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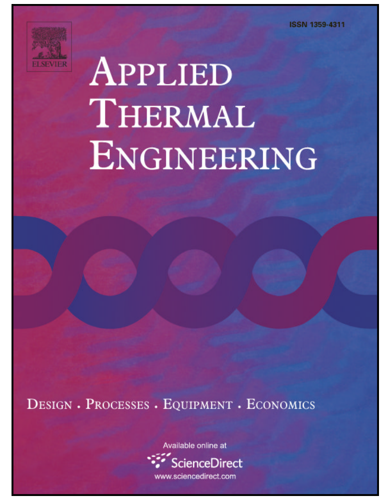

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PII: S1359-4311(17)36813-8
DOI: https://doi.org/10.1016/j.applthermaleng.2018.08.035
Reference: ATE 12538

To appear in: *Applied Thermal Engineering*

Received Date: 26 October 2017
Revised Date: 21 June 2018
Accepted Date: 8 August 2018

Assembly and attachment methods for extended aluminum fins onto steel tubes for high temperature latent heat storage units

Abbreviated Title: Finned-tube assembly in latent heat storage

Maike Johnson[a]*, Stefan Hübner[b], Markus Braun[a], Claudia Martin[a], Michael Fiß[a], Bernd Hachmann[c], Manfred Schönberger[d], Markus Eck[a,1]

a German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

b Linde AG, Seitnerstraße 70, 82049 Pullach, Germany

c F.W. Brökelmann GmbH & Co. KG, Oesterweg 14, 59469 Ense, Germany

d Linde AG, Carl-von-Linde-Straße 15, 83342 Tacherting, Germany

*maike.johnson@dlr.de

[1] Present address: University of Applied Sciences Osnabrück, 49706 Osnabrück, Germany

Highlights: Assembly and attachment methods for extended aluminum fins on steel tubes for high temperature latent heat storage units

- Clipping, crimping and heat shrinking of longitudinal fins onto tubes tested.
- Testing with thermal cycling in air and in salt conducted.
- Heat shrinking not stable under thermal cycling
- Clipping maintains good thermal contact but is weaker than crimping.
- Crimping is a very strong bond but does not maintain contact over the fin length.

Abstract

High temperature latent heat storages are being developed for both concentrating solar thermal power applications as well as integration in industrial processes. One of the concepts being developed is an extended finned-tube in a shell-and-tube assembly. This concept can be used at high pressures for steam applications and be built at a large scale. The design of the extended fins allowing for independent thermal expansion of the steel tubes and the aluminum fins with a physically possible assembly has not thus far been optimized. Due to the large fin surfaces necessary for storing large amounts of heat, conventional finned-tube assemblies have to date not been applicable for thermal energy storage systems.

Designs using spring steel clips on axial fins have been proven, using conservatively high numbers of clips. In this paper, various fin and tube diameters with spring steel clips as well as other mounting methods are compared. Experiments were conducted to analyze the mechanical strength of the assembly; these are described and the results discussed. In addition, two assembly methods were tested using the same fin geometry and testing environment, allowing for a thermodynamic comparison of the assemblies. The tests have shown that while the steel clips allow for the best heat transfer, the crimping method has a higher bond strength. These results can be used for reducing costs and optimizing design of high temperature latent heat storages.

Keywords

extended fin, PCM, latent heat, assembly method, clip, crimp

Abbreviations

C: cycled
CS: carbon steel
EF: extended fin
F: fin
HTF: heat transfer fluid
PCM: phase change material

R: reference
S: sheath
SS: stainless steel

1. Introduction

High temperature (>100 °C) latent heat storages are in development for concentrating solar power as well as industrial applications [1]-[7]. Due to the varying integration requirements of the different systems, as well as research development of new technologies, several latent heat storage concepts have been developed such as micro/macro particle [8], metal foam [9], encapsulated phase change materials (PCM) [10] and moving PCM based systems [11], [12]. The concept that has been researched at the greatest depth is a shell-and-finned-tube design. Finned-tube designs offer significant advantages with regard to heat transfer enhancement at low amounts of additional material and are therefore the focus of this paper. These concepts have been researched by, among many others, Garcia et al. [13],[14], Walter et al. [15], and Laing et al. [16].
One of the reasons for the variety of concepts in development is the relatively low thermal conductivity of PCMs. Nitrate salts can be used in the temperature range between 130 °C and 350 °C and have a thermal conductivity below 1 W/mK [17]. In finned-tubes in a shell-and-tube concept, the fins are designed to increase heat transfer to the storage medium on the shell side by extending the surface area for heat transfer using a highly conductive material. The shell-and-tube concept can be used at high pressures for steam applications. Large-scale shell-and-tube heat exchangers are built for power plants and industrial processes. An adaptation of these shell-and-tube heat exchangers for thermal energy storages is in testing or has been tested at a large scale by Garcia et al. [14] and Laing et al. [16].
Due to a pressurized heat transfer fluid (HTF), steel is the preferred tube material in finned-tube storage concepts. The fin material and design, on the other hand, are selected for very good thermal conduction and low storage material displacement. Various fin materials have been researched, including aluminum, graphite and steel, as discussed by Steinmann et al. in [10], [18]. Aluminum has been shown to be a very good choice for temperatures up to 350 °C, due to its high thermal conductivity, malleability, availability and corrosion properties [19]. Aluminum has a higher coefficient of thermal expansion in comparison to steel, which can result in elevated stresses, dismantling of the fin-tube bond or a disconnection between the fin and tube materials, if the mounting type is not designed correctly. Therefore, this needs to be considered in the bi-metal finned-tube configuration for the thermal cycling operation of a thermal energy storage unit.
As the aim of the fins is to conduct heat between the HTF and the PCM, it is generally considered necessary to have a good thermal contact between the fins and the HTF containment (i.e. tubing). Recent theoretical research by Pizzolato et al. [20] has shown, however, that this may not be the case for storages with longer discharge times and lower power levels. This contact necessity needs to be further researched for various application requirements.
All of the above discussed factors result in the need for an extended fin (EF) with a bi-metal mounting method that withstands differing thermal expansion in thermal cycling. As discussed in section 3, there are thus far no commercially available methods for assembling steel tubes with long/high aluminum fins, which are necessary for large energy capacities in latent heat thermal energy storage systems. The fin manufacturing and assembly also needs to be technically and economically feasible for a storage unit or system to be realized for large numbers of finned-tubes.
Thus far in the development of high temperature latent heat storages, the focus has been on concept development, geometry optimization, proof-of-concept testing and analysis of application integration. The analysis of specifics such as the feasibility and the economics of mounting fins onto tubes has not been the published research and development focus. With the build of larger scale storage units, this factor becomes more critical. These aspects were therefore analyzed and compared with large-scale realizable storages in mind, with a focus on longitudinal fin concepts. In this paper, three mounting methods are experimentally analyzed for their applicability in large scale high temperature latent heat storage units.

