Influence of the Fin Design on the Melting and Solidification Process of NaNO_3 in a Thermal Energy Storage System

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Abstract: The melting and solidification process of sodium nitrate, which is used as energy storage material, is studied in a vertical arranged energy storage device with two different bimetal finned tube designs (with and without additional lateral fins) for enhancing the heat transfer. The finned tube design consists of a plain steel tube while the material for the longitudinal (axial) fins is aluminum. The investigation analyses the influence of the lateral fins on the charging and discharging process. Three-dimensional transient numerical simulations are performed using the ANSYS Fluent 14.5 software. The results show that, every obstruction given by lateral fins reduces the melting and solidification velocity in direction to the outer shell.

Key words: Thermal energy storage, latent heat, sodium nitrate, numerical simulation, fin design.

Nomenclature

c_p	Specific heat at constant pressure (J/(kg·K))
H	Total enthalpy (J/kg)
H_s	Sensible enthalpy (J/kg)
H_{lat}	Latent enthalpy for the phase change in a numerical control volume (J/kg)
k	Thermal conductivity (W/(m·K))
L	Latent heat of fusion (J/kg)
S	Source term (J/(m ³ ·s))
t	Time (s)
T	Temperature (K)
$\vec{v}$	Velocity (m/s)

Greek Letters

γ	Liquid fraction (-)
ϕ	Volume ratio (-)
ϑ	Celsius temperature (°C)
λ	Thermal conductivity (W/(m·K))
ρ	Density (kg/m ³)

η Dynamic viscosity (kg/(m·s))

Subscripts

lat	Latent
liq	Liquidus
ref	Reference
s	Sensible
sol	Solidus
W	Wall

1. Introduction

A reduction of the greenhouse gas emissions (referred to 1990) as well as an increase of the energy efficiency of 20% is set by the European Union as a target up to 2020. To achieve this ambition goal, it is necessary to increase the target share of renewable energies in the energy consumption as well as the energy efficiency. This relates to the situation that renewable energies, energy storage and energy distribution will be the most important and strongly growing market of the next decades and hence also key topics for research and development [1].

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As described in Ref. [2], a measure to increase the energy efficiency is the increased use of the industrial and manufacturing sectors waste heat [3, 4]. For manufacturing purposes, many of these industries require steam from industrial furnaces which operate to a large extent in batch mode. Therefore they have a large potential for waste heat utilization. A thermal energy storage device can help to transform the intermittent waste heat flow to a continuous heat flow. The well-known problems of some renewable energy sources—discrepancy between power generation and demand—result in a problem for the power grid frequency, which must be constant. At the moment, conventional power plants are driven by demand to keep the frequency stable. Based on the discontinuous feeding of e.g., solar and wind energy a drastically expansion of the power supply as well as of energy storage systems is needed. Here too thermal energy storage devices can be used because it is more cheaply to store heat than electricity [5]. But the creation of storage capacity is slow compared to the increase of the renewable energy sources.

So the thermal energy storage systems (sensible as well as latent) illustrate, beside other storage possibilities, an attractive method to store electrical energy as well as heat if they are integrated in thermodynamic cycles such as Rankine-, Brayton cycle, or heat pump process, etc. [6-9].

The present paper deals with the numerical analysis of the charging and discharging of thermal energy into a latent heat storage system with sodium nitrate (NaNO_3) as storage material. In such a system, the thermal energy transfer occurs when a so called PCM (phase change material) changes the aggregate state (phase) from e.g., solid to solid, solid to liquid, liquid to gas, or solid to gas and vice versa. Initially, the temperature of PCMs increases like a conventional storage material as they absorb heat. Compared to sensible storage materials, PCM absorbs and release heat at a nearly constant temperature and they can store 5-14 times more heat per unit volume than sensible

storage materials such as water, sand, or rock [10]. This result in a significant reduction of the storage volume using PCMs as storage material compared to sensible heat storage devices.

