Development of a Vacuum Insulated Thermal Energy Storage for Industrial Applications

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Abstract

In this article the development of a high performance, double-wall vacuum insulated hot water thermal energy storage for high temperature applications is presented. In this concept, the main heat losses of the tank are limited to radiation and to the thermal bridges present in the wall of the tank and fittings. This concept is well suited for high temperature applications such as those found in the industrial sector where storage energy losses are an important issue. Few studies on double wall evacuated tanks were found in the open literature and none fully employed a completely evacuated gap as proposed in this study. A structural analysis was performed to validate the proposed design and ensure conformity to high temperature applications. Heat transfer calculations assessed the impact of low emissivity coatings on the radiative heat transport in the evacuated gap. An evaluation of the investment cost of the novel concept was also performed and comparisons made with conventional insulated TES on the market. A numerical model of the tank was developed and the thermal behaviour investigated under different configurations. An economic analysis presented the investment attractiveness with respect to the common TES alternatives on the market. Overall, the presented concept is clearly viable not only in terms of technical feasibility but also in terms of economic practicality.

Keywords: thermal energy storage, vacuum insulation, industrial applications, simulation, economic analysis

1. Introduction

In Switzerland, thermal energy accounts for some 75% of the final energy consumption. More than 50% of this energy is used for space heating, domestic hot water production and industrial process heating (OFEN, 2017; Kemmler *et al.*, 2018). Moreover, 20% of the industrial process heat demand is between 100 and 400 °C (Pardo *et al.*, 2012). In these applications, full use of renewable energy can only be achieved by providing adequate energy storage options. Therefore, thermal energy storage (TES) could play a major role in global energy efficiency improvement by increasing the share of renewable energy production and of waste heat recovery.

In Europe, it has been estimated to about 1.4 million GWh/year, the potential savings from a wider use of hot and cold storage systems in the industrial and domestic sectors (IRENA, 2013). Within the Swiss context, the estimated value is about 4500 GWh/year in the building sector alone. The use of TES for industrial waste heat recovery is also of great importance with over 300 TWh/year of waste heat potential in the EU while for Switzerland, the estimated value is about 5.3 TWh/year (Papapetrou *et al.*, 2018; Padey *et al.*, 2015).

In recent years, some developments have been made regarding insulation of TES. Double-wall vacuum insulated systems for sensible heat storage using low levels of vacuum (0.08 to 1 mbar) and gap filling materials to increase thermal resistance, are one of them, please see the review of Villasmil *et al.* (2019). This article presents the development of a new vacuum gap insulation concept of high performance TES without filling materials, the VITES concept. Such a device should be of interest to high temperature solar thermal industrial systems as well as to store thermal energy from any other energy source. In terms of investment cost, the goal is to design a storage device that does not exceed the maximum acceptable storage capacity cost (SCC_{acc}) as defined in the IEA SHC Task 42/ ECES Annex 29, see Rathgeber *et al.* (2016) that indicates 112 CHF/kWh for industry applications.

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2. VITES design concept

Thermal energy storage is defined as the temporary storage of thermal energy at high or low temperature levels. These systems are required when the heat demand is not in phase with heat production. Of great importance in many engineering fields, they are particularly used in buildings for short-term storage of domestic hot water and for industrial processes.

Storage of heat is traditionally in the form of sensible heat with water as the most common storage medium. A key aspect of sensible TES systems is the insulation of the tank to reduce heat losses. The simplest and most cost-effective solution is insulation applied to the storage outside wall. In this case, conventional building insulation materials such as mineral wool, expanded polystyrene and polyurethane foams (Jell, 2011), dominate the market. Improving the current insulation ability of these materials is difficult because an increase in thermal resistance can only be achieved through an increase of the insulation thickness, which in turn results in a larger and more costly storage solution. Therefore, advanced insulation materials, the so-called superinsulators, have been developed and tested in real case studies, see for example Fuchs *et al.* (2010) and Beikircher and Demharter (2013).

Alternatively, insulation can be applied within the storage wall by creating an evacuated gap between two concentric vessels. The open literature indicates an important research and development activity in Europe particularly for evacuated gaps filled with powders, a technology proven and widely used in cryogenic applications. The availability of some commercial products based on this technology is also reported in different case studies (Villasmil *et al.*, 2019).

In practice, as summarised by Villasmil *et al.* (2019), superinsulators are fragile in handling, vulnerable to moisture and quite expensive when compared to traditional insulation materials. On the other hand, there are concerns regarding gas leakages into the evacuated powder containing space that could negatively affect the insulation performance.

These findings led to the development of a double-wall hot water thermal storage tank with high vacuum (<0.001 mbar) and no filling material in the gap between the walls to decrease heat losses. VITES consists of two concentric stainless steel cylindrical tanks with end caps. The inner tank contains pressurised hot water. The outer tank must withstand the vacuum between the two cylindrical shells to insulate the inner tank and minimise the heat exchange between the water and the outside ambient environment. This tank can be charged with solar energy or any other renewable energy and even waste heat. Its functional principle is to store heat in the form of temperature-layered hot water with minimised heat losses. The concept is developed to withstand storage medium temperatures up to 180 °C at 16 bar. For calculations, a reference operating temperature of 160 °C was considered.

By definition, vacuum (space devoid of matter) is often considered to be the best known insulator. In fact, the lack of matter greatly minimises heat losses by conduction and convention and only radiation prevails. In this concept, the vacuum insulation is obtained in the gap between the two concentric metal cylinders that form the tank. To maintain and inspect the high vacuum level (<0.001 mbar) over the entire lifetime of the tank, a patented and compact getter-pump is used (TVP Solar, 2019). This proven technology has been used for more than 10 years in a high-vacuum flat solar collector in the Swiss market.

