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Natural convection melting in a high temperature flat plate latent heat storage system: Parameter study of enclosure dimensions

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1. Abstract

The impact of natural convection melting in a high temperature flat plate latent heat thermal energy storage system is studied numerically. The storage material is the eutectic mixture of sodium nitrate and potassium nitrate (KNO_3-$NaNO_3$). A parameter study on storage material enclosure dimensions is conducted for various widths and heights. Low to very high aspect ratios between 0.5 and 40 and Rayleigh numbers from $1.2\cdot10^4$ to $1.6\cdot10^6$ are obtained. The liquid phase fraction evolution with time is scaled to non-dimensional form and the impact of natural convection on the heat flux is shown with a convective enhancement factor that is the ratio of heat flux to a hypothetical heat flux only by conduction. The results can be used for future design optimizations considering the effect of natural convection.

Keywords: High temperature flat plate latent heat storage, Phase change material (PCM), Melting and solidification, Natural Convection, Rectangular enclosures, Numerical Simulation

2. Introduction

Thermal energy storage systems can be integrated whenever there is a mismatch between supply and demand of thermal energy. When a phase change material (PCM) is used as storage material, additional energy is stored in the latent heat at constant temperature. Recent information on latent heat storage is found in the book by Mehling and Cabeza [1] and the review by Agyenim et al. [2]. This article focuses on latent heat thermal energy storage (LHTES) systems with a high temperature PCM for industrial applications. A flat plate LHTES feasible for temperatures up to 300 °C was simulated, designed and operated at DLR by Johnson et al. [3]. The design consists of rectangular enclosures alternatingly filled with storage material and heat transfer fluid (HTF). Additional heat transfer enhancing structures can be introduced into the enclosures to vary the ratio of power to capacity of the system. From the different possible concepts, this flat plate LHTES system is advantageous in terms of flexibility, simplicity and modularity. The impact of natural convection melting and solidification on the heat transfer in this system without heat transfer structures was investigated by Vogel et al. [4]: A strong heat transfer enhancement during melting but a negligible effect during solidification is found. The purpose of this work is to investigate the influence of enclosure size variations on the performance of the flat plate LHTES concept by numerical simulations. For similar problems, dimensional analysis was used by numerous researchers. For example, Shatikian, Ziskind and Letan [5] investigated a PCM-based heat sink with internal fins. However, for the configuration of a flat plate LHTES and the large range of possible aspect ratios, similar investigations were not yet conducted to the best knowledge of the authors.

3. Numerical model

The numerical model used in this study [4] is an approximate representation of the storage system at DLR [3] illustrated in Figure 1. From this 3D model, only the two-dimensional mid-plane is simulated. It is assumed that the boundary effects are restricted to a small region near the end walls in the third dimension, which enables a 2D-Simulation to be sufficiently accurate. The symmetry of the storage system allows further simplification to regard only half of one inner enclosure containing the PCM. The numerical domain shown in Figure 2 consists of a solid zone for the wall of the half flat plate HTF chamber and a PCM zone for the half PCM region. Boundary conditions and dimensions of the PCM containment are also illustrated in Figure 2. The numerical model is realized with ANSYS Fluent [6], which utilizes a finite volume discretization in space, implicit time integration and the SIMPLE method for pressure-velocity-coupling. The Boussinesq-Approximation is used, which results in a constant density except in the buoyancy term and excludes volume expansion effects. For the phase change process the enthalpy-porosity approach by Voller and Prakash [7] is used and the mushy-zone constant in the Darcy term is set to 10^5. A study to show the independence of the solution from mesh sizes and time step reveals an optimum non-equally spaced mesh with cell sizes 0.1…0.5 mm and refinement at the walls. The residual convergence criterions are set to 10^{-3} for continuity and momentum equations and 10^{-9} for the energy equation. Model validation is obtained with experimental data [4]. Temperatures at two different locations are compared for simulation and experiment in Figure 3.