Compared to the solid to liquid transition, the liquid to gas and solid to gas phase changes have a higher latent heat of phase transition. But the transition to the gas phase is associated with a large change in volume. This will result in a containment problem (by increasing the system pressure during the phase change) and therefore the potential for thermal energy storage is small. According to Refs. [11, 12], this large change in volume makes the system complex and non-practical. However, the phase change from solid to liquid is also connected with a change in volume. Refs. [10, 11] have reported that, the transformation from solid to liquid and vice versa involve only a small change (of order of 10% or less relative to the original volume) in volume. On the other hand, many salts and composition materials undergo considerable changes in volume at the fusion, exceeding 10% [13].

Based on the latent heat of melting (enthalpy of fusion), the heat storage capacity of PCMs is large. However, the low thermal conductivity of many prospective PCMs, especially organic material with e.g., approx. 0.15 up to 0.3 W/(m·K) or the salt hydrates with approx. 0.4 up to 0.7 W/(m·K) [13-19], makes it difficult to utilize this capacity effectively. To enhance the heat transfer into PCMs, various techniques have been suggested, like fins [17, 20-22], metal and graphite-compound matrices [23-25], dispersed high-conductivity particles inside the PCM [26, 27], and micro-encapsulation [28, 29].

In the last decades, a higher number of analytical [30-37] as well as numerical methods [38-43] were developed to describe the melting and freezing process of a material under the influence of gravity. The main problem concerning the numerical simulation of the melting and/or solidification process is the change with time of the position of the phase interface. As reported in Ref. [30], more than the half of all investigations done

on latent heat thermal storage systems were numerically and the most used models are 2D [39, 41, 43]. The very slow laminar flow (buoyancy-driven flow) and the variation of the physical properties of the PCM during the phase change result in difficulties for the numerical simulation. But the main challenge of such problems is the presence of a moving liquid-solid interface involving a strong coupling of mass and heat transfer. To get accurate results, very small time steps as well as a fine structured computational grid is necessary. Therefore long computation time can be expected even for small 3D models.

A roughly classification of the mathematical models used for the numerical simulation of phase change problems with free convection can be done into multi-domain and single-domain methods [42].

The balance equations for momentum and energy are solved in each phase in the multi-domain method [39, 41, 44]. Between the two phases, a time dependent interface (phase change boundary) is arranged, which is modeled by a porous zone. While in the porous zone, a very fine mesh is necessary to calculate the physical process in a correct way the computational grid in the surrounding area can be coarse meshed. Based on the moving interphase between the two phases, it is reasonable to implement an adaptive grid.

In the most commercial programs, the so call h-method is used for such an adaptive grid. This method starts the simulation with a uniform mesh. During the simulation, additional cells are added or removed at required positions in the computational domain. However, the handling of the data structure is the major challenge of the method, because at every time step, the position and the number of cells changes. To avoid this problem, the so called r-method (relocation) can be used, where the number of cells is constant. The required mesh density will be achieved by moving the cells at the phase interface.

Compared to the multi-domain method, the single-domain method uses the balance equations for

momentum and energy for the entire physical domain [45-47]. The region between the liquid and solid phase will be calculated also with a porous zone. Based on the continuous transition between the two phases strong discontinuities, which can result in numerical instabilities, are avoided. The size as well as the quality of the discretization of the porous zone is important for the calculation result. A widely used single-domain method is the enthalpy-porosity method [38, 42, 47-52]. This model includes latent heat effects as a source term and includes a technique to ensure that, the velocity field vanishes in the solid region [42].

With the above described methods, detailed investigations on the melting and solidification behavior can be done. However, based on the long computation time, which is a result of the high number of computational cells, among others, only small systems can be analyzed. For investigations of e.g., the overall behavior of thermal energy storage devices other approaches must be chosen [35, 37].

In the present paper, results of a numerical study on the melting and solidification behavior of a latent heat storage device with NaNO_3 as heat storage medium will be presented. To enhance the heat transfer into the storage material vertical arranged tubes with longitudinal fins are used. The paper compares the results of 3D simulations with two different heat exchanger tube designs (with and without lateral fins). The tube design with lateral fins is installed in the test rig at the laboratory of the IET (Institute of Energy Systems and Thermodynamics) at the Vienna University of Technology (Fig. 1).