2.1 Structural analysis

Because of the design operating pressures: up to 16 bar inside the tank, less than 0.001 mbar in the double-wall gap and atmospheric pressure at the outside, the structural assessment of the proposed design was performed. Due to confidentiality issues, the geometry of this concept is not presented here. The final design of the tank evolved from three base design models. The aim was to arrive at a design close to that of conventional tanks on the market. The final design has therefore optimised characteristics that bear an impact on the size, weight, heat losses and ultimately cost of the tank while preserving the design strength and stability for safe operation. The Finite Element Analysis (FEA) of the concept was performed with ANSYS and indicate the suitability and safety of the chosen design for the required applications. Further details can be found in Eicher *et al.* (2019).

2.2 Thermal analysis – emissivity impact of gap wall

To assess the heat transmission process, estimate thermal bridges and the influence of several parameters on the overall thermal behaviour of the tank, a thermal analysis was performed. As previously mentioned, vacuum insulation reduces dramatically the heat transfer by conduction and convection with no effect on the radiation transfer that becomes the dominant heat exchange phenomena, which depends on the emissivity of the walls and their temperatures. In order to anticipate the performance simulations, a thermal loss calculation for the radiation component was undertaken to evaluate the effect of emissivity coatings, applied to the walls of the annular gap, on the heat losses of the tank design. For this calculation, the VITES tank was assumed to be a closed cylinder with flat ends. The theoretical heat losses are the net radiation exchange between the top and bottom flat ends added to that between the two concentric cylinders. The net radiation heat transfer between two surface-enclosures was calculated as follows (Incropera and DeWitt, 1985):

$$q_{plates} = \frac{A_p \sigma \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad \text{(eq. 1)} \qquad q_{cylinders} = \frac{A_1 \sigma \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)} \quad \text{(eq. 2)}$$

where

q is the specific heat transfer (W/m²), A_p is the top and bottom flat plate surface area (m²), A_1 the inner cylinder surface area (m²) σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m²/K⁴), ε_1 and ε_2 are emissivities of surface 1 (inner tank) and 2 (outer tank), respectively. T_1 and T_2 are surface temperatures 1 (inner tank) and 2 (outer tank), respectively.

This result was compared to the case where the VITES tank is insulated with 100 mm mineral wool material, affected by a high water content (caused by humid air or rain infiltration), having a thermal conductivity (*k*) of 0.06 W/mK (Chadiarakou *et al.*, 2007). The results are illustrated in Fig. 1 for two emissivity values, 0.03 and 0.08, for the walls of the annular gap, corresponding to common copper and stainless steel coating values.

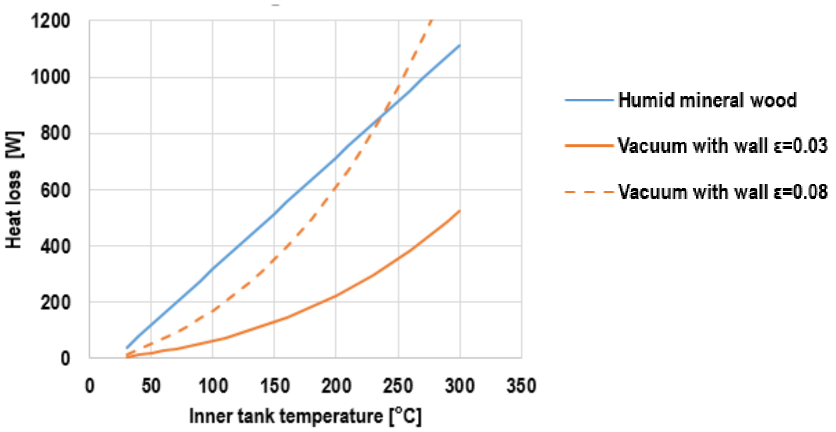

Fig. 1: Comparison of the heat loss rate between VITES and an equivalent conventional insulated storage tank for two emissivity values (ε_{copper}=0.03 and $\varepsilon_{StainleeSteel}$=0.08)

As expected, the higher the temperature difference between the inner tank and the ambient conditions, the higher the heat loss to the outside. Vacuum insulation is seen to be more effective in preventing heat losses particularly at high temperatures, about 30% lower in comparison to conventional. Low emissivity coatings are able to further reduce the radiative thermal transport to values well below those of conventional conduction losses (nearly 75 % reduction). In addition, usual insulation materials such as mineral wool can be affected by moisture that heavily deteriorates their insulation properties due to an increase in the thermal conductivity. For dry mineral wool (k=0.04 W/mK), VITES would still perform better, see Fig. 2.