2. Description of extended finned-tube assemblies

In order to better discuss the differences in mounting methods, first the requirements and aspects of the fins and tubes in the EF tube assemblies are discussed. In EF tube assemblies for high temperature applications, steel tubing is used due to its strength at both higher temperatures and under pressure. Fins are used to increase the heat transfer surface area, thereby transferring the thermal energy more directly from the pressurized HTF into a greater portion of the PCM, which is contained at or near atmospheric pressures. Since fin and tubing material displace PCM, a minimal volume should be introduced into the system in order to maximize the PCM volume and thereby storage capacity per volume of storage unit. The requirements of the tube and fin are detailed here, including brief information about three fin designs that were tested with the clipping mounting method.

2.1. Steel tubing

In an EF shell-and-tube latent heat storage unit, the tubing has to fulfill various requirements. It needs to withstand the pressure requirements of the HTF and temperature gradients between this fluid and the PCM during both charging and discharging. In order to assemble the pressure vessel, the material must be welded together and have acceptable corrosion properties with both the HTF (water/steam) and the PCM, in these cases nitrate salts. In addition, the tubing must transmit heat between the HTF and the PCM. For these requirements, the materials 16Mo3 or P265GH were used in the discussed work, depending on the temperatures and pressures operated. There are various manufacturing methods for seamless cold rolled steel tubes [21], resulting in outside diameters varying within either ±1 % or ±0.5 mm, standardized in DIN EN 10216-2 (for tubes with less than 210.1 mm outer diameter). This variation in outside diameter can lead to variations in the physical contact between fins and tubes.

2.2. Fin designs and considerations

The fin material in EF tube assemblies needs to have a high thermal conductivity, have good corrosion characteristics with the other materials and be both malleable or be able to be manufactured in a required and desired geometry as well as be affixed to the tube.
In this analysis, mounting methods for extruded aluminum axial fins are analyzed. The alloy EN AW 6060-T6 is used for the extrusion. The T6 heat treatment results in a considerably higher strength, which allows for less sensitive handling during the assembly process. Later, during operation above the precipitation hardening temperature (ca. 120 °C) [22], the strength drops again.
Three extruded aluminum fin designs have been developed and analyzed for differing applications within work done by the authors. Due to the application differences, the storage units have differing tube materials, wall thicknesses, tube diameters and tube pitches. The fin labeled ‘A’ is discussed in more detail by Seitz et al. [1] as well as in [23]- [26]. The fin labeled ‘B’ is discussed in more detail by Johnson et al. in [27] and [7] and the fin labeled ‘C’ is discussed in more depth by Laing et al. [13]. In this article, the focus is not on the geometry or design of the fins, as this has been discussed elsewhere.
The A-fins have been mounted both with clipping and with crimping. The B- and C-fins have been mounted using the clipping method.

3. Mounting methods of aluminum extended fins

Aluminum EF need to be attached to the steel tube to allow for both the differential thermal expansions of the metals as well as maintaining good thermal contact during thermal cycling. The mounting method needs to withstand corrosion between the steel, aluminum, nitrate salts and the mounting material itself. The method needs to be practical in terms of assembly methods and economically feasible for larger scale deployment. In this paper, the authors differentiate in terminology between the mounting method – how the fins are attached to the tube – and the assembly method – how this mounting method can be assembled to produce the mounted finned-tube.

3.1. State of the art

Finned-tubes are a common design feature in heat exchangers, and as such have been widely developed and are commercially available from many companies. Methods for wrapping, extruding or shrinking the fins in various dimensions are available, among many others from [28]-[30]. Wrapping is a common method, resulting in a helical fin that can be welded, soldered or only affixed at the ends to the tubes. The fin material can also be wrapped into a pre-cut groove. The resulting fin can be serrated to allow for increased fin height at larger diameters, or can be crunched for increased turbulence on the fin side of the heat exchanger. In extruded fins, the fin material is mechanically rolled and pulled out of the tube material. This results in a uniform contact between fins and base, as it is one material. This base can be the tube itself or a second material attached to the tube. The fin height is, however, limited to a couple of centimeters. Fins can also be shrunk onto a tube by heating the fins and cooling the tube and then assembling the two. This method was analyzed for large fin heights in this work.

These existing methods are applicable for small fin spacings (< 5 mm) and small fin heights (< 20 mm), and only some of which can be used at temperatures up to 350 °C. The fin assembly methods have been developed for round fin cross-sections, which, in the case of a latent heat storage unit, lead to low packing densities of finned-tubes in the storage material and therefore would lead to large volumes of poorly used PCM. Due to these limitations in existing fin designs, EF with a higher fin height of 100 mm and more have been developed for latent heat storages.

Some of the analysis that has been done has been only theoretical in nature, analyzing which fin geometries would ideally be applicable under a variety of parameters. The methods applied in these works are, to some degree, purely mathematical and do not attempt to analyze the feasibility of the designs [31]-[33]. Fin designs analyzed theoretically as well as experimentally have been developed by, among others, Garcia et al. [13], [14], Walter et al. [15], Laing et al. [16], as mentioned in the discussion of storage concepts. The focusses in these published works were on the analysis of the fins themselves or the storage components as a whole, and not on analyzing or optimizing the mounting method. Mounting methods have been tested by Urschitz et al. for longitudinal fin structures in [34], using hose clamps or so-called expansion-ears to hold the fins onto the tube. Both results were promising, with the bending ear likely being most applicable for large-scale design. However, further development work is necessary in terms of design and manufacturability. Other published analyses of bi-metal EF mounting methods are not known to the authors.

Three different mounting methods were developed and are analyzed here – heat shrinking the materials together, using plumber's crimps [35], and clipping of the fins to the tubes [36] – as shown in Fig. 1 (a), (b), and (c) respectively.

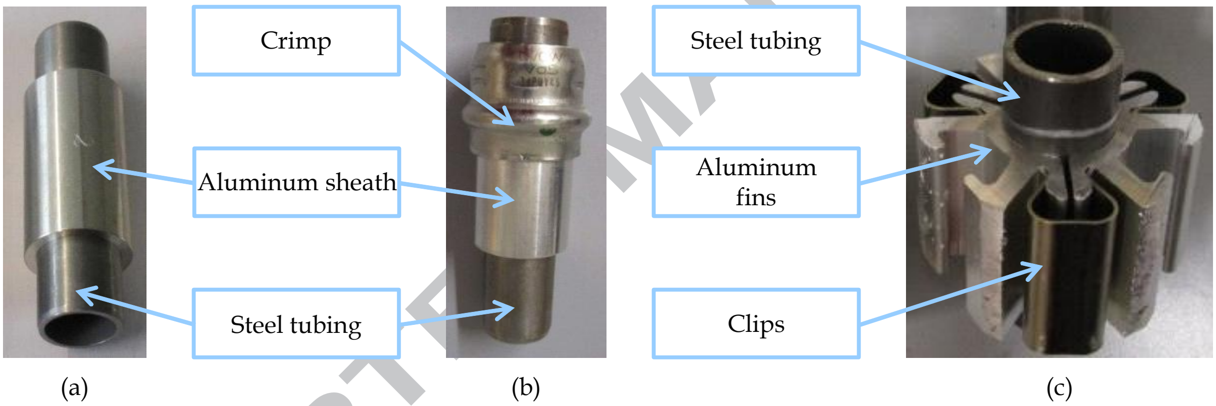


Fig. 1. Samples of mounting methods (a) heat shrinking, (b) crimping, and (c) clipping (with trimmed A-fins). The pictures show the mounting of either an aluminum sheath or the aluminum fins to steel tubing.