This tube design should be optimized in direction of a fast charging and discharging process and also in direction of an increasing volume ratio (ratio between the volume of PCM divided by the volume of PCM plus volume of finned tube) of the storage device. In a first step of this optimization process, the influence of the lateral fins on the charging and discharging process was analyzed numerically.

2. Physico-Mathematical Model of the Latent Heat Storage System

2.1 Physical Model of the Latent Heat Storage System

Fig. 1 shows the heat exchanger tube used in the present study for the heat transfer from the working fluid inside the bimetallic tube to the surrounding NaNO_3 which is used as phase change material. The heat exchanger tube is used in a vertical arrangement and is part of a test rig in industrial scale at the laboratory of the IET [53, 54]. The heat exchanger tube consists of a circular steel tube and an aluminum tube with longitudinal fins (total tube length is 3 m) to overcome the low thermal conductivity of the PCM material. To reduce the costs for the extrusion profile of the aluminum tube with the longitudinal fins, only a segment, which is a sixth of the total aluminum profile, was manufactured (Figs. 1 and 2). To secure a good contact and an approx. constant surface pressure between the steel and the aluminum fins, heavy-duty clamps are used for the heat exchanger tube implemented in the test rig (Fig. 1). The TES (thermal energy storage system) contains a higher number of

such units that are cascaded and stacked to meet the needs of TES capacity and operating parameters. But the thermal expansion will be hindered by the heavy-duty clamps. Therefore lateral fins are implemented to stabilize the structure of the aluminum segments. As heat transfer fluid Therminol VP-1 with a maximum flow temperature of approx. 400 °C (at approx. 11 bar) is used. Therminol VP-1 is thermally stable and suitable for operation over long periods at bulk temperatures up to 370–400 °C. As mentioned in Ref. [55], aluminum fins can be applied for temperatures below 400 °C. It has been proven that, there is no degradation of the material after testing more than 400 h with NaNO_3 as PCM [11, 55].

Fig. 2 shows a schematic view of the cross section of the analyzed heat exchanger tube with the denotations used in the present paper.

2.2 Mathematical Model

In the present work, the commercial computational fluid dynamics-code ANSYS Fluent was used to obtain the numerical solution. In ANSYS Fluent, the enthalpy-porosity approach [47] is used to calculate

Fig. 1 Sketch of a segment of the aluminum fin and layout of the bimetallic tube used in the test rig at IET.

Fig. 2 Sketch of the heat exchanger tube with denotations.

the phase change problem. The enthalpy-porosity method depends on the liquid volume fraction γ which denotes the ratio of volume of liquid to the total volume in each cell. Therefore, the liquid fraction γ describes the fraction of a cell volume which is filled with liquid. For the calculation, the computational domain in the PCM will be divided into three regions: solid, liquid and mushy zone. With this technique, the melting front is not calculated explicitly. Instead of that, the quantity liquid fraction γ is computed at each time step for every cell based on the enthalpy balance [56]. Computational cells where the phase of the material changes (mushy zone) are modelled as a pseudo porous media with liquid fraction γ ranging between 0 and 1, for solid and liquid, respectively, while $0 < \gamma < 1$ denotes the mushy zone. Thus, the energy equation used here for the PCM system yields to:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + S \quad (1)$$

with the total enthalpy:

$$H = H_s + H_{lat} \quad (2)$$

and the sensible enthalpy:

$$H_s = H_{sref} + \int_{T_{ref}}^T c_p dT \quad (3)$$

The enthalpy change during the phase change (latent heat) can be written as a function of the liquid fraction and the latent heat of fusion $H_{lat} = \gamma L$. Based on the method proposed by Ref. [57], the liquid fraction γ can be determined by the temperature:

$$\left[\begin{array}{lll} \gamma = 0 & \text{if} & T < T_{sol} \\ \gamma = 1 & \text{if} & T > T_{liq} \\ \gamma = \frac{T - T_{sol}}{T_{liq} - T_{sol}} & \text{if} & T_{sol} < T < T_{liq} \end{array} \right] \quad (4)$$

In which the temperature T_{sol} and T_{liq} determines the size of the mushy zone. As described in Ref. [56], an iteration between the energy Eq. (1) and the liquid fraction Eq. (4) is done for the calculation of the temperature. This method was suggested by Ref. [57], because a direct calculation of Eq. (4) to update the liquid fractions results in poor convergence of the energy Eq. (1). The basic conservation equations of continuity, momentum and energy were solved numerically, using the ANSYS Fluent 14.5 software. The pressure-velocity coupling is solved with the help of the COUPLED scheme, which is implemented in ANSYS Fluent.