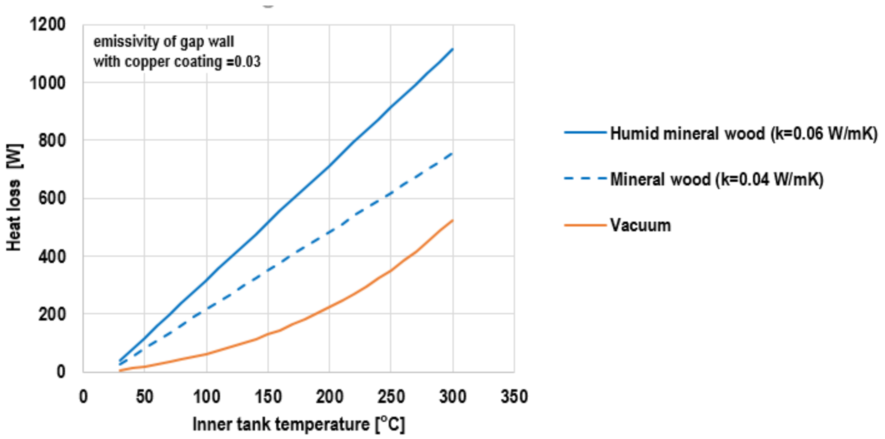

Fig. 2: Effect of humidity on the heat losses of conventional insulation in comparison with the VITES technology

For the reference operating temperature of 160 °C, heat loss is estimated to be nearly four times lower when using vacuum insulation with a low emissivity coating when compared to conventional humid mineral wool insulation. This value decreases to 2.5 in case of non-humid insulation conditions. This result demonstrates that a low emissivity coating in the evacuated gap offers a tremendous advantage in the development of long-term sensible heat storages. Advanced coatings such as silver coatings were not considered because of their high cost.

2.3 Thermal analysis – thermal bridges calculation

In the VITES prototype, spacers are used to maintain the space and properly position the two cylindrical concentric tanks. Spacers are available in a variety of shapes and materials to meet the particular needs of different applications. For this case, the choice of a proper spacer was defined by performing a conduction heat loss calculation in order to evaluate thermal bridges and minimise their impact. In the preliminary designs, two materials, borosilicate and stainless steel, were considered for the spacers, as they are commonly used for this type of fixture. Borosilicate with their low thermal expansion and high surface strength was found not resistant enough when compared to stainless steel. In the final design, stainless steel spacers and bottom supports with suitable design were considered to reduce heat losses. Losses through the water connections, including a top gas purge port and a bottom drain port, were also calculated to evaluate the impact of thermal bridging and provide solutions to minimise it. Fixtures and water connections heat losses were found to amount to 5 and 16 W, respectively.

According to Fig. 1, the overall radiation heat loss of the VITES concept with applied copper coating, at the reference operating temperature of 160 °C is about 145 W. The addition of the different conduction heat losses was found to amount to about 21 W, representing less than 15% of the overall losses of the tank at 160 °C.

3. VITES cost estimation

The uptake of any new technology requires, in addition to reliability assurance, cost-effective evidence over the common alternatives on market. In this way, a cost estimation of the VITES tank was performed and the result compared with the cost of a conventional storage with 100 mm mineral wool insulation. The investment cost of the storage is determined based on catalogue prices and quotes. Economic evaluation of the VITES tank was performed using the methodology developed within the framework of IEA SHC Task42/ ECES Annex29 (Rathgeber *et al.*, 2016).

3.1 Investment cost evaluation

In this method, the total investment cost is the sum of all costs to produce the storage unit and is expressed as the combination of components, manufacturing and insulation costs. Component costs relate to the costs associated with different tank parts such as end caps, cylinder and fittings and were obtained from catalogue prices and quotes. Manufacturing costs, including welding, labour and pressure control costs, were also obtained from quotes. Finally, insulation costs are those associated with the chosen insulation solution. Conventional insulation includes material and labour costs while vacuum insulation considers vacuum technology costs: baking oven and pump.

For industrial processes requiring water above 120 °C, the storage is usually in the form of a pressurised stainless steel tank with either internal or external heat exchangers. In this study, both conventional and VITES tank are made from stainless steel 304 L with external heat exchangers. For the industrial application, both tanks are pressurised at 16 bars. Only investment cost (excluding the transport cost) are considered and the values in CHF are taken for a reference size of 1 m³. For comparison purposes, the specific cost is related to the water storage volume. It is important to note that the VITES inner tank is taken to be the same as the tank of the conventional insulated option. Only the insulation solution makes up for the cost difference. The 1 m³ conventional storage cost estimated using this methodology was validated with a quote.

A scale-up exercise was also carry out for volumes up to 10 m³, the maximum size for which VITES is designed. Here the scaling method was to keep the same end caps and hold constant the tank diameter while adding constant height cylindrical parts to reach the required volume. Therefore, the additional cost for the inner tank takes into account the cylindrical parts to be added as well as the additional welding to be done and the higher pressure control in terms of labour. The insulation cost, mineral wool for the conventional tank and double wall vacuum insulation for VITES, also considers this specific tank enlargement.

Fig. 3 shows the cost breakdown for both VITES and conventional insulated tank for the high temperature industrial application.

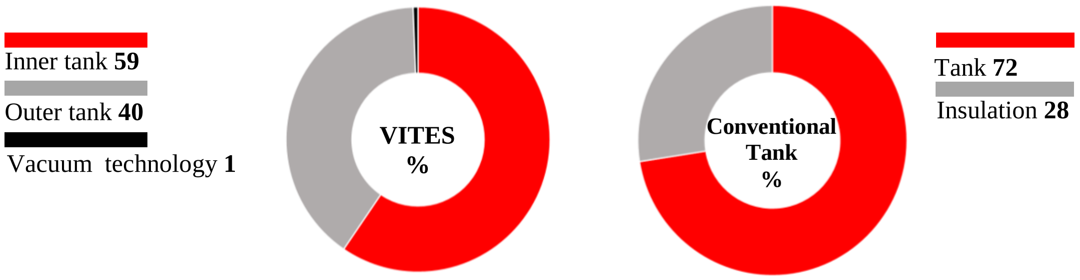

Fig. 3: Cost breakdown of VITES and conventional insulated tank for the high temperature industrial application

The major fraction of investment costs associated with the investigated tanks relates to the water storage container (red colour label). The vacuum technology (e.g baking oven and pump), often considered expensive, accounts for less than 1% of the overall VITES investment cost. Fig. 4 indicates that costs are only slightly higher for the VITES tank.