3.1.1. Heat shrinking

Heat shrinking was analyzed as a mounting method based on the thermal expansion of the fin material at higher temperatures prior to assembly onto a colder steel tube. This method has the benefits that it is well studied and known and that it introduces no new materials into the corrosion system.

The samples, shown in Fig. 1 (a) use a tube of 21.3 mm in diameter and an aluminum sheath with an outer diameter of 27.5 mm.

3.1.2. Crimping

In the crimping mounting method analyzed thus far, a so-called plumber's crimp was used to mount the fins onto the tube [35]. In this method, a part of the fins are removed from the fin bases, so that the crimp can be slid over both the tube and the fin bases. Samples used in one of the testing methods used an aluminum sheath instead of re-worked fins. One of these crimp sheath samples is shown in Fig. 1 (b).

This novel mounting method has been analyzed for its strength after thermal cycling (section 4.1) and in a large lab-scale latent heat storage unit (section 4.3). In this unit, a crimp was affixed around the tube and the inner fin layer using a Viega® press gun 5 with a constant pressure of 32 kN at the top of the fin length. At the bottom of the fin length, an overlapping crimp was mounted on an additional sheath, such that the fins were affixed radially but could move axially. The goal of this assembly technique was to allow for an axial expansion of the fin material during cycling, while maintaining a radial contact between fin and tube.

The development of an assembly method for this mounting style on a larger scale has not yet been conducted. As plumber's crimps are commercially available and standardized, these do not cost very much, and the strength of the crimping tool can be set as necessary. Three crimp sample types were analyzed, as shown in Table 1.

Table 1. Crimp sample parameters.

Parameter ↓/Sample →	Unit	Carbon Steel crimp with Sheath (CS-S)	Stainless Steel crimp with Sheath (SS-S)	Carbon Steel crimp with Fin (CS-F)
Crimp material		Carbon steel	Stainless steel	Carbon steel
Sheath diameter	mm	27.5	27.5	34.9*
Tube diameter	mm	21.3	21.3	26.9

* The A-fin was used here with a base thickness of 4 mm as detailed in Fig. 2 and Table 2.

3.1.3. Clipping

The third mounting method analyzed uses spring-steel clips to hold the aluminum fins onto the steel tubing, as shown in Fig. 1 (c) [36]. The clips hold the fin, which is separated into segments, to the outer tube wall. Attachment nubs for the clips are designed into the fin geometry. The tube, fin, and clip parameters are shown in Table 2. Fig. 2 shows these parameters on the A-fin using a clipped fin/tube assembly for clarification of the terms.
The spring-steel type used in the clips, type 1.4310, maintains its shape and strength through the operable temperature ranges of aluminum. Therefore, this mounting method should allow for the differing thermal expansion of the aluminum and steel parts, while maintaining sufficient contact between fin and tube to have good heat transfer by conduction. Under pressure, at higher temperatures and during thermal expansion, the soft aluminum is pressed onto the steel tube, improving the contact.
Longitudinal EF using clips (with the C-fin design) have been tested in a lab-scale storage module operated up to 330 °C for approximately 200 cycles using sodium nitrate as the PCM [13], proving their feasibility.
As the spring steel clips are costly to produce and at current rates of production cannot be standardized to reduce costs, minimizing the number of clips used per length of tubing is desirable. In addition, a better understanding of the strength of the connection in comparison to other methods can be gained by further testing.

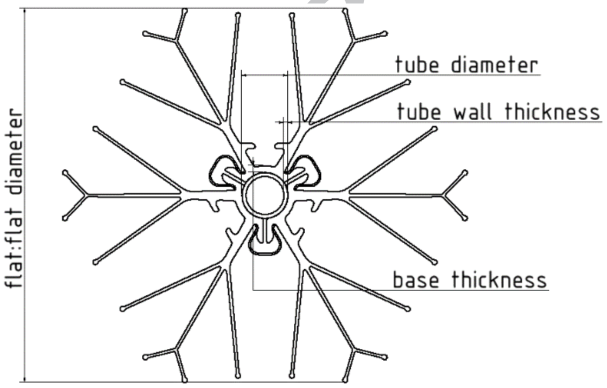
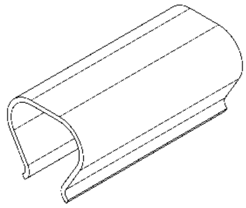
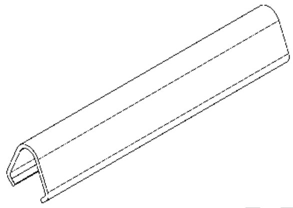
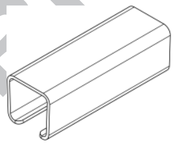


Fig. 2. Drawing of the A-fin assembled with clips to a steel tube showing the fin diameter, the fin base thickness and the tube diameter and wall thickness.

Table 2. Fin, tube and clip parameters for the analyzed clip assemblies.

Parameter ↓/Fin →		Unit	A-fin	B-fin	C-fin
Tube	Material		P265GH	16Mo3	16Mo3
	Diameter	mm	26.9	17.2	21.3
	Wall thickness	mm	2.3	2.3	2.3
Fin	Hex-Diameter (flat:flat)	mm	218.58	68.19	149.0
	Base thickness	mm	4.0	2.0	2.5
Clip	Design (at same scale)				
	Length	mm	40	60	30
	No./ Circumference		3	2	2

4. Testing methods and experimental setup

In order to analyze the connection between fins and tubes, various factors need to be assessed. On the one hand, the connection needs to be mechanically stable, also after thermal cycling. On another hand, the connection needs to allow for a good thermal contact during storage operation. Several tests were constructed to analyze these factors.

The mechanical stabilities of the three mounting methods were assessed on a small scale after thermal cycling in a salt bath through physical removal of the mounting method.

The stability of the clipping method was analyzed in vertically mounted finned-tubes that were thermally cycled and analyzed for movement of the fins.

The two most promising mounting methods from the mechanical removal tests – clipping and crimping – were tested in a lab-scale storage unit, so that a direct comparison of charging and discharging characteristics as well as analysis of the bond pre- and post-operation was possible.

This testing spectrum allows for a more complete analysis of the various manufacturing factors than an analytical approach does. Each of these methods is described here, with the results and discussion following in sections 5 and 6.

4.1. Description of cycling and mechanical removal tests

One of the tests conducted is designed to assess the thermal cyclical stability of the strength of the different mounting methods. For this, samples were mounted in an apparatus and then pressure was applied to the ‘fin’ material in a pulling motion until either the maximum load of the pneumatic cylinder was reached or the ‘fin’ base was mechanically removed, thereby measuring how much force was needed to remove the fin material. The ‘fins’ in this test were either a sheath or a reduced fin geometry. Samples were either first thermally cycled in salt and then mounted in the apparatus and reheated to the operating temperature or only heated to the operating temperature and then tested, without prior cycling. These non-cycled samples tests are the reference samples.