The following assumptions are made for the numerical simulations:

- (1) Both the solid as well as the liquid phase is homogeneous and isotropic, and the melting process is symmetric within a segment;
- (2) The NaNO₃ in the liquid phase is considered an incompressible and Newtonian fluid;
- (3) The volume change upon phase change is ignored;
- (4) For the molten PCM laminar flow as Newtonian fluid is assumed;
- (5) It is assumed that, the PCM has an ideal solidification behavior. Therefore the subcooling effects are neglected and the solidification temperature is constant.

We assume that, the solid is homogeneously distributed in the mushy region. As mentioned above, the enthalpy-porosity approach [47] is adopted for the PCM. For the mushy zone constant, the standard value of ANSYS FLUENT with $C = 10^5$ was used.

The thermo-physical properties for the aluminum finned tube and the steel tube are taken from the ANSYS Fluent properties data base and they are summarized in Table 1.

Table 1 Thermal physical properties of aluminum and steel.

Materials	Thermal conductivity (W/(m·K))	Density (kg/m ³)	Spec. heat (J/(kg·K))
Aluminum	202.40	2,719.0	871.00
Steel	16.27	8,030.0	52.48

For the phase change material NaNO₃ no thermal physical properties are available in the ANSYS Fluent data base. Therefore a UDF (user defined function) was programmed for these properties.

Important values for the numerical simulation of phase change problems are the melting temperature, the heat of fusion, the spec. heat capacity, the heat conduction, the dynamic viscosity and the density. In the literature, different data for the melting temperature of sodium nitrate are available. In this work, a melting temperature of $\vartheta = 306^\circ\text{C}$ is used for NaNO₃, which is based on Refs. [58, 59]. The heat of fusion is taken from Ref. [59] with $L = 176.256\text{ kJ/kg}$. It can be seen in Refs. [58, 59], which have made a comparison with a higher number of published data, that the gradient of the spec. heat capacity in the liquid region of the NaNO₃ is approx. constant. In the solid region of the sodium nitrate, the spec. heat capacity shows a slight upward trend starting from the environment temperature up to the melting temperature. Additionally, in the region close to the phase change (approx. $250^\circ\text{C} < \vartheta < 300^\circ\text{C}$), the spec. heat shows a local maximum as a result of the change of the crystal structure. However, the spec. heat capacity for the solid as well as liquid NaNO₃ was modelled with the constant value of $c_p = 1,635\text{ J/(kg·K)}$ (this is the value of the liquid NaNO₃) based on Refs. [58, 59].

For the density of the sodium nitrate in the solid region, the value of $2,119.6\text{ kg/m}^3$ was used according to Refs. [58, 60, 61], while for the liquid region, an equation based on the data of Ref. [62] is developed:

$$\rho_{liq} = 1,890 - 0.6(T - 593.15) \quad (5)$$

A comparison with available data in the literature shows that, Eq. (5), which is used for the liquid density of NaNO₃ in this work, is located between the data of Refs. [63, 64].

Following [65], the dynamic viscosity of the liquid PCM has been expressed as:

$$\eta_{liq} = 0.0251 - 6.054 \times 10^{-5}T + 3.871 \times 10^{-8}T^2 \quad (6)$$

For the thermal conductivity in the liquid region, the correlation of Ref. [66]:

$$\lambda_{liq} = 0.62 - 1.787 \times 10^{-4}T \quad (7)$$

was used in the UDF. Based on the measurement data of Ref. [58], following equation for the thermal conductivity in the solid region was derived:

$$\lambda_{sol} = 1.2 - 9.067 \times 10^{-4}T \quad (8)$$

If different values for a physical property at the solidus and the liquidus line are given, then a linear interpolation between these values is done to get the thermo-physical properties in the mushy region.