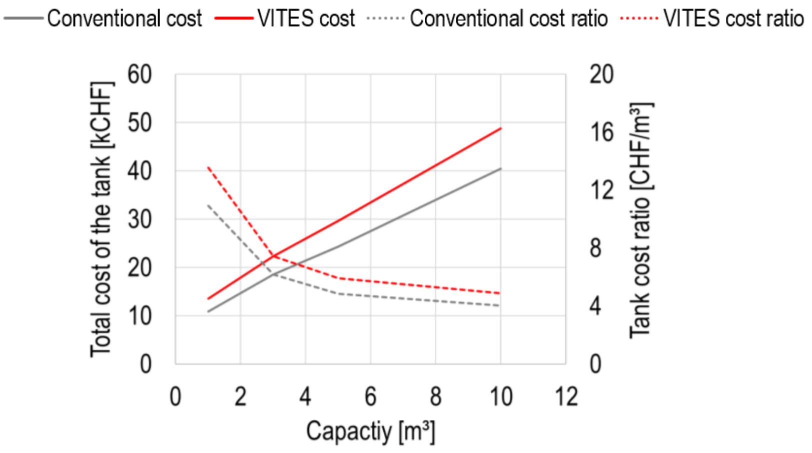

Fig. 4: Cost comparison between VITES and conventional insulated tank for industrial applications

For example, the insulated 100 mm mineral wool stainless steel tank for a nominal operating pressure of 16 bar costs about 11000 CHF whereas the VITES tank sums up to 13500 CHF. A cost difference of only 2500 CHF that still places VITES as an interesting cost-effective technology with the additional advantage that VITES is moisture protected and has lower heat losses.

For the scale-up cases, VITES average specific costs for industrial applications were found to range from 13500 CHF/m³ to 5000 CHF/m³ for volumes ranging from 1 to 10 m³ in comparison with 11000 and 4000 CHF/m³ for a conventional insulated tank.

3.2 Economic evaluation according to IEA SHC Task42/ ECES Annex 29 methodology

The economic assessment of the VITES technology was also performed using IEA SHC Task 42/ ECES Annex 29 methodology (Rathgeber *et al.*, 2016). The maximum acceptable storage capacity cost (SCC_{acc}) can be easily computed from the interest rate (i) assigned to the capital cost, the expected payback time (n), the reference energy cost (REC) and the annual number of storage cycles:

$$SCC_{acc} = \frac{REC.N_{cycle}}{ANF} \; with \; ANF = \frac{(i+1)^n .\ i}{(i+1)^n - 1} \qquad \text{(eq. 3)}$$

The realised storage capacity cost (SCCreal) is the investment cost (INC) divided by the storage capacity (SC):

$$SCC_{real} = \frac{INC}{SC} \qquad \text{(eq. 4)}$$

However, these parameters differ from one application to another. According to Rathgeber *et al.* (2016) interest rates over 10% and short payback times of less than 5 years are usual in the industry sector.

Results are presented in Fig. 5. Four storage capacities for the VITES tank containing pressurised water temperature at 180 °C with a return flow at 90 °C were analysed. The gas price was taken between 0.05 – 0.1 CHF/kWh based on current Swiss industry gas prices.

For short-term storage with several hundred storage cycles, VITES seems quite attractive with specific costs ranging from 130 to 47 CHF/kWh (black full lines) for 1 to 10 m³, respectively. Compared to an existing 1 m³ industrial short-term storage with conventional insulation (dotted blue line) with an SCC_{real} of 107 CHF/kWh, it can be seen that VITES is well within the range of acceptable storage capacity cost (SCC_{acc}).

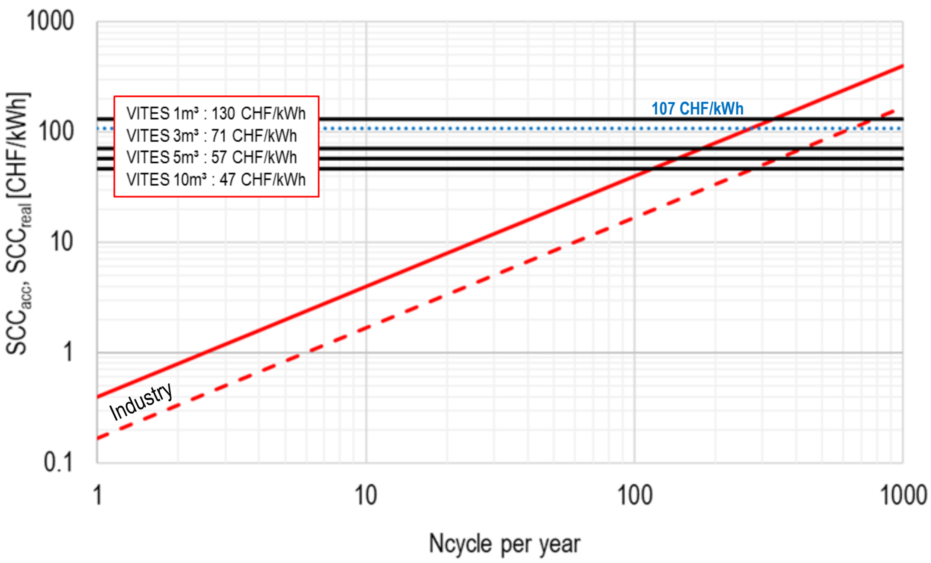

Fig. 5: SCC_{acc} for the VITES storage and SCC_{real} for an equivalent conventional insulated storage for industrial applications (*i*=10%; *n*=5 years, REC_{gas}=0.05-0.1 CHF/kWh). Solid and dashed red lines are the SCC_{acc} theoretical limits for industry.