The samples were cycled in alumina crucibles containing sodium nitrate in thermal ovens. The samples of the heat shrinking and crimping methods were mounted using aluminum sheaths, as shown as an example in Fig. 1 (a) and (b) with an Al 6060 aluminum sheath as the ‘fin base’. The samples of the clipping mechanism were assembled using fins. In these, the fin arms were removed, leaving the tube piece, clips and fin base as depicted in Fig. 1 (c) for the sample of the A-fin clip. This was done so that the samples fit in the crucibles; as the fin arms were not necessary, this was deemed acceptable.

The cycling was conducted between 250 °C and 350 °C, with a 2 K/min heating or cooling rate and a 2 h holding plateau. For each of the cycled samples, 100 cycles were conducted. Due to the length of the cycling, availability of samples and length of the project, two samples of each type were tested.

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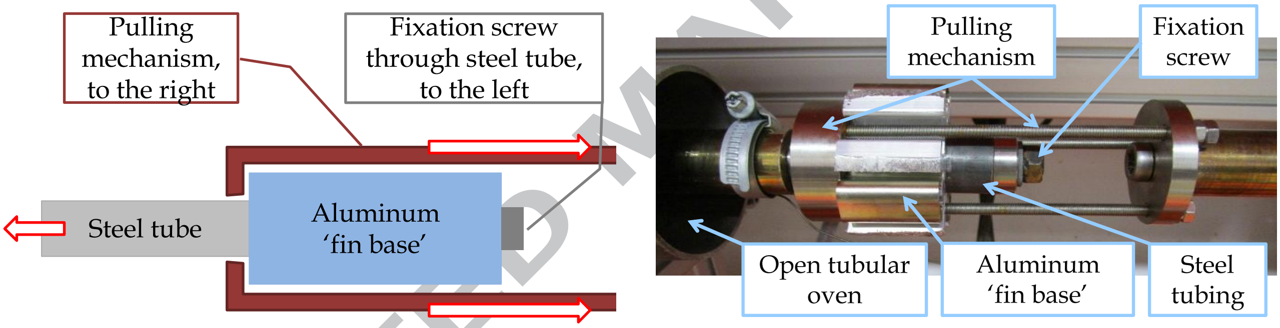
Samples are mounted into the pulling device as shown in Fig. 3. More detail is given in Fig. 4 in (a) a schematic and (b) a close-up picture.

Fig. 3. Mechanical removal testing: Pulling device with tube held on the left while the pneumatic cylinder pulls the sheath the aluminum 'fin base' to the right shown, shown with the tubular oven open.

A pulling mechanism is put over the sample, so that it can pull, via a pneumatic cylinder, on the aluminum 'fin base' to the right. A rod is slid through the steel tube and affixed with a washer and bolt of the same outer diameter as the tube, and held steady on the left. The sample is mounted in a tubular oven, in order to operate at defined temperatures (350 °C). The pneumatic cylinder pulls on the 'fin base' while distance and load are measured. For initial tests, a smaller pneumatic cylinder with a maximum load of 1700 N was used. This was exchanged for a larger one with a maximal load of 2700 N in later experiments.



(a) (b)

Fig. 4. Mechanical removal testing: Pulling device with tube held on the left while the pneumatic cylinder pulls the sheath the aluminum 'fin base' to the right shown as (a) schematic and (b) picture.

4.2. Description of cycling and movement measurement tests

In the gravity tests with vertically mounted finned-tubes, a test was constructed to determine the movement of fins on a tube during thermal cycling while subjected to gravity. To this end, tests were conducted using specimens with clipped-on fins, thermally cycled to assess movement. In this rig, tests are conducted using hot air on the HTF side of the finned-tube. On the PCM side of the finned-tube, air is heated but not circulated. The test infrastructure consists of an air heater mounted to a lower flange and an upper flange from which samples are hung, as shown schematically in Fig. 5. Surrounding the samples are removable heat tracing insulation units, and the entry and exit (top and bottom) of the testing area is closed off from the surroundings using insulation mats, in order to reduce the influence of natural convection.

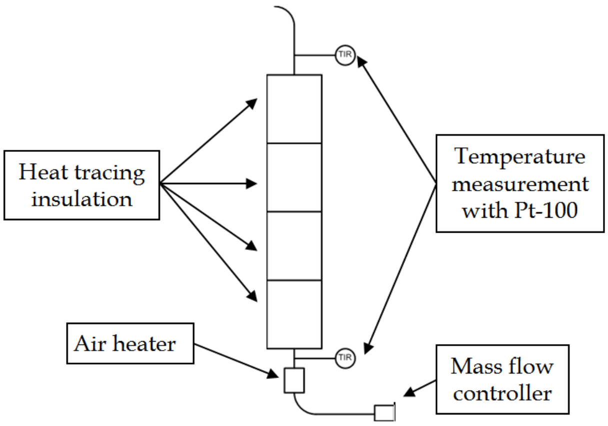
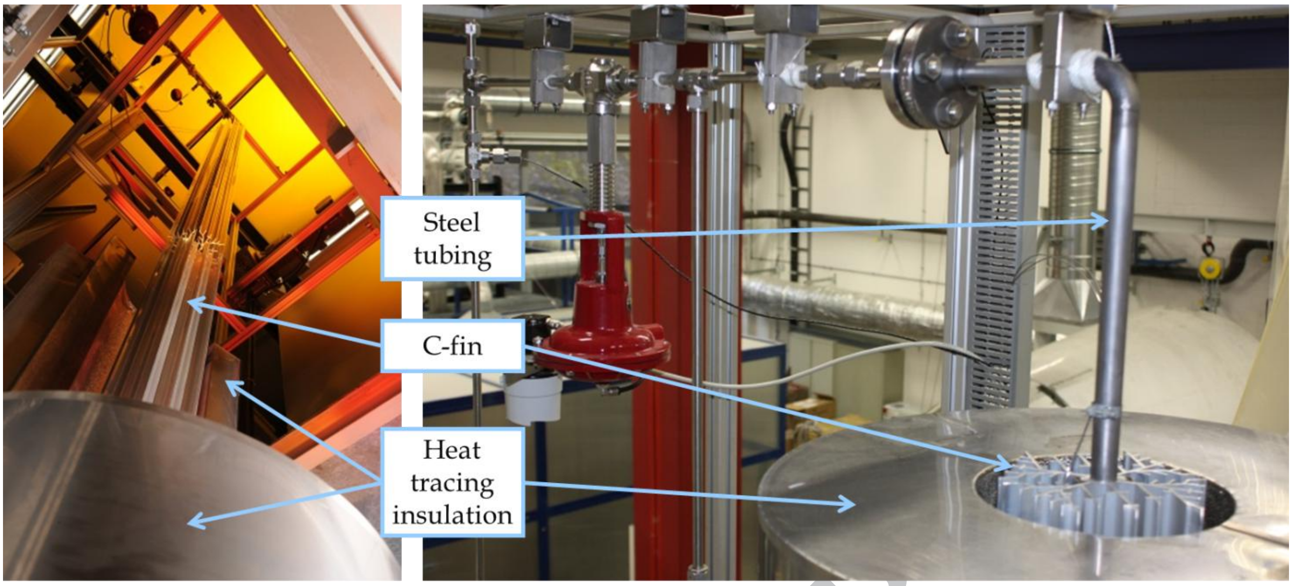
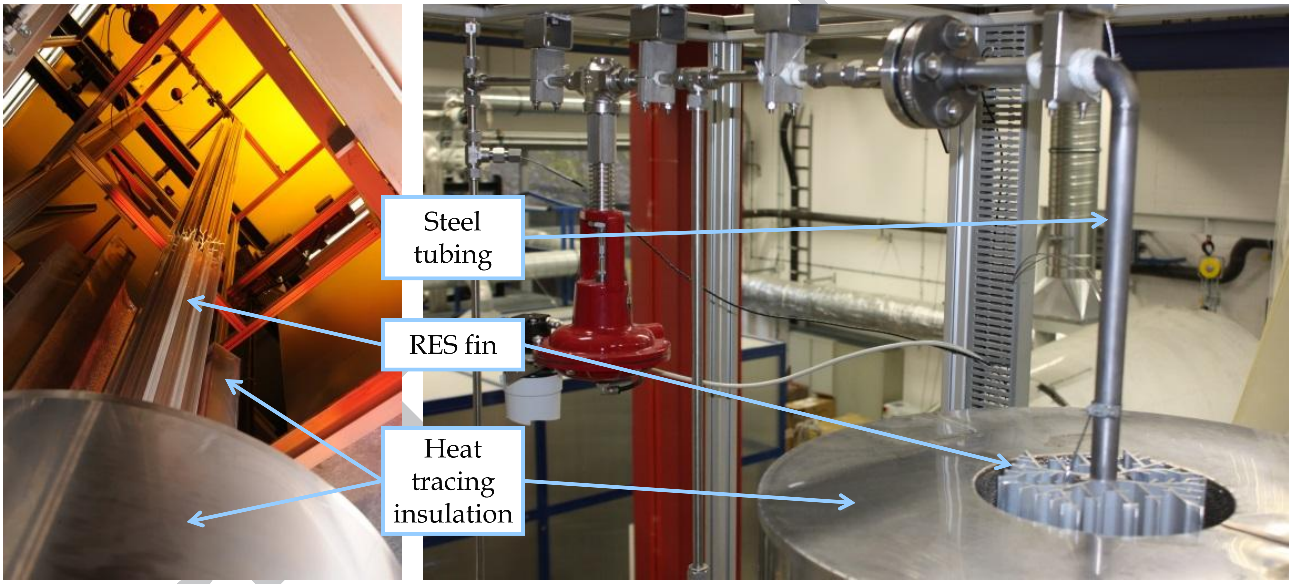


