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Coil-wound heat exchangers for molten salt applications

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Abstract

In this paper, the application of two types of heat exchangers under molten salt service in thermal energy storage plants is investigated. At first, relevant TES processes (direct and indirect) are analyzed and boundary conditions for the heat exchangers are defined. As a more detailed example, application for indirect storage in a parabolic trough plant employing HTF-oil is investigated and a comparison of shell-and-tube and coil-wound type exchanger is presented.
It is shown, that the coil-wound type exchanger can leverage its specific advantages as e.g. compactness, higher efficiency of heat transfer and inherent ability to withstand thermal shocks leading to a cost-effective and innovative solution which ultimately enhances operation of a thermal energy storage plant and reduces investment cost in various aspects.

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1. Introduction

Thermal Energy Storage (TES) is seen as one measure to reduce levelized cost of electricity in concentrating solar power (CSP) plants. In addition TES delivers added value through providing dispatchable solar power, which is important, if a high level of renewables energies like wind and photovoltaics fed into the grid. Currently, two-tank indirect molten salt TES is seen as proven and bankable technology. However, various technological concepts are in research and development phase or even being deployed like direct storage in molten salt receiver tower plants.

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In any TES plant, the molten-salt heat exchanger is a central plant component and much development effort has been seen to qualify shell-and-tube heat exchangers for operation with the storage fluid, commonly a mixture of nitrate salts. The reason for having special attention to this type of equipment are challenges of thermal design due to the requirement of low temperature approaches, thermal stresses during start-up or temperature and pressure cycles during change of modes of operation as well as the special nature of the storage fluid with the risk of freezing at temperatures below 238°C or increased corrosion at elevated temperatures.

This paper investigates the use of an alternative type - a coil-wound heat exchanger (CWHE) – for this application.

2. Features of CWHE

Generally, a CWHE comprises multiple layers of tubes spirally wound around a central pipe termed mandrel. The tubes are typically wound from tube coils which allows for a design with comparatively long tube lengths. Spacer bars are used to fix tube position and adjust layer spacing. The winding direction is changed for each tube layer. The tubes are welded to one or more tube sheets at the end of the exchanger and after completion the bundle is wrapped into a shroud to reduce bypass flows at the exchanger shell. Finally, the bundle is inserted into the prefabricated shell. Figure 1 shows a large tube bundle before wrapping into a shroud.

Fig. 1. CWHE tube bundle during production process and schematic drawing

It can be seen that several smaller tube sheets instead of one big tube sheet are used in this design, which is an option to reduce tube sheet size within one exchanger. Alternatively, the CWHE allows for several tube side streams, which is favorable if different media have to be heated or cooled by the same shell-side fluid. Tube sheets can either be arranged on the sides, but it is also possible to arrange a tube connection on the top and the bottom.

Several variants can be designed with the tubes being connected to the central mandrel, to a half-sphere or directly to a tube sheet welded to the shell. In all cases, there will be a so-called pigtail which is the summary of all tubes forming a bow. This is one special feature and provides elasticity to the tubes in cases of thermal shock. An example of a 2-stream exchanger with the tube sheet located on the top and bottom and shell-side access nozzles on the sides if shown in Figure 2.

Tube diameters, tube spacing, inclination and tube length as well as number of tube layers are optimized during thermal and hydraulic design. CWHEs have been built in various materials of construction like aluminum, carbon and stainless steels as well as special alloys. Single units of up to 250 metric tons can be manufactured in the workshop and if required, larger sizes can be built on external yards.

The benefit of a CWHE is its compactness, i.e. large exchanger area per volume, which lies between shell-and-tube and plate heat exchangers. Specific volumetric surface values are ranging between 20-300 m^2/m^3. Heating surfaces of up to 40'000 m^2 can be installed in one unit. Furthermore, favorable heat transfer conditions due to continuous cross flow over tubes allow for efficient use of exchanger area. Counter-current flow with very low amount of bypasses provides possibility for very close temperature approaches down to 1.5 K. The special mechanical design mentioned above with the tube bundle acting as a spring allows for quick start-up and transient operation. Also during upset or plant trip conditions, robust behavior is a key element of this type of equipment.