4. Simulation analysis

The simulation investigates the VITES tank integrated in a solar heating system for an industrial process and provides comparisons with conventional insulated tanks. The main elements of the simulated system are, therefore, solar thermals collectors, the tanks (VITES and conventional insulated) and the heating loads. The final objective of the simulation is to provide the thermal performances and the potential energy savings of the VITES concept compared to conventional tanks for the investigated case study.

Annual simulations of the overall system under different solar thermal system sizes were performed. The simulations were carried out in TRNSYS 17 (Klein et al., 2017) with standard components or with validated, well-known third-party models. The reference weather conditions were taken from the Meteonorm package provided with TRNSYS for the city of Bern-Liebenfeld. The detailed modelling of the VITES tanks and the parametrisation of components can be found in Eicher *et al.* (2019).

4.1 Description of the industrial case study

To evaluate and compare the performances of the VITES tank in industrial applications, a case study was defined from literature data. Fig. **6** show a simplified hydraulic scheme of the chosen process and the integration of a solar thermal system. The integration of the solar heat is implemented at the process level with a preheating strategy. This means that the heat exchanger (HX) is placed before the conventional one, this latter will deliver the rest of heat needed for the process. The solar system is set to work between 128 °C and 180 °C with storage temperatures between 100 °C and 180 °C.

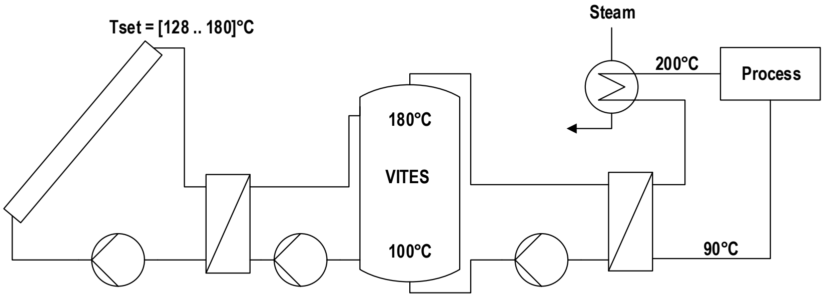

Fig. 6: Simplified hydraulic scheme of the solar thermal system and integration into the industrial process

The investigation is focused on the TES with the simulation of three different type of tanks:

1. The VITES concept (see *cf. 2*).
2. A well-insulated tank with 10 cm of dry mineral wool with a conductivity of 0.04 W/mK
3. A low-insulated tank with 10 cm of humid mineral wool with a conductivity of 0.06 W/mK

In order to analyse the performances of the storage and investigate up-scaling capabilities, four different solar system sizes are investigated for the same process and for a constant TES capacity to solar collector area ratio of 50 litre/m^2. This means that for the given process, four different solar fractions are obtained.

4.2 Process and Load Profile

The considered process is a spray dryer in the food and beverage industry using humid air as the heat transfer fluid (HFT) with a required temperature of 200 °C. The HTF leaves the spray drier at 100 °C and is then regenerated with fresh air at 25 °C reducing the temperature further to 90 °C corresponding to a HTF recirculation factor of 87%. The process was designed according to the tank volumes investigated in the project. This resulted in a daily energy consumption of 159 kWh and a nominal heat flow rate of 10 kW.

The process is modelled with an hourly load file where the required flow rate and temperature are defined. The process runs 24 hours per day and 7 days a week with the profile given in Fig. 7. The process schedule was adapted to stress the solar thermal system with short pauses (1h) during the day, specifically between 12:00 and 13:00 where high solar production is expected.

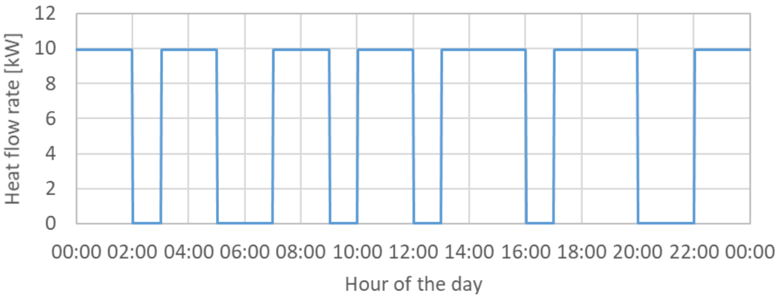

Fig. 7: Daily hourly profile of the spray drying industrial process

4.3 Solar field and TES sizing

Given a maximum temperature of 180 °C for the solar heat provided to the process and a return flow of 100 °C, the maximum heat flow covered by the solar field falls roughly under 80%. From the mean absorber temperature of 145 °C, the specific peak power of the TVP solar collector is 379 W/m^2 for an ambient temperature of 30 °C. In order to cover 80%, e.g. 8 kW of the process heat flow rate, the area of the solar field (A_c) is estimated to be around 20 m^2 for an irradiance of 700 W/m^2. For every case, the hot water tank is sized with a constant specific volume of 50 litre/m^2. To investigate other solar fractions, the storage and solar field is enlarged to the investigated storage volumes of 1, 3, 5 and 10 m^3. Further details of the simulation model can be found in Eicher *et al.* (2019).