Fig. 5. Movement measurement testing: Schematic of the test rig for analyzing movement of the fins on a tube, showing the tube entering and exiting the heated insulated test section. The air in the tube is heated prior to entering the test section in the air heater at the bottom, and the temperature is measured at the entrance and exit of the test section. Mass flow is controlled prior to the heating of the air flow.

The testing tube has up to 4 m of EF mounted onto it and is vertically suspended in the rig. Using adapters, various tube diameters and a fin diameter up to 130 mm can be tested. Thermocouples are used in the control of the heat tracing insulation. For added clarity, photos of the C-fin in the test rig are shown in Fig. 6.
The temperatures were cycled to mimic the temperature ranges of various PCMs, with heating and cooling cycle lengths set to 6 h each due to the low thermal conductivity of air. Testing of both the B- and the C-fins has been conducted. The A-fin is too large in outer diameter, so that these cannot currently be tested.
The heights of the fins were measured either using a laser distance measurement or a notched cable at the beginning and end of each cycle at room temperature. This simple comparison of the position allows for the determination of permanent movement, and therefore of the stability of the bond.



(a) (b)



(a) (b)

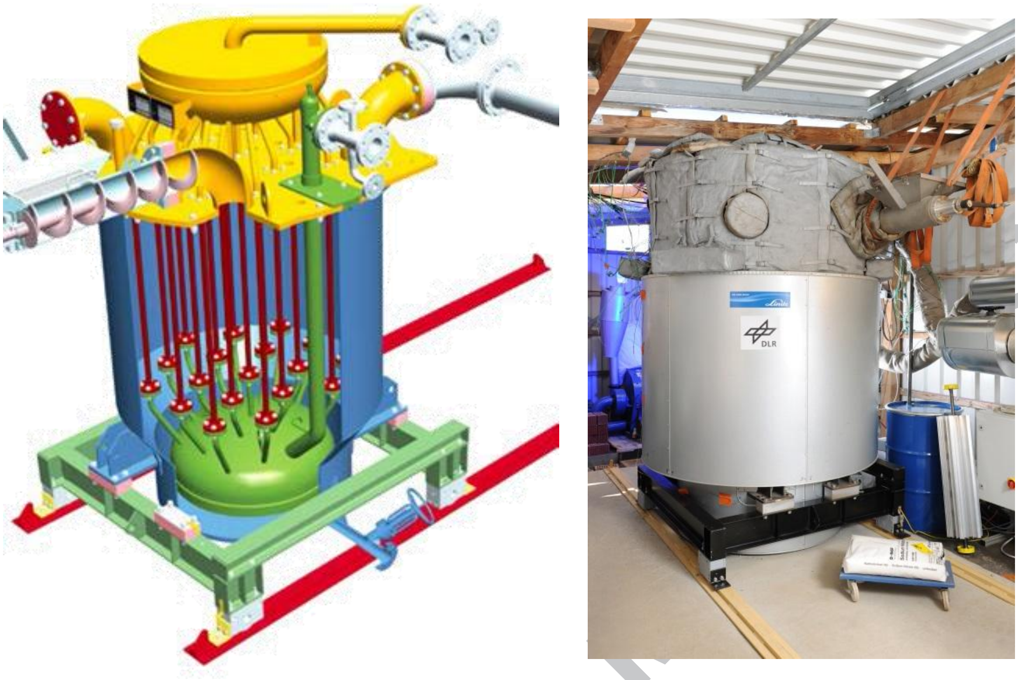
Fig. 6. Movement measurement testing: Pictures of the C-fin mounted in the gravity test rig, showing (a) the heat-trace insulation partially removed and (b) the top of the rig, with the fin at the top of the heat-trace insulation, shown without the insulation as a barrier.

4.3. Description of testing under operating conditions

A storage unit was built to verify modeling of the A-fin geometry and to test several design features, as reported in [23]-[26]. A schematic of the storage unit and a picture of the assembled unit are shown respectively in Fig. 7 (a) and (b). Two mounting methods – crimping and clipping – were tested in this environment. This gives more insight into thermal cycling in salt of longer fin pieces and their mounting methods than can be determined from lab-scale oven tests. Data from thermocouples mounted in the PCM are used to compare similar test parameters for the thermodynamic properties of the fin-tube connection in a PCM environment.

