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Experimental investigation on bimetallic tube compositions for the use in latent heat thermal energy storage units

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ABSTRACT

Based on the high energy density of phase change materials, latent heat thermal energy storage devices can play an important role in the future energy market. Therefore, the latent heat thermal energy storage technique is an interesting technology for industrial applications (e.g. batch processes) and power cycles. A key technology for such a storage device is the design of the heat exchanger tube, because the heat transfer rate by charging and discharging is the limiting factor based on the low thermal conductivity of the phase change material. The heat exchanger tube material used for such an application should have a high thermal conductivity and also a high mechanical resistance. Such a behavior can be found in a combination of different materials. The present paper deals with the design of such a heat exchanger tube composition consisting of a plain steel tube and an aluminum tube where fins can be attached. A novel bimetallic tube composition will be presented and compared with three common compositions. First, the mechanical stability of the bimetallic compositions was determined. Additionally a creep test of the used aluminum under operation conditions for a storage device using sodium nitrate as phase change material confirmed the utilizability for the operation in a latent heat thermal energy device.

One of the main challenges for the compositions under investigation is based on the different thermal expansion coefficient for aluminum and steel, which results in different strain and creeping tendencies of the aluminum at operation temperature of the storage system, which is up to 340 °C. A good heat transfer from the heat transfer fluid through the steel tube to the storage material around the fins can only be guaranteed through a close and stable connection between the two tubes. Compared to former solutions the fin circumference and the fin design are independent from the connection to the steel tube and allows individual arrangements of tubes and high packing densities.

The experimental investigations have shown that the novel bimetallic tube composition is able to compensate these different strains and is capable to guarantee a stable connection between the steel and the aluminum tube. This high pressure and high temperature resistant bimetallic heat exchanger tube is easy to assemble and may play a key role for the development of thermal energy storages and other heat exchanging processes.

1. Introduction

Worldwide the proportion of the renewable energy feeding electricity into the electrical net is increasing. The well-known problems of these forms of energy source – discrepancy between power generation and demand – result in a problem for the power grid frequency, which should be constant. At the moment, conventional power plants are driven by demand to keep the frequency stable. Due to the decreased full load hours, conventional power plants often cannot be operated profitable anymore. In Germany a total of 8071 MW_{el} of generation capacity (25.2.2015) is listed on the power plant closure notification list for final shutdown [1]. The creation of storage capacity is slow compared to the increase of the renewable energy sources. Currently, three large scale applications exist, typically greater than 10 MW h: Pumped hydroelectric storage consists in elevating water in an upper reservoir. Compressed air energy storage (CAES) systems using a cavern to store pressurized air and offer a capacity of several hundreds of MW h. Flow batteries, in which the electrolyte contains dissolved electro-active species flowing through a power cell/reactor, can also provide storage capacities. Especially CAES can be improved by using a thermal energy storage (TES) device for storing the released heat as it is described in [2] based on dynamic

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Nomenclature

d_{0_a}	inner diameter aluminum tube (m)	l_{0_s}	initial length steel tube (m)
d_{0_s}	outer diameter steel tube (m)	Δl_{as}	length difference aluminum and steel tubes (m)
Δd_{as}	diameter difference aluminum-steel tube (m)	R_m	tensile strength (N/mm^2)
Δd_{as_en}	diameter difference aluminum-steel at environmental temperature (m)	T	temperature (°C)
		T_{env}	environmental temperature (°C)
Δd_{as_op}	diameter difference aluminum-steel at operation temperature (m)	T_{op}	operational temperature (°C)
		ΔT	temperature difference (°C)
E	Young's modulus (N/mm^2)	$\alpha(T)$	thermal expansion coefficient (10^{-6} K^{-1})
l_0	initial length (m)	λ	thermal conductivity (W/(m K))
l_{0_a}	initial length aluminum tube (m)	ρ	density (kg/dm^3)