4.4 Simulation results

The simulation results were analysed according to two indicators: the solar fraction f_{sol} and the TES efficiency η_{TES}. The solar fraction is the ratio of the solar field energy yield Q_{sol} over the sum of solar yield and the steam consumption Q_{stm}:

$$f_{sol} = \frac{Q_{sol}}{Q_{sol}+Q_{stm}} \qquad \text{(eq. 5)}$$

As for the TES efficiency, it is the ratio of the total energy discharged from the TES $Q_{TES,out}$ corrected by the internal energy change between the start and end of the simulation ΔQ_{int} over the total energy supplied to the tank $Q_{TES,in}$:

$$\eta_{TES} = \frac{Q_{TES,out}+\Delta Q_{int}}{Q_{TES,i}} \qquad \text{(eq. 6)}$$

Fig. 8 presents on the left the solar fraction and on the right the TES efficiency as a function of the tank volume and for the three tank insulations: VITES, low-insulated conventional tank (k=0.06 W/m K) and well-insulated conventional tank (k=0.04 W/m K). It can be seen that VITES presents high TES efficiency with values as high as 0.9 while the conventional insulated tanks have efficiencies below 0.74.

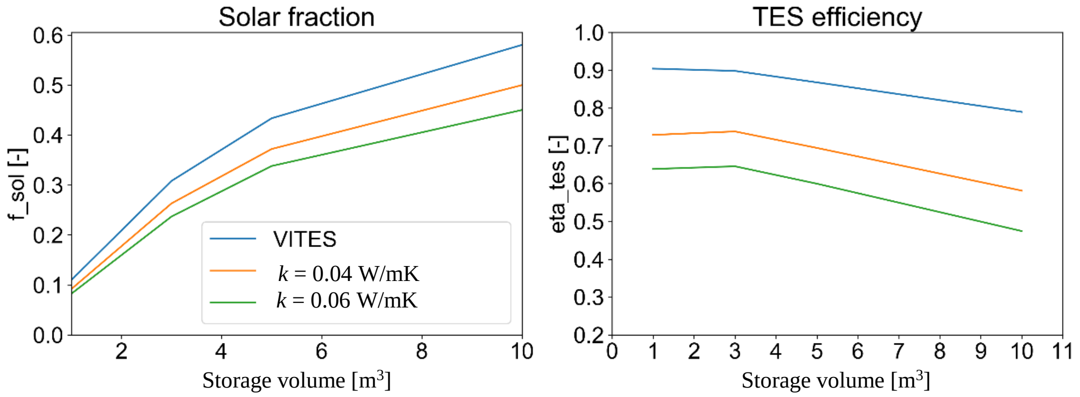

Fig. 8: Solar fraction (left) and TES efficiency (right) as a function of the volume of the tank and for the three tank insulation solutions: VITES, conventional low-insulated tank (*k*=0.06 W/m K) and conventional well-insulated tank (*k*=0.04 W/m K)

Thanks to the improved insulation capacity of the VITES tank, the energy savings lead to higher solar fractions, meaning that the avoided losses are used to supply the process with solar thermal energy. As expected, the efficiency of the storage decreases when the system size is increased. However, this decrease is less pronounced in the case of the VITES tank meaning that high solar fractions can be reached without increasing significantly the heat losses of the system. VS stands for storage volume and A_c for collector field surface area.

Fig. 9 shows that the monthly mean storage temperature according to each system size for the VITES tank on the left and the low-insulated conventional tank on the right. For the 1 m^3 tank the monthly mean temperature is low, around 100 °C, which is the cut-off threshold for the tank discharge. This indicates that most of the solar heat is consumed directly and that very little is stored from one day to another.

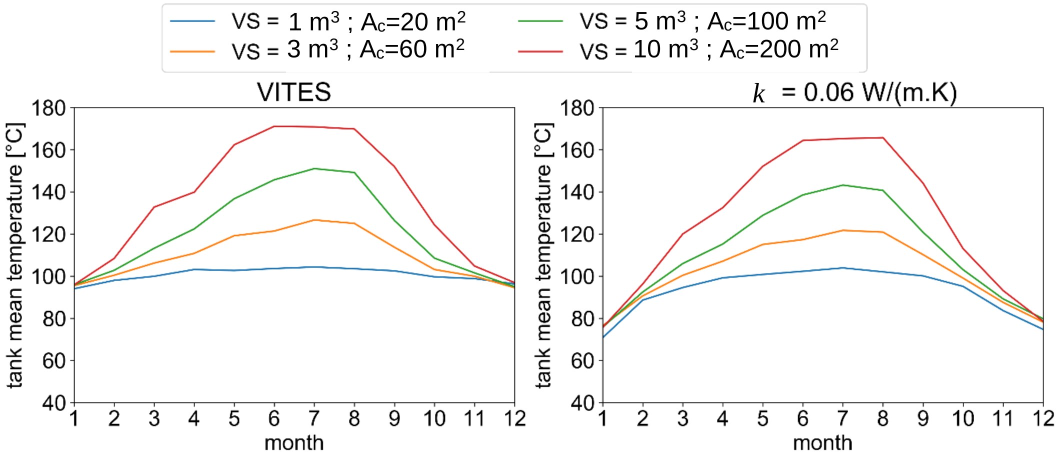

Fig. 9: Monthly mean storage temperature according to each system size for the VITES tank (left) and for the low-insulated conventional tank (right)

For systems with higher solar fractions (larger solar fields and storage capacities), the VITES tank reaches higher temperatures with the largest difference occurring in the winter period as it can be seen in Fig. 10 for a storage size of 3 m³.