The storage unit is built with an upper header from which the tube register hangs. This is surrounded by an insulated container with 3.3 tons of sodium nitrate as the PCM. The 18 finned tubes with a 0.8 m finned-tube length in this test rig are flanged between the two headers. These flanges make it possible to change tubes in the assembly. Thermal cycling was conducted up to 350 °C, with temperatures measured during cycling and

optical analysis of the mounting method conducted before and after testing. A full set of tests were conducted with the clipping mounting method.
For the crimping mounting method, two central tubes were switched to this type of mounting method and comparative tests measured. Switching only two tubes allowed for a comparison between tubes in the same test, to ensure that other parameters remained the same.



(a) (b)

Fig. 7. Operating condition testing: Laboratory scale storage unit for testing the optimized fin design and comparing the clipped and crimped fin-tube assemblies shown in (a) the design cut-out, without fins on the (red) tubes for clarity and (b) as-built in the testing environment.

5. Results

Results from the three testing methods – cycling and mechanical removal tests, cycling and movement measurement tests and testing under operating conditions – are described with the test plans in the following sections.

5.1. Results of cycling and mechanical removal tests

Mechanical removal tests were conducted with all three assembly methods. As the heat shrinking samples disassembled with gravity while removing them from the cycling crucible, all further work with this method was abandoned.
The load displacement diagrams comparing reference (uncycled) and cycled samples of three different crimp samples detailed in Table 1 are shown in Fig. 8. Data from one of the samples is shown. Results from the sample pairs were comparable.
Both crimp samples using a carbon steel crimp (CS-F in red/skinny and CS-S in green/mid-thickness) show no relevant change in the load displacement between a reference (R) and a cycled (C) sample. Due to the similar coefficient of thermal expansion of the carbon steel tube and the carbon steel crimp, the thermal cycling and elevated temperatures do not affect the mounting. In all four sample types, the aluminum sheaths could not be removed from the tubes. Also, a difference in general slope is observed, with the CS-F sample having a steeper slope. This shows that the sample is mounted even more firmly.
The SS-S sample (grey), on the other hand, has a significant loss of strength between the reference (R, solid) and cycled (C, dash) sample. The stainless steel crimp material has a slightly higher coefficient of thermal expansion in comparison to the tube material. This difference results in a loosening of the mounting at elevated temperatures and the removal of the aluminum sheath with a force of approximately 1500 kN. Thus, stainless steel crimps are not suitable in combination with carbon steel tubes.

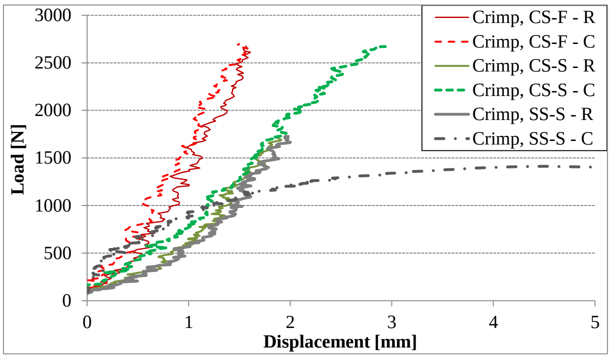


Fig. 8. Mechanical removal testing: Load displacement diagram of reference (R) and cycled (C) samples of the carbon steel (CS) and stainless steel (SS) fin (F) and sheath (S) based samples.

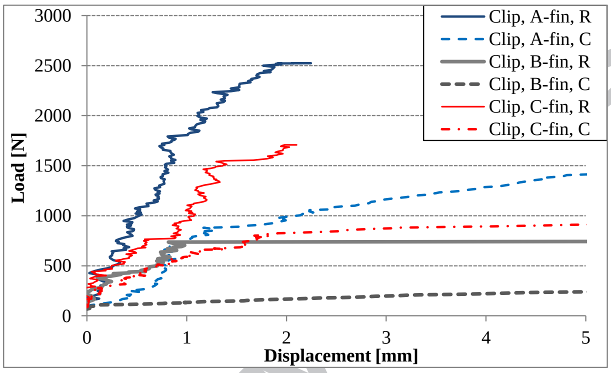


Fig. 9. Mechanical removal testing: Load displacement diagram of reference (R) and cycled (C) samples of the clip mountings.

In the clip samples shown in Fig. 9, the differences between reference (solid) and cycled (dash) samples is clear for all three types. The A-fin (blue) and C-fin (red) mountings are firm as reference samples; after cycling, both of the A-fin and C-fin mounting can be pulled along the tube, though the A-fin mounting requires a higher load. The B-fin (grey, thick) can be dismounted even in the reference state. After sampling, the B-fin (grey, dash) is moved constantly with increasing load.

5.2. Results of cycling and movement measurement tests

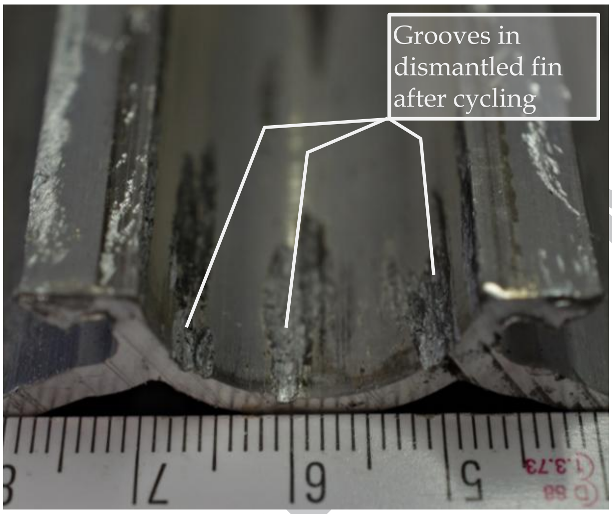
Shown in Table 3 is a summary of the tests and results with the C- and B-fins, mounted in the cycling and movement measurement test rig via clipping with different numbers of clips. The temperature was cycled between an upper and a lower temperature.

Two C-fin mountings were tested; one with two segments, each 2 m long, with 50 % clips per length and the other with four fin segments, each 0.95 m long and with different numbers of clips. After each temperature range, the unit was cooled to room temperature and movement was checked. Thereafter, the next higher temperature range was cycled. None of the segments showed any enduring movement. All tests were conducted on the same inner tube. Dismantling of the fins from the tubes showed material deposits on the tube and grooves on the fins (see Fig. 10), showing evidence for a thermal weld between the aluminum and the steel during cycling and likely a very good thermal contact.

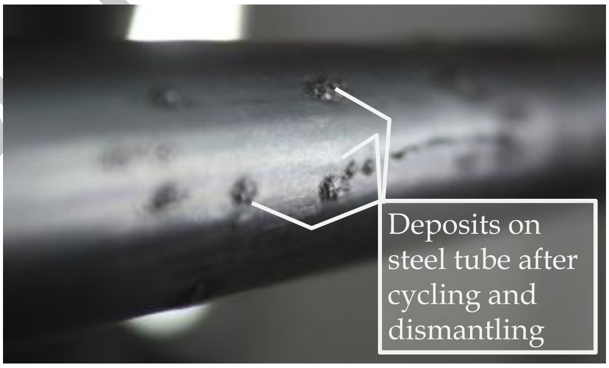
Two B-fin samples with 20 % and 26 % clips were tested, which were mounted in two 1.8 m sections per tube. In the 20 % tests, with the lowest number of clips per length, there was 4 mm movement of the fins at the lowest cycling temperature range of 100-220 °C. There was no further movement during the higher temperature ranges. With 26 % clips, there was no movement in any of the temperature ranges.