2.3 Numerical Model for the Simulation

For the numerical simulation of the melting and solidification behavior of the phase change material, it is impracticable to model the whole heat exchanger tube (for large storage devices, the tube can have a length up to maybe several meters, for example as mentioned above, in the test rig of IET, a finned tube length of approx. 3 m is used) because of enormous computing resources consumed. Therefore many studies are made with a 2D domain.

As shown in Ref. [49], it is not possible to use a 2D domain for the complex heat exchanger tube which is analyzed in the present study, because in the 2D case, a plane crosswise to the center axis must be used for the numerical simulation. The results presented in Ref. [49] have shown that, natural convection is neglected and only heat conduction is taken into account by the 2D simulation of a computational plane crosswise to the center axis using this complex tube geometry.

Therefore, a 3D simulation was made in the present study.

For the 3D simulations, only a half of the aluminum fin segment presented in Fig. 1 was used for the computational domain (Figs. 3 and 4) to reduce the number of control volumes and shorten the computation time. A normal downwardly-directed gravity field (in direction of negative z-axis, see Fig. 3), with the corresponding gravitational acceleration of 9.81 m/s^2 , is considered in the 3D simulations.

Figs. 3 and 4 show a sketch of the computational domains used for the numerical simulation of the two different analyzed finned tube geometries. The geometries of the heat exchanger tubes used for the numerical simulation of the charging and discharging behavior of the NaNO₃ are equivalent to the finned tube segment presented in Fig. 1. Design case 1 (Fig. 3) includes lateral fins, while the second analyzed case,

Fig. 3 Computational domain of the heat exchanger configuration with lateral fins (design case 1).

Fig. 4 Computational domain of the heat exchanger configuration without lateral fins (design case 2) and boundary conditions for both cases.

which is presented in Fig. 4 do not include the lateral fins (design case 2). In both cases, the computational domain consists of a steel tube and an aluminum tube with fins and the PCM sodium nitrate. The dimensions of the aluminum fin segment used for the numerical models are depicted in Fig. 1. The dimension of the steel tube, which is not included in Fig. 1, is $\varnothing 33.7 \times 2 \text{ mm}$. The vertical dimension of the model (height in direction of the z-axis) is 20 mm. The volume ratio φ , which is defined as:

$$\varphi = \frac{\text{Volume of the PCM}}{\text{Volume of the PCM} + \text{Volume of the finned tube}} \quad (9)$$

for the computational domain of the heat exchanger design, with lateral fins is 0.8544 and that for the design without lateral fins is 0.8628.

In Fig. 4, also the boundary conditions used for the numerical simulations of both design cases are depicted. At the top and the bottom as well as at the outer shell, an adiabatic wall is defined. For both lateral surfaces, symmetry boundary conditions are used. For the numerical simulations, the initial temperature of the whole system (steel tube, aluminum profile and NaNO₃) was 296 °C for the melting and 316 °C for the solidification process. The surface temperature T_w , which represents the boundary condition at the inner steel tube diameter surface to the heat transfer fluid, was 326 °C for the melting and 286 °C for the solidification process. For the melting as well as solidification process, T_w was kept constant during the whole simulation.

The number of computational cells used for the 3D simulations depends on the model and was built of approx. 107,420 control volumes for the model with lateral fins and 121,889 for the model without lateral fins [67]. The grid was determined after a careful examination of the results of a grid refinement process [67]. As time step for the numerical simulation, a value of 0.05 s was used, which is also a result of preliminary tests [67]. A further decrease of the time step did not shown noticeable changes in the results.

3. Results and Discussions

3.1 Comparison of the Analyzed Design Cases

3.1.1 Melting Process

In Figs. 5 and 6, the evolution of the liquid fraction of the sodium nitrate at specific points of time (180 s, 450 s and 1,050 s after simulation start) for the two different heat exchanger tube designs are presented. As it can be seen in these figures, the melting of the PCM is not vertically symmetric—it starts at the upper surface and then the melting front grows downwards and synchronous in direction to the outer shell of the sodium nitrate. Thus, an asymmetric melting behavior over the height is given. The molten NaNO_3 rises up along the aluminum tube wall and the cooler liquid sodium nitrate flows downward along the solid NaNO_3 . A vortex flow arises in the melted zone, which helps to enhance the heat transfer to the solid-liquid layer of the NaNO_3 . This indicates that, the influence of natural convection (buoyancy-driven currents) during the charging process plays an important role. This behavior

of the PCM during the melting process compares well with e.g., Refs. [53, 54, 68].