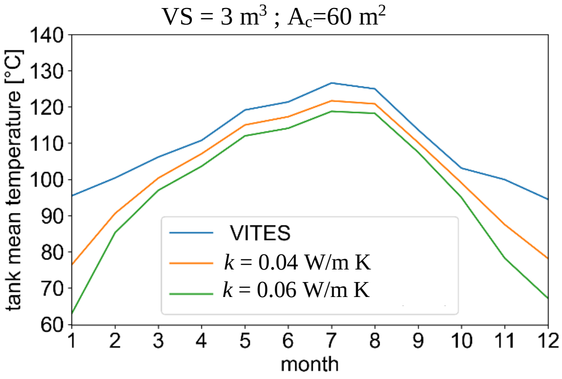

Fig. 10: Monthly mean storage temperature for a TES capacity of 3 m^3 and for the three tank insulation solutions: VITES, conventional low-insulated tank (*k*=0.06 W/m K) and conventional well-insulated tank (*k*=0.04 W/m K)

Fig. 11 presents the evolution of the heat losses of the three considered tank insulation solutions as a function of the storage volume. As expected, the VITES tank shows the lowest losses. When compared with the conventional insulated tanks, the heat losses are reduced by 65 to 75% according to the conventional insulation level, well and low, respectively.

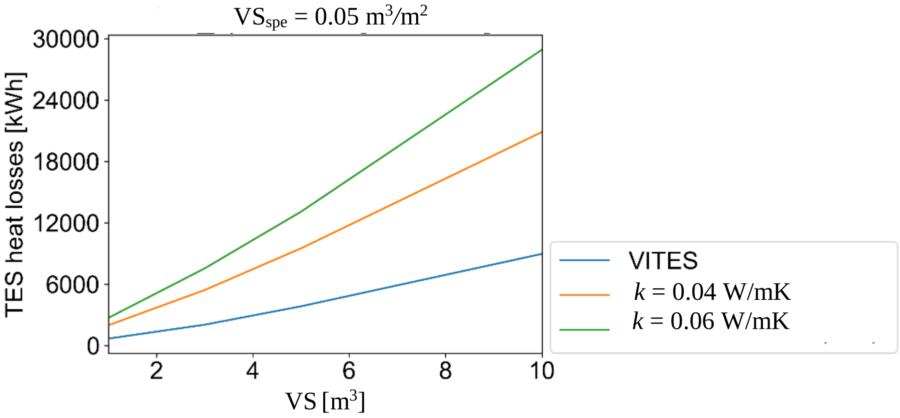

Fig. 11: Evolution of the yearly heat losses of the three considered tanks

In conclusion, the VITES tank performs better than the conventional insulated tanks considered in this study. The improved insulation ability substantially reduces the heat losses, which translates into higher TES efficiencies and solar fractions. As the consumption is constant on a daily basis, the stored solar energy is directly discharged, thus the storage period is relatively short but it allows a high number of cycles. If the process is scheduled over half a day and mismatch from the solar resource, the VITES concept will perform even better than for the case study presented here. This could open the way to new applications for solar thermal systems and therefore increase the share of renewable energy use.

5. Economic considerations

The economic feasibility of the VITES concept was evaluated by comparing the payback period of the VITES technology against that of conventional mineral wool insulated tanks. For market deployment, it is essential to rank the VITES concept to determine its investment attractiveness with respect to common TES alternatives on the market.

The payback period is a common investment evaluation and a quick ranking measure to gauge the cost-effectiveness of competing technologies. It calculates the length of time required to recover the initial or additional investment through savings generated by the investment. For TES, it provides the level of profitability of a TES technology in relation to time. The shorter the payback period, the better.

The payback period is calculated by dividing the additional investment (over cost) of VITES (see *cf.* 3) by the cost of the annual energy savings computed from the simulations (see *cf.* 4). The energy savings are specific to the application and depend on the energy demand (amount and profile).

Computing the resulting cost-savings from the annual energy savings requires knowledge of the actual costs of energy in the Swiss industrial sector. These values, besides varying with location, are also expected to change over time. To evaluate the impact of the evolution of the Swiss industrial REC, three different scenarios are considered based on average Swiss industrial gas prices. The first scenario corresponds to the Swiss actual average REC (0.07 CHF/kWh). The second scenario (0.1 CHF/kWh) corresponds to an upper limit of the actual Swiss REC and the third one (0.13 CHF/kWh) accounts for an enthusiastic scenario where fossil energy becomes expensive.

Fig. 12 presents a comparison between VITES and a low-insulated (humid mineral wool) tank based on the actual average REC scenario. Solid lines indicate the over cost of VITES for different storage capacities while dotted lines the cumulative cost savings.