Table 3. Movement measurement testing: Test plan and results for the cycling and gravity tests. Each temperature range was cycled 100 times.

Fin	Fin length(s) [m]	Clips [%]	Lower and upper plateau temperatures [°C]	Movement
C-fin	2*2 m	50	100-220 175-275 285-325	none
	4*0.95 m	47 40 27 9.5	175-275 285-325 Constant at 340 ca.2months	none
B-fin	2*1.8 m	20	100-220	4 mm
			175-275 285-325	no further movement
		26	100-220	none
			285-325	none



(a)



(b)

Fig. 10. Movement measurement testing: Material exchange and marking of fins after thermal cycling and dismantling of the fin-tube assembly in fins mounted with clipping to tube with (a) grooves in the fin on the mounting surface between fin and tube and (b) deposits on the steel tube.

5.3. Results from testing under operating conditions

Various cycles were measured with both the clipping and the crimping mounting of the A-fins in the storage unit. First results were reported by Johnson et al. in [24]. The aspect of interest in this paper is the direct comparison of the thermodynamics of the two mounting methods as well as analysis of the fins and tubes after dismantling.

The analysis of a discharging cycle shows a large time difference between clipped and crimped finned-tubes in reaching a reference temperature. This reference temperature is set to 300 °C to make sure that all PCM is solidified. Fig. 11 presents the results of a cycle with an HTF temperature that is 20 K below the melting temperature (306 °C) for two thermocouple measurement positions (pos20 and pos30) in the fin geometry of the central tube's middle measurement level. The measurements at other positions are discussed in [24]; these positions were chosen for analysis for their representative positions. The blue lines refer to pos20 for both the clipped and crimped mounting and the red lines refer to pos30 of the same. The crimping method results in a several hour slower discharge with + 27 % and + 21 % for the two positions under the same conditions. This shows that the heat transfer is much better in the clipped mountings than in the crimped ones.

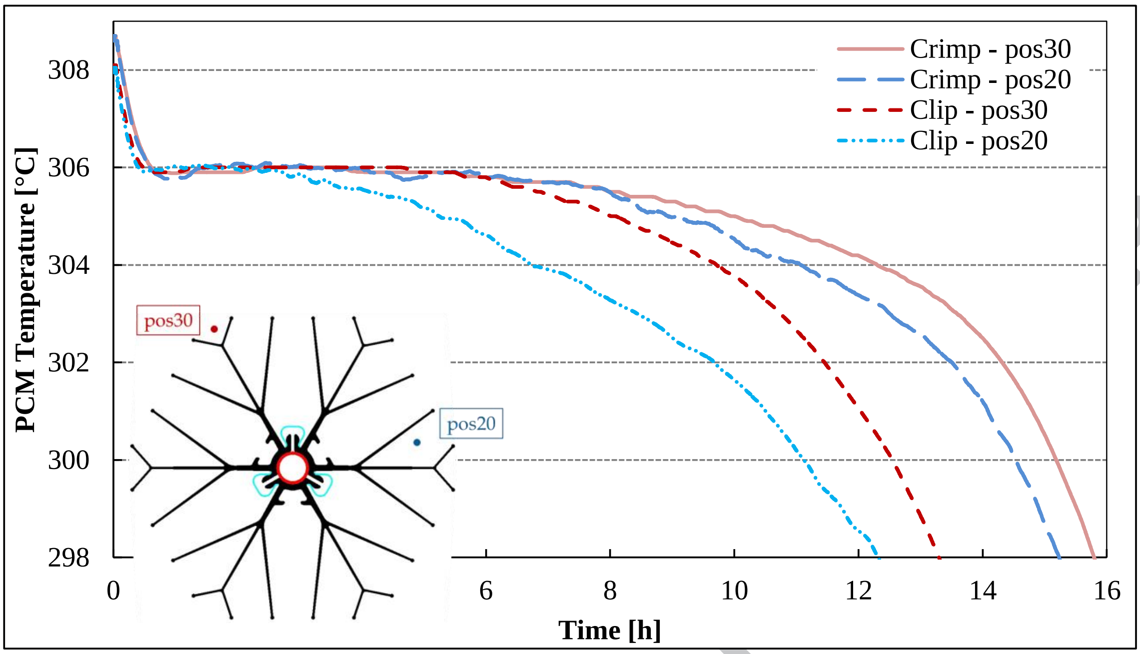


Fig. 11. Operating condition testing: PCM temperature over time for two measurement positions during discharging with HTF temperature 20 K below PCM melting temperature for both clipped and crimped A-fin geometries.

A similar behavior is observed when analyzing a charging cycle with an HTF temperature that is 20 K above the PCM's melting temperature. The reference temperature for measuring the time difference is set to 306.3 °C for two reasons. First, in contrast to the solidification process, a clear end of the phase change process is visible. Secondly, the natural convection balances the temperature distribution with the PCM, meaning that the temperature increase in positions that melted early is slowed down. Once all of the PCM is melted, the temperature increases uniformly in all positions. This effect is not observed in the solidification process because of the heat transfer limitation due to heat conduction only. This limitation during solidification has been shown in [24] and can be observed by comparing the much faster melting time in Fig. 12 to the slower solidification time shown in Fig. 11 for comparable test conditions.

Fig. 12 also compares the clipping and crimping mounting method using the A-fin geometry, based on the temperature for the pos20 and pos30 in the central tube's medium measurement level. Again, this tube is chosen for its representative results. The figure shows a significantly slower melting time and, thus heat transfer for the crimping mounting method differing by + 41 % for pos20 and + 30 % for pos30.