In a detailed view, it can be observed in Fig. 5a that, the melting zone at the upper surface of the sodium nitrate first starts to grow in the edge of the main chamber (denotation see Fig. 2) of the heat exchanger tube where the aluminum tube and the main fin are connected together. In the following, the main melting process occurs in the main chamber and in the space between the main and second fin (see Fig. 5b, 450 s after simulation start).

The first lateral fin of design case 1 prevents the buoyancy-driven fluid flow of the liquid NaNO_3 in the main chamber in direction to the outer shell. Therefore, the melting front in the main chamber moves downward. This results in a decreasing temperature difference between the main chamber and the steel tube. As a consequence, the total heat transfer into the sodium nitrate decreases too. The averaged liquid fraction of the NaNO_3 450 s after simulation start is 6.81% (for comparison, the design without the lateral

Fig. 5 Contours of the liquid fraction evolution of the PCM during melting, design without lateral fins.

Fig. 6 Contours of the liquid fraction evolution of the PCM during melting, design with lateral fins.

fins has an averaged liquid fraction of 8.12% at the same point of time). The melting process of the sodium nitrate in the small chamber starts very slow. Because the temperature difference between the solid NaNO_3 and the fin material is low. 1,050 s after simulation start the sodium nitrate in the small chamber is still in the melting process. It can be seen in Fig. 5c that, compared to the melting process presented in Fig. 6c, a relatively great part of the NaNO_3 is still in the solid state.

Compared with the design case 1, the development of the melting process of the NaNO_3 of the second analyzed fin design, which is presented in Fig. 6 for specific points of time, is different. While the starting phase of the melting process is identical for both fin designs, the development of the melting front over the time is changed. This can be observed already in Fig. 6a, which shows the liquid fraction 180 s after simulation start. The buoyancy-driven circulation of the melted NaNO_3 is not restricted by a lateral fin and thus, the melting front can be spread unobstructed along the fin branch in direction to the outer shell. As presented in Fig. 6b, the main melting front is developed along the branch of the fourth fin. This behavior illustrates a total different melting process of the sodium nitrate compared to design case 1, where the main melting process occurs in the main chamber. During this period, the melting process of the PCM for the design case 2 is mainly detached at the top with a low inclination downwards. Compared to that, the developing of the melting process in the spaces between the main and fourth fins is approx. the same for both design cases during the first 450 s of simulation.

A comparison of the melting process presented in Fig. 5c and Fig. 6c shows that, in case of the design without lateral fins, the melted region of the NaNO_3 is larger and therefore a faster charging can be realized.

It can be also observed in Figs. 5c and 6c that, the development of the melting front for both design cases is different. The melting process of the PCM in the

main chamber of design case 1 is finished and the natural convection of the NaNO_3 in the small chamber in direction to the outer shell is hindered by the second lateral fin. Thus, the cooler sodium nitrate flows downward along the second lateral fin. The heat transfer mechanism in direction to the solid sodium nitrate located behind the second lateral fin is heat conduction. During this period, a great part of the melting process of the PCM of design case 1 takes place in the space also between the main and second fin and between the second and third fin.

Based on the circumstance that, no lateral fin is implemented in design case 2, the melting front grows along the branch in direction to the fourth fin. After reaching the top of the fourth fin, the melting front flows around the fourth fin into the space between the third and fourth fin and with a time delay also around the top of the third fin into the space between the second and third fin. This will result in a larger melted NaNO_3 region by using the heat exchanger tube design case 2.