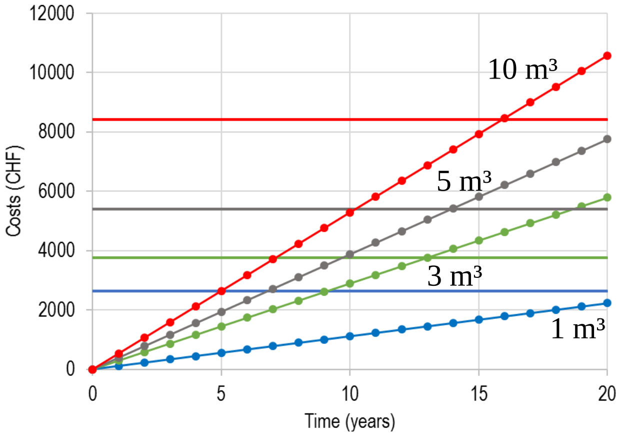

Fig. 12: Payback time as a function of the storage capacity and based on the actual average REC (VITES vs. low-insulated tank) Solid lines indicate over cost and dotted lines cumulative cost savings

Results show clearly the dependence of the payback period with the storage capacity. For example, for a 10 m^3 the estimated payback time is nearly 16 years while a 1 m^3 results in over 20 years.

The variation of the payback time with storage capacity also suggests an optimum storage capacity between 3 and 5 m^3 for the investigated industrial process where the payback period is minimum, see Fig. 13.

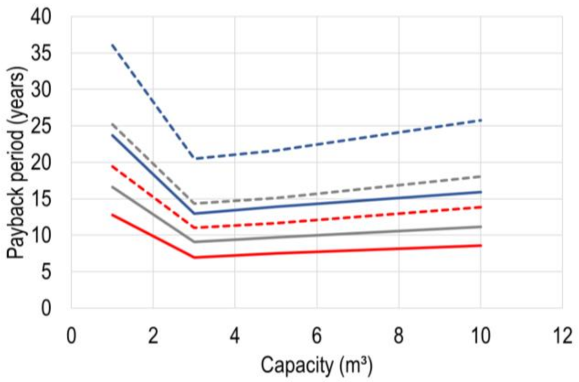

Fig. 13: Payback period for the investigated industrial process as a function of the storage capacity considering two different conventional insulation references (solid lines: humid insulation and dashed lines: dry insulation) and three Swiss REC scenarios: actual average, REC = 0.07 CHF/kW(blue solid/dashed line); upper limit, REC = 0.1 CHF/kW (grey solid/dashed line); and enthusiastic scenario, REC = 0.13 CHF/kW (red solid/dashed line)

The variation is U-shaped, the payback period declines with capacity up to 3 m³ (minimum) after which rises less steeply. The economies of scale seem to be more effective up to 3 m³, capacity beyond which the payback time starts to increase. This suggests that a capacity between 3 to 5 m³ is the adequate storage dimensioning for the specific industrial process investigated. Here, the payback period is relatively long (13 years) when considering low-insulated tank in the actual REC scenario. The use of conventional tanks with low insulating materials, shifts the curves downwards because the resulting energy savings are also more significant. It is clear that the closer the energy savings are from the over cost, the more interesting the technology investment becomes.

Overall, in this case, the investment is not interesting as the payback period is not below 5 years, value commonly found in the industry sector. In general, the higher the REC, the lower the payback time for a given storage capacity. Apart changes in the REC, other ways to obtain short payback periods are to reduce the over cost or benefit from financial incentives to promote high efficiency TES. In any case, the VITES concept is still cost-effective and the economic viability within reach.

6. Conclusions

The technical feasibility and the economic viability of a high performance, vacuum insulated sensible thermal energy storage tank was investigated for industrial applications. The literature review indicates that despite a considerable amount of research activities related to reducing TES heat losses, no concept has so far fully investigated the feasibility of using a vacuum annular gap without filling materials as insulating TES concept.

From the structural point of view, VITES was developed to resemble conventional storage tanks on the market while minimising heat losses. The structural analysis performed reveal that the selected design is structurally suitable and safe for the required high temperature applications.

To improve the insulating capability of the concept beyond the integrated vacuum technology, the use of reflective, low emissivity, coatings on the inner wall of the evacuated gap, was found to improve substantially the radiation losses. For the nominal operating temperature of 160 °C, thermal losses reductions from 40% to 75% were predicted in comparison with conventional well-insulated and low-insulated (humid affected) storage tanks, respectively. Thermal bridges due to piping, fittings and spacers were greatly reduced by applying a suitable design and were estimated to account for less of 15% of the overall losses of the tank at 160 °C.

Scalability of the investigated VITES concept was also investigated. To maintain and inspect the high vacuum level (<0.001 mbar) over the entire lifetime of the tank, a patented and compact getter-pump is used. This proven technology has been used for more than 10 years in a high-vacuum flat solar collector on the market.

In terms of investment cost, the major fraction is associated to the materials and manufacturing of the inner and outer tank. The vacuum technology, often considered expensive, accounts for less than 1% of the overall VITES investment cost. The slightly higher cost of VITES still places it as an interesting cost-effective technology with the additional advantage that VITES is moisture protected and has lower heat losses. In addition, the advantages of scale were clearly shown with specific capacity costs progressively reduced as the size of the TES is increased.

The economic assessment of the VITES technology according to the IEA SHC Task 42/ ECES Annex 29 methodology provided additional economic arguments where the investment cost was found not to exceed the application related, maximum acceptable storage capacity cost.

Simulations indicate that for the specific industrial application, the VITES tank performs better than the conventional insulated tanks considered in the study. The improved insulation ability substantially reduces the losses, which translates into higher TES efficiencies and solar fractions.

The economic viability of VITES evaluated through the payback period, revealed that for industry applications, the investment is currently not interesting with values well over 5 years but is still within reach.

Overall, this study clearly indicates the viability of the VITES concept not only in terms of technical feasibility but also in terms of economic practicality. The research should therefore pursuit to validate the technical and economic analysis based on experimental results and further investigate potential reductions of the radiative component as well of the thermal bridges.

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