simulations, the isentropic plant efficiency can achieve values up to 70% as it is shown in [3]. An adiabatic CAES system was planned by a consortium under the lead of RWE Power in Germany called ADELE-R&D project and is explained in detail in [4]. An isobaric adiabatic CAES system is simulated in [5] including an analysis of profitability. However, the storing of energy will play a key role in the future energy market. Therefore, great effort will be made to find appropriate solutions to store energy in an adequate way. The present paper deals with the enhancement of the heat exchange while charging and discharging of thermal energy into a latent heat thermal energy storage (LHTES) system with e.g. sodium nitrate ($NaNO_3$) as storing material. The heat storage capacity of phase change materials (PCMs) is large due to the fact that it is based on the latent heat of melting (enthalpy of fusion). PCM storage based on reversible solid–liquid transition requires relatively small volumes with the additional advantage that energy is stored and retrieved at a constant operating temperature. However, the low thermal conductivity of many prospective PCMs, especially the organic ones, makes it difficult to utilize this capacity effectively [6]. To enhance the heat transfer into PCMs, various enhancement techniques have been suggested in [7] while a more general review of PCM materials, heat transfer and phase change problems is presented in [8]. Fins and multiple PCMs are numerically investigated in [9]. The results show an improvement regarding a uniform exit temperature of the heat transfer fluid by obtaining a multiple PCM LHTS unit in comparison to a single PCM unit. A numerical model for simulating the melting process of a PCM in an internally finned metal enclosure is presented in [10]. For a quick estimation of the melting time of the PCM an simplified analytical model was developed. The results are compared with a detailed numerical model. Metal and graphite-compound matrices are investigated in [11] for paraffin and in [12] for salts and eutectic's at a higher temperature level. Dispersed high-conductivity particles inside the PCM like expanded graphite can improve the thermal conductivity about seven times [13]. As reported in [14], aluminum powder in paraffin wax can reduce the charging time about 60%. Different encapsulation methods are discussed in [15] and significant heat transfer rate can be reported due to encapsulation. It was observed in [15] that a higher thermal conductivity of shell material, a lower shell size and high temperature of HTF results in rapid melting of the encapsulated PCM. The influence of nanomaterials on PCMs and micro-encapsulation is discussed in [16] besides a general review of the potential PCM materials. Heat transfer enhancement in laminar flows with the help of micro-sized phase change particles at a layer near the heated wall of a parallel plate channel is discussed in [17]. A further method to enhance the heat flux into the phase change material is the use of heat pipes as described in a state-of-the-art review in [18]. A numerical study of heat pipes for LHTES is presented in [19] which underline the importance of natural convection, pipe spacing and fin geometry for the melting and solidification of the PCM.

As described above, the use of finned tubes as enhancement method to increase the heat flow rate is a common method for indirect heat exchanger concepts. As reported in [20] a storage module based on a sandwich design developed by DLR Germany uses transversal finned tubes for enhancing the heat transfer while longitudinal finned tubes in a vertical arrangement are used in a semi-industrial shell-and-tube test rig in [21]. In [22] a further test rig is described which uses also finned tubes for increasing the heat transfer rate into the PCM. In all storage devices sodium nitrate is used as phase change material. Beside experimental investigations many numerical studies can be found in open literature which investigates the influence of finned tubes on charging and discharging time. As reported in [23] more than half of all investigations done on latent heat thermal storage systems were numerically and most of the used models are 2-dimensional. A comparison between a longitudinal, transversal and spiral finned tube in a vertical arrangement is presented in [24]. The authors have made 3-dimensional simulations and conclude that the longitudinal finned tube show the best charging performance while no significant difference is given during the discharging process. The results of 2 dimensional axial symmetric simulations on a vertical shell-and-tube LHTS system using transversal fins and also a dispersion of high conductive nano-particles in the PCM is described in [25]. The analysis shows that in comparison to the standard design (plain tube), the performances of the LHTS unit in terms of charging time could be improved by up to 40% for nano-particle enhancement. When fins are considered charging time can be reduced to one-third of its original value. With the implementation of finned tubes instead of plain tubes in LHTES units the heat transfer area as well as the heat transfer rate within the PCM is increased. To reduce the ratio of the volume occupied by the finned tube to the volume occupied by the PCM the height of the fins must exceed the dimensions of the commercial available finned tubes (this results in a lower tube number by perpetuation of an constant overall storage container volume). Decisive for a successful implementation of the finned tubes in LHTES systems is the selection of the fin material. A solution seems steel fins, which are compatible to the steel tube. But the thermal conductivity of steel however, is low compared to other materials. Hence, other materials than steel – like aluminum – are used in latent heat thermal energy storage units for increasing the heat transfer rate into the storage material. Beside metals, also graphite (foil) was used successfully in several PCM storage systems with the advantage of a higher thermal conductivity than stainless- or carbon steel [26].

The selection of the PCM material used in an application depends on the process parameters as well as the thermodynamic, physical, chemical, and economic aspects. By selecting a PCM material for a specific application the melting temperature must