CWHEs are used in various processes e.g. for the liquefaction of natural gas, for cooling in gas treatment plants (Rectisol®, cryogenic) and as isothermal reactor in methanol plants or CO shift units. Up to now, no reference exists employing molten salt as heating medium. This paper is the first step to investigate feasibility of a CWHE for the use with molten salts.

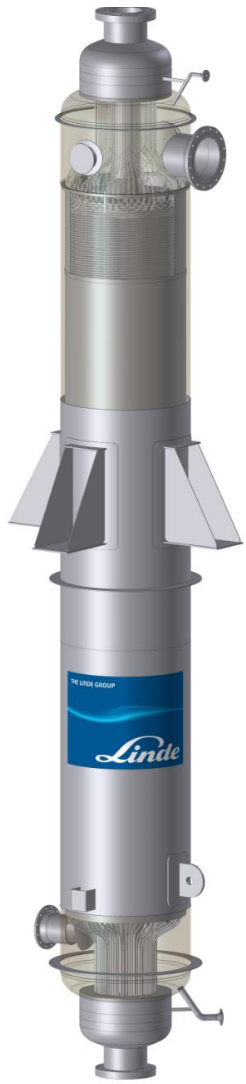

Fig. 2.Model drawing of 2-stream CWHE.

3. Application in CSP

3.1. Overview of thermal energy storage processes.

Various CSP technologies are being deployed at the moment, utilizing line (parabolic trough, fresnel) and point focus (solar tower, dish) concentrating approaches. The heat transfer fluids (HTF) that may be used to recover absorbed energy from the sun are among others HTF-oil (e.g. Dowtherm® A, Therminol® VP1, Lanxess Diphyl®), water/steam, air or CO_2.

Also molten nitrate salts, with composition depending solidification temperatures between 140°C-238°C, are used as HTF. Furthermore, new types of molten salts with constituents like $LiNO_3$ or $Ca(NO_3)_2$ are being researched at the moment [1] with the aim to reduce the melting point. Molten salts are also preferential as storage media due to their comparatively high heat capacity, non-toxicity, low vapor pressure and availability in large quantities. Currently, the typical mixture of 60% $NaNO_3$ and 40% KNO_3 by weight termed "solar salt" is used in the vast majority of all TES plants in operation and under construction.

Concepts employing molten salt both as storage medium and HTF are termed direct storage concept. In this case the molten salt heat exchanger is essentially a steam generator. During the Solar Two project, a molten salt steam generator was tested. The system consisted of shell-and-tube heat exchangers and a Kettle type evaporator, see e.g. [2].

In contrast, concepts with differing HTF and storage medium are termed indirect storage. In this case, the storage medium is charged by the HTF during the day. If irradiation is not sufficient to operate the power block directly from the solar field/tower, the storage medium discharges thermal energy to the HTF. To reduce equipment and consequently cost, the molten salt heat exchanger is typically operated in both modes, charge and discharge mode sequentially. Indirect storage has been shown with HTF-oil and molten salt, e.g. in the Spanish Andasol plants. Again, shell-and-tube exchangers are used, typically 6 shells in series [3] are installed with a total heat exchanger area in excess of 15'000 m^2. This high amount is required due to the low mean temperature difference (MTD) of approximately 7 K over the whole temperature range.

Concepts and patents exist, where also water/steam is used as primary HTF and molten salt as storage medium. In contrast to a steam generator in direct storage concept, also de-superheating and condensation has to be realized in the salt heat exchangers to charge the storage fluid, as published in e,g, [4].

In all cases, the risk of freezing salt as well as thermal shocks during start-up and cyclic operation require a high effort of engineering and specialized solutions. In the next paragraph, general requirements for operation with "solar salt" will be defined. However, in principle the requirements are also valid for other salt mixtures.

3.2. General requirements

First and foremost, special attention has to be taken to the fact that the salt starts crystallization below 238°C and completely solidifies at 221°C. Consequently, during start-up and operation, the HTF or water entering the heat exchanger shall have a temperature above 240°C. In a direct storage plant for example, a start-up electrical heater has to be installed to guarantee this precondition for the feed water.

Proper insulation and heat tracing reduce heat losses and allow for maintaining the temperature of the content of the heat exchanger during stand-by periods. Furthermore, heat tracing can be used to heat-up the shell during start-up from ambient temperature and therefore reduce thermal shock on the shell as well as excessive temperature differences between shell and tube bundle. To achieve this, the exchanger shell should be heat traced in several separated circuits or zones as to already establish a shell-side temperature profile during heat-up.