A comparison of the temperature distribution in the sodium nitrate 180 s after simulation start between both design cases is depicted in Figs. 7 and 8. It can be identified in Fig. 7 that, a higher temperature field in the NaNO_3 is surrounding the main chamber at the top and along the fins whereas a lower temperature is given in the center and the bottom of the main chamber. This is a result of the higher heat conductivity in the aluminum fins compared to the NaNO_3 and the buoyancy-driven flow. The same behavior can be observed in Fig. 8 for the design without the lateral fins. But based on the absence of the lateral fins, the natural convection flow is not retarded and thus the higher temperature field is only given at the top and along the fins. In this case, the development of the higher temperature is mainly given at the top of the sodium nitrate.

The time sequences of the volume averaged temperature and of the volume averaged liquid fraction of the NaNO_3 for both analyzed design cases are

Fig. 7 Geometry with lateral fins: contours of the temperature in the PCM 180 s after simulation.

Fig. 8 Geometry without lateral fins: contours of the temperature in the PCM 180 s after simulation.

compared in Fig. 9. It can be also observed for the different analyzed cases, the point in time where the melting process of the sodium nitrate is completed. As mentioned above, the lateral fins slow down the melting process. Thus a time difference of approx. 600 s is given between both melting end points. As a consequence of the faster melting process of the model without lateral fins, the increase of the liquid fraction is sharper compared to the design with lateral fins.

Fig. 10 shows the evolution of the charged power. It can be seen that, the graphs for the charged power differs between the two heat exchanger tube designs. The charged power for the design with lateral fins is approx. constant over a long period of time. This constant period consist over the most of the melting time and is based on the blockade of the natural convection fluid flow by the lateral fins. Based on this circumstance, the overall charging time is greater compared to the design case 2. The decrease of the

Fig. 9 Chronological sequence of the volume averaged temperature and liquid fraction for the models with and without lateral fins during the melting process.

Fig. 10 Chronological sequence of the charged power for the models with and without lateral fins.

charged power after the complete melting of the PCM (increase of the sensible heat in the PCM up to the storage temperature) is similar for both fin designs.

It can be concluded for the melting process that, the unrestricted natural convection plays a key role for a faster melting process. Every obstruction given by e.g., lateral fins or branches from radial arranged fins reduces the melting velocity in direction to the outer shell.

3.1.2 Solidification Process

In Figs. 11 and 12, the contours of the volume averaged liquid fraction of the sodium nitrate during the discharging process at selected points of time for both analyzed design cases are presented. At the beginning of the discharging process, the NaNO_3 is in the state of liquid phase and circulates over the whole external shell of the finned tubes. This is a result of the natural convection which is based on the temperature difference between the sodium nitrate (based on the initial condition) and the heat transfer fluid (represented by the boundary condition of the inner tube wall

Fig. 11 Contours of the liquid fraction evolution of the PCM during solidification, design with lateral fins.

Fig. 12 Contours of the liquid fraction evolution of the PCM during solidification, design without lateral fins.

surface temperature T_w). As it can be seen from Figs. 11a and 12a, the solidification process starts at the bottom of the computational domain and along the outer tube surface. This is on the one hand, a result of the natural convection where the cooler NaNO_3 moves down to the bottom and on the other hand, on the lower wall surface temperature of the aluminum compared to the NaNO_3 -temperature during the discharging process. It is evident that, this result is in good agreement with results presented in e.g., Refs. [53, 54, 68].

A direct comparison of the solidification process presented in Figs. 11a and 12a shows a different behavior between the two analyzed design cases at this early stage of discharging process. While for the design case 2, the solidification of the sodium nitrate starts over the whole bottom of the computational domain with a decreasing solid thickness in direction to the outer shell, the solidification process of the NaNO_3 used in the design case 1 takes place primarily in the main chamber.

With progress of the discharging process, the

solidified layer of the NaNO_3 increases. Thus the buoyancy driven flow will be restricted by the growing solid sodium nitrate. An additional heat resistance is given by the solidified NaNO_3 layer. As a consequence heat conduction takes place in the solidified NaNO_3 region, which will be the significant heat transfer mechanism during the solidification process and the natural convection gets less relevant.

