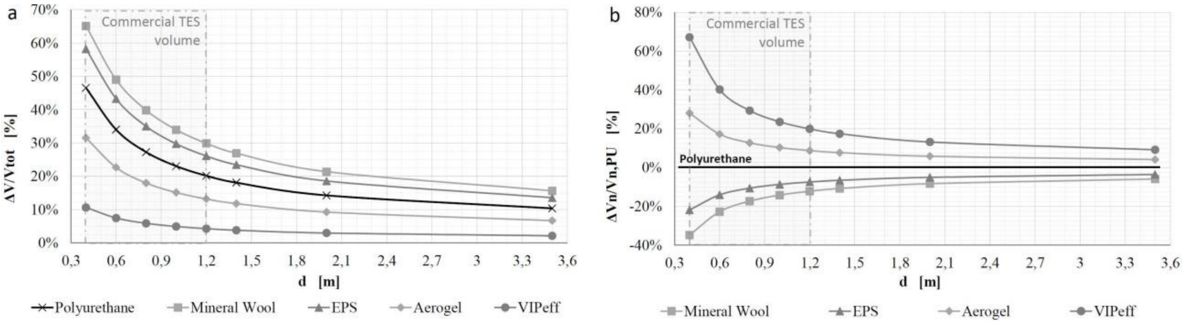

Fig. 3. Effects of different insulating materials for each TES diameter: (a) $\Delta V/V_{tot}$; (b) $\Delta V_n/V_{n,PU}$.

The results underline that the variation of net volume has not negligible effect, in particular the smaller the tank the higher is the reduction of the net volume V_n (Fig. 3(a)).

Moreover for each insulating material the results of the comparison with a traditional PU insulation in the range of commercial TES volume between 0.25 and 2.25 m^3 (corresponding in a diameter between 0.4 and 1.2 m) shows:

- For VIPs, an increase of the net storage volume approximately between 19 % and 65 % were detected (taking into account the VIPs thermal bridging effects);
- For ABPs, an increase of the net storage volume ranges between 9 % and 28 % (Fig. 3.(a)).

As expected, a decay of the heat storage capacity was observed for the materials with higher thermal conductivity than PU rigid foam i.e. (EPS and Mineral wool insulation).

To deepen investigate the effect of the net volume reduction, the analysis was carried out also for non-commercial TES dimensions (diameter *d* more than 1.2 m), showing an asymptotic trend for large diameter size.

4. Conclusions

The area of effective usage of TES with super insulating materials was investigated in this article. VIP and ABP hold the strong position as the best insulating materials for TES with certain dimentions. For instance, it was shown that they can significantly increase the performance of cylindrical TES with diameter from 0.3 to 1.2 m. However, it was demonstrated that the thermal bridging effects cause an increase of effective thermal conductivity of the TES VIPs insulating layer of around 10 %. These phenomena occur where borders of the VIPs joint to each other. Therefore, these drawbacks might increase especially when TES has a complex or a large size. Moreover, for large size TES usage of VIP becomes less effective and this technology becomes not reasonable from economical point of view. There is a promising research field on the application of SIMs and their coupling with TES creates a new area of investigation of its effectiveness. Scope of this work was to provide some instrument and parametrical analyses in to preliminary review potentialities and possible problems of this area.

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