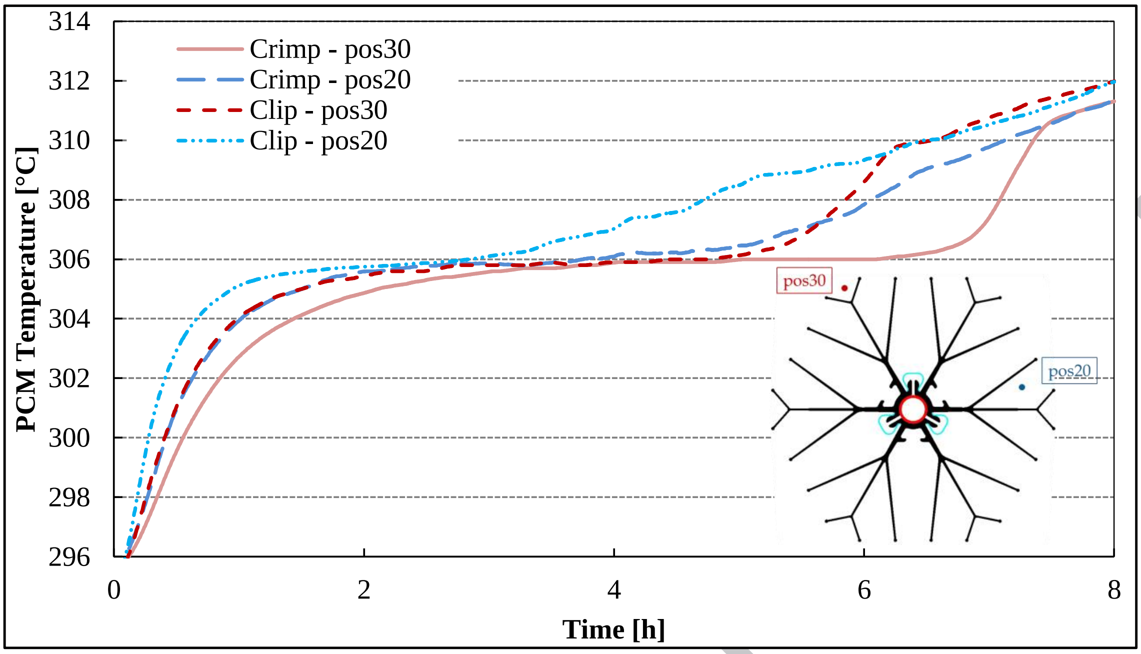


Fig. 12. Operating condition testing: PCM temperature over time for two measurement positions during charging with HTF temperature 20 K above PCM melting temperature for both clipped and crimped A-fin geometries.

After the experiments were concluded, the tubes were dismantled. In the clipped fins and tubes, there was a constant layer of rust along the entire fin length, as shown in Fig. 13(a). This shows that there were large surface areas with contact between the fins and tubes, confirming the results of the cycling and movement measurement tests discussed above.

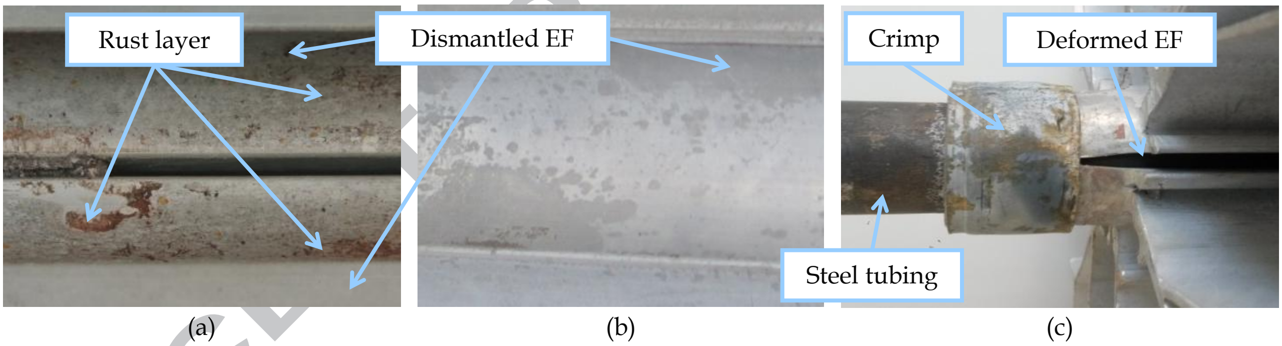


Fig. 13. Operating conditions testing: Dismantled components after testing under operating conditions. Inner side of a fin from a (a) clipped assembly and (b) crimped assembly. (c) Crimped assembly showing gap between fins and tube.

Dismantling of the crimping showed no rust on the fins (Fig. 13(b)). In addition, a gap had developed between the tubes and the fins, shown by the fin deformation in Fig. 13(c). The fins were mounted with a fixed bearing crimping at the top and a sliding bearing crimping at the bottom, to allow for thermal expansion. A radial expansion in the middle of the fins was expected, as the fins were held radially only at the top and bottom. However, the size of the gap, also at the bottom of the tube, suggests that the sliding bearing did not slide as much as would have been necessary for an acceptable level of thermal contact. With a gap between the fin and the tube, there is no good thermal contact. This explains the much slower cycle times seen in Fig. 11 and Fig. 12.

6. Discussion

The mechanical removal of the mounting method only gives insight into one bond, and not the strength created by the friction of an entire fin length pressed to an entire tube length. Therefore, the results for the clipping method in the mechanical removal tests are conservative. In addition, testing of a larger number of samples would strengthen the results shown here.

The movement measurement tests were conducted with air as both the HTF and the surrounding ‘storage material’. In a storage unit, there is PCM salt around the tubes and aluminum fins. Salt has a negative change in volume from the liquid to the solid state, see [17], so that any salt that creeps between the fins and tubes does not expand during solidification as water/ice does, but shrink. Therefore, a ratcheting of the space between fin and tube would not occur. The results show that a possible issue of concern – the softness of aluminum at higher temperatures – is actually of little concern. Even the B-finned-tube with only 20 % and the C-fin with 9.5 % clips per tube showed no movement at higher temperatures. This is likely due to the weld-type bond formed between the aluminum and steel at higher temperatures with the movement of the materials in thermal expansion.

Testing under operating conditions showed that the crimping method has significantly slower discharge times than the clipping method. This time difference is caused by a gap between the HTF tube and the fins, limiting the heat transfer at this interface. Both charge and discharge cycles show similar time differences, meaning that the main heat transfer limitation is caused by this gap, but not by the dominant heat transfer between PCM and fin, i.e. heat conduction during discharge and natural convection during charging. However, for a detailed understanding of the creation of the gap and the quantitative heat transfer performance, further research with a different experimental setup is necessary.

Apart from the mentioned assembly methods, first trials were conducted by soldering the fins to the steel tubes. The trials at ambient temperatures showed promising results with regard to the bond strength, but further development and testing concerning the assembly method and thermal cycling is required.

7. Conclusions

Although these tests were conducted with a variety of tubes and fins as described above, the combination of all of these tests gives good insight into the methods of creating a durable mounting method in finned-tube assemblies in high temperature latent heat storages. Only the clipping method showed promising results with regard to the bond strength and the heat transfer performance. The crimping method offered the highest bond strength, but could not achieve a similar heat transfer performance as achieved for the clipped tubes. Finally, the heat shrinking method proved not to be feasible due to the missing bond strength at high temperatures.

However, to better understand why the gap for the crimping method occurred, a more detailed analysis of a single finned-tube and the fin-tube connection is recommended. First gravity cycling tests for the preferred clipping mounting method show that even with a low number of clips per tube, the fin can be held through thermal cycling. Another possibility is to combine the crimping and clipping methods for ensuring both a high bond strength as well as sufficient thermal contact. These results can be used for reducing costs and optimizing design of high temperature latent heat storages.

Acknowledgements

The authors thank the German Federal Ministry of Economic Affairs and Energy for the financial support given to the DSG-Store project (Contract No. 0325333A and 0325333D) and the TESIN project (Contract No. 03ESP011A).

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