In case of long term stand-by or for maintenance purposes, the operator will need to drain the heat exchanger from molten salt. Hence, full drainability of the heat exchanger has to be guaranteed. Salt, that that isn't drained, will freeze. This in turn leads to a volume contraction of the freezing salt, which is not critical. An issue with frozen salt will occur only during remelting of frozen salt. As the salt will expand, stress will be enacted on the equipment, if the expansion is hindered. This may be for example the case in the shell side of the tube sheet, where little voids between the tubes and tube sheets may exist. Consequently, proper heat exchanger design has to guarantee full drainability by elimination of dead zones.

Thermal shock during start-up, change in modes of operation or plant trips effect in thermal stress and eventually in fatigue failure of the heat exchanger. Attention to mechanical design and selection of thermal shock resistant types of heat exchangers supported by finite element analysis are therefore required to reduce the risk of tube leakage. A heat exchanger with higher resistance to thermal shock will also give a benefit to the operator due to quicker start-up and therefore reduced loss of thermal energy. For example, start-up gradients of 5 K/min were realized during the Solar Two project [2] whereas by selecting a once-through benson-type boiler, it is hoped to increase this value to 15 K/min in the future [5].

Finally, depending on the quality of the salt, corrosion aspects need to be considered during material selection. It is well known from the literature that with higher chloride content in the salt and higher salt temperature increased corrosion is observed. Mo-alloyed carbon steels are typically resistant up to 450°C if sufficient corrosion allowance is provided. Higher corrosion resistance is provided by stainless steels. In addition, salt quality also determines the content and size of insoluble particles, typically sand. Even though the specified content is in the range of 0.02%, for a typical Spanish TES plant, this accumulates to 6 metric tons of insolubles. Of course, part of these insolubles can be separated during the initial melting process, see Figure 3.

Fig. 3. Insolubles separated during initial melting process.

However, as there is no guarantee that all insolubles can be removed and particles may accumulate especially in dead flow zones in the tanks or heat exchanger. Consequently, a heat exchanger design with very low amount of dead flow zones is more favorable.

4. Design comparison

4.1. General

In order to gain detailed information about the impact of the advantages of molten salt CWHE, a design comparison between CWHE and STHE is made for a reference project. This reference project consist of a TES using “solar salt” as storage medium and Therminol-VP1 as HTF-oil, with a maximum temperature of 391°C. Storage capacity is designed to be in the range of 8 hours with approximately 28 MW_{el} electrical power generated. In charge mode, the HEX heats up the salt coming from the cold tank and entering the hot tank from approx. 286°C to 386°C by using hot HTF from the solar field. In discharge mode, the same heat exchanger operates the other way around and heats up cold HTF to approx. 377°C by using the hot molten salt of the hot storage tank.

For this task a complete thermo-hydraulic design has been carried out for each exchanger. The requirements like basis of design, process data, allowed pressure drop limits, fouling resistances and design temperature and pressure are set equal for both exchangers. The exchangers itself are designed in a way, that each technology can make best use of its specific advantages to minimize the necessary heat transfer area. A separate cost optimization for the CWHE lead to the conclusion that the exchanger can be manufactured cheaper with stainless steel tubes, as they are available in long tube coils. Due to the higher material quality, less corrosion allowance is required for the tubes.

For the STHE, the TEMA (The Tubular Exchanger Manufacturers Association) type BFT is used. F-shell design is required to have a long pass of counterflow and T-head (floating head) design is selected to provide good thermal expansion properties. For material of construction, Molybdenium-alloyed carbon steel is selected, which is in line with standard molten salt practice.

The results of this comparison are divided into different aspects and shall be presented in the following.

4.2. Number of units

Due to the compactness, the CWHE can be built in one shell only. This shell has a length of approx. 26m with a diameter of approx. 2.4m. The total weight of this heat exchanger is around 140 metric tons.

When using the TEMA design, 3 shells in series are required to cover the necessary heat transfer area. Those shells have outer dimensions of approximately 26m length and 1.7m diameter. The diameter of these shells is limited by the tube sheet thickness, which is necessary to withstand the pressure difference between the tube side and shell side passage. The maximum tube sheet thickness is given by the feasibility of manufacturing. The total weight of the 3 TEMA heat exchangers is approx. 300 metric tons.