With the help of Figs. 11 and 12, it can be seen that, the lateral arranged fins hinder the progress of the solidification process in direction to the outer shell. Therefore the process of the solidification of the sodium nitrate for the design case 1 is different to the design case 2, which can be also observed in the curves for the volume averaged liquid fraction in Fig. 13. But a comparison between the melting and solidification process shows that, the lateral fins do not have such a great influence on the solidification process than to the melting process. Furthermore, it can be seen that, the solidification process is more uniform compared to the melting process.

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Fig. 13 Chronological sequence of the volume averaged temperature and liquid fraction for the tube designs with and without lateral fins during the solidification process.

Fig. 14 Chronological sequence of the discharged power for both heat exchanger tube designs during the solidification process.

In Fig. 13, the time evolution of the volume averaged temperature as well as of the volume averaged liquid fraction of the NaNO_3 for both analyzed heat exchanger tube designs is illustrated. From Fig. 13, it can be seen that, there is no significant difference in the graphs of the volume averaged temperature between the different design cases during the first 2,500 s after simulation start. The temperature drop down to approx. melting temperature during the first period of the discharging process is fast compared to the temperature decrease after reaching the melting temperature. Similar behavior was also observed in experimental measurements, e.g., Refs. [53, 54].

If the main part of the NaNO_3 is solidified the sensible portion of discharging heat prevails, which results in a faster decrease of the volume averaged temperature. Based on the faster solidification process of design case 2, the decrease of the volume averaged temperature starts at an earlier point of time.

The time evolution of the volume averaged liquid fraction indicates a faster solidification of the NaNO_3 of the heat exchanger tube design without lateral fins.

A comparison of the discharged power during the solidification process is presented in Fig. 14. The time evolution of the power shows that, during the first approx. 1,200 s of the solidification process, the discharged power of the tube design without lateral fins is greater compared to the design with lateral fins. This is a consequence of the unhindered solidification process, which takes place over a larger region compared with the tube design case 1.

It can be concluded for the solidification process that, heat conduction plays the main key during the solidification process. Every obstruction given by e.g., lateral fins reduces the solidification velocity in direction to the outer shell.

Considering the complexity of the problem, including the multi-dimensionality of the melting and solidification process, the non-uniform heating along large tubes, the transient character of the process, the irregular melting patterns, the subcooling of the PCM during solidification and the heat transfer to the surroundings, it is clear that, much additional work is required before a complete understanding of the complex overall processes can be reached. In a next step, the change in volume of the PCM will be included in the mathematical models for the simulation of the melting and solidification process and these results will be validated with measurements made with the test rig at IET. Finalizing it should, however, be noted that, in the present study, the height of the computational domain was low. Therefore, the height of the model should be enlarged in further studies for a better investigation of the buoyancy-driven flow. But all the measures mentioned above will lead to a considerable increase of the used CPU (central processor unit) time.

4. Conclusions

In the present work, a numerical investigation of the melting and solidification process of sodium nitrate has been performed. For the numerical analysis, an enthalpy-porosity formulation was used to get quantitative information about the development of the melting as well as the solidification front within the

phase change material. For improving the heat transfer into the NaNO_3 , two complex bimetal heat exchanger tube designs with longitudinal fins are used. The two designs differ in the number of additional lateral fins.

The numerical analysis was done for a three dimensional computational domain. The numerical analysis of the melting process has shown that, during the first period of the charging process, where the melted zone is very small, the heat conduction is the dominant heat transfer mechanism. With increasing of the melted region, it was found that, natural convection plays the main role for the melting process. This result in a faster melting progress at the top of a storage device compared to the bottom. The numerical analysis of the melting process has also shown that, for a fast melting process, heat exchanger tubes should be designed in such a way that, an unrestricted natural convection (buoyancy-driven currents) is guaranteed. Therefore, every obstruction given by e.g., lateral fins or branches from radial arranged fins reduces the melting velocity in direction to the outer shell.

The numerical results of the solidification process indicate that, the dominant heat transfer mechanism during solidification is heat conduction. The investigation has also shown that, the solidification starts at the bottom and grows more uniformly compared to the melting front. Furthermore, every obstruction given by lateral fins reduces the solidification velocity in direction to the outer shell.

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