Several aspects can be concluded from the information given above. For the TEMA version, interconnecting piping is needed in between the shells, which is not necessary when using the CWHE. Further, more shells have also disadvantages regarding the inert mass for warm-up and dead spots. More shells stand also for a higher number of tube sheets, which increases the risk of tube leakages. As the shells are to be connected in series, regarding the higher number of shells as a redundancy aspect is not valid here. Higher weight of the STHE concept will also infer higher cost for steel structure. In summary, the weight difference between the two concepts stems from three different aspects. Firstly, higher number of shells require more tube sheets and shell material. Secondly, as stated above due to less corrosion allowance required, the tube bundle made from stainless steel in case of the CWHE also reduces overall amount of material. Third, the two concepts have a difference in exchanger area, which is shown in the next paragraph.

4.3. Exchanger area

To reach the required duty, the CWHE needs an area of approx. 8100 m². The overall heat transfer coefficient for discharge case is around 1470 W/m²K with an EMTD of 6.9 K (effective mean temperature difference).

The total area of the 3 TEMA heat exchangers is approx. 11950 m². The overall heat transfer coefficient for those exchangers is approx. 1150 W/m², the EMTD is 6.0 K.

Due to the better flow distribution and mixing in the CWHE, this technology shows a higher overall heat transfer coefficient. Further, this type of heat exchanger has nearly no bypass streams, which contributes to a higher EMTD compared to STHE. Apart from bypass streams, one reason for the worse EMTD of the TEMA heat exchanger is heat loss over the longitudinal baffle. Both, the higher heat transfer coefficient and the better EMTD of the CWHE result in a significantly lower necessary heat transfer area of this exchanger type.

4.4. Pressure drop

Since both exchanger types are designed with the aim of minimizing both area and investment costs, the maximum allowed pressure drop is fully exploited if possible. For the tube side, this results in using 16 mm tubes for the STHE and 12 mm tubes for the CWHE. The reason for the smaller diameter of the CWHE type is the fact, that the tube length is around 100 m in contrast to a total tube pass length of 150 m of all three STHE in series. Single tube lengths of 100 m are possible in the case of the CWHE as tube coils are used. With this configuration, both types show a tube side pressure drop of 5 bar.

On the shell side, the pressure drop of 6 bar is fully exploited by the TEMA heat exchanger. Because of limitations in height, the CWHE cannot be designed long enough to make full use of the available pressure drop. Therefore, the shell side pressure drop of the CWHE version is approx. 3 bar, which saves pumping cost on the molten salt pump. Leveraging higher pressure would potentially further reduce the exchanger area, which is not necessary in this case as the CWHE already shows a high improvement compared to STHE. Furthermore, reduced pumping cost will also influence overall project economics due to lower parasitic consumption.

5. Conclusion

The present work investigates basic requirements for heat exchangers in molten salt service and provides a detailed comparison of two types of heat exchangers.

It was shown that a CWHE provides advantages in various aspects relevant for cost, as e.g. less exchanger area due to higher EMTD and higher overall K-value and less number of shells. These aspects not only relate to less exchanger cost but also reduce cost on steel structure and piping. Apart from these obvious factors, soft factors provide additional benefit. For example lower pressure drop on the shell side will reduce parasitics due to lower pumping cost. In addition, stainless steel quality materials of construction will give higher safety margin regarding corrosion. Furthermore, the tube bundle acting as a spring can be regarded as inherent design against thermal shock which in turn improves start-up times for the CWHE.

The following Table 1 gives an overview about the main results of the comparison between STHE and CWHE design.

Table 1. Comparison Overview CWHE vs. STHE (TEMA)

	Unit	CWHE	STHE (TEMA)
Total Effective Area	[m²]	8100	11950
Shell ID	[m]	2.4	1.7
No. of Shells	[]	1	3
Total Length of Bundle	[m]	20	26
Total Length of Shell	[m]	26	28
Tubes OD	[mm]	12	16
Tubecount per Shell	[]	2150	3300
Tube lengths	[m]	100	25.8
Shellside dp	[bar]	3	6
Tubeside dp	[bar]	5	5
Overall K	[W/m²K]	1470	1150
EMTD	[K]	6.9	6.0
Total Duty (combined)	[MW]	82	82

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