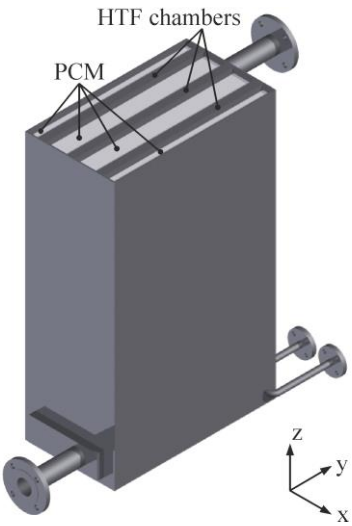

Figure 1: Storage Design

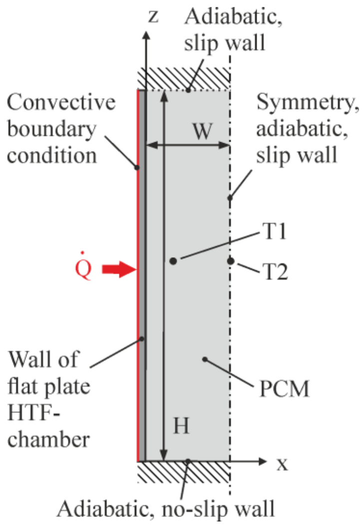

Figure 2: Simulation domain

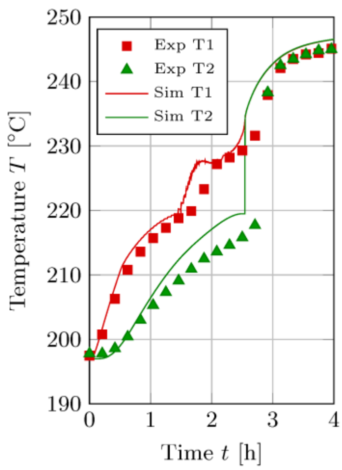

Figure 3: Experimental validation

Material properties for the PCM, which is the eutectic mixture of sodium nitrate and potassium nitrate (KNO_3-$NaNO_3$), characterized by Bauer, Laing and Tamme [8] are given in Table 1. Material properties for the containment, which is made of steel, are also given. Constant properties are used at the melting temperature in the liquid state, because the liquid phase is more important in this convection dominated process.

Table 1. Thermophysical material properties

Material	$\frac{\rho}{\mathrm{kg\,m^{-3}}}$	$\frac{c}{\mathrm{J\,(kgK)^{-1}}}$	$\frac{k}{\mathrm{W\,(mK)^{-1}}}$	$\frac{T_m}{\mathrm{°C}}$	$\frac{\Delta H_m}{\mathrm{kJ\,kg^{-1}}}$	$\frac{\beta}{\mathrm{K^{-1}}}$	$\frac{\mu}{\mathrm{Pa\,s}}$
Steel	7800	540	51	-	-	-	-
KNO_3-$NaNO_3$	1959	1492	0.457	219.5	108	$3.5 \cdot 10^{-4}$	$5.8 \cdot 10^{-3}$

4. Parameter study

A dimensional analysis of the problem reveals the Fourier, Stefan, Prandtl and Rayleigh numbers and the aspect ratio as non-dimensional groups:

$$Fo = \frac{at}{L^2}, \qquad St = \frac{c_p \Delta T}{\Delta H_m} = 0.17, \qquad Pr = \frac{a}{\nu} = 19.9, \qquad Ra_W = \frac{g\beta \Delta T W^3}{\nu a}, \qquad A = \frac{H}{W}. \qquad (1)$$

The first is time-dependent; the next two are constant for the chosen parameters and the latter two depend on the case dimensions. The dimensions of rectangular enclosures and the corresponding non-dimensional groups are given in Table 2.

Table 2. Dimensions, aspect ratio and Rayleigh-number

Case name	W/mm	H/mm	$A = H/W$	Ra_W
W25H12.5	25	12.5	0.5	$1.5 \cdot 10^6$
W25H25	25	25	1	$1.5 \cdot 10^6$
W25H50	25	50	2	$1.5 \cdot 10^6$
W25H100	25	100	4	$1.5 \cdot 10^6$
W25H200	25	200	8	$1.5 \cdot 10^6$
W25H500	25	500	20	$1.5 \cdot 10^6$
W25H1000	25	1000	40	$1.5 \cdot 10^6$
W10H200	10	200	20	$9.7 \cdot 10^4$
W05H200	5	200	40	$1.2 \cdot 10^4$

The evolution of liquid phase fractions over time for all parameter variations is shown in Figure 4. This time-dependent liquid phase fraction is scaled with the non-dimensional groups Fo, St, Ra_W and A. The optimum scaling is obtained with exponents of 1/6 for Ra_W and $-1/4$ for A. The exponent of Ra_W would actually be the commonly found value of $1/4$ for different widths at constant height. However, further scaling with the aspect ratio A to include different heights additionally scales the width W, which exactly leads to an exponent of $1/6$ for Ra_W. The scaling works well and the curves are close together, as shown in Figure 5. However, the case with the smallest width shows slightly more deviations, because conduction is still dominant and scaling with the Rayleigh number overestimates the impact of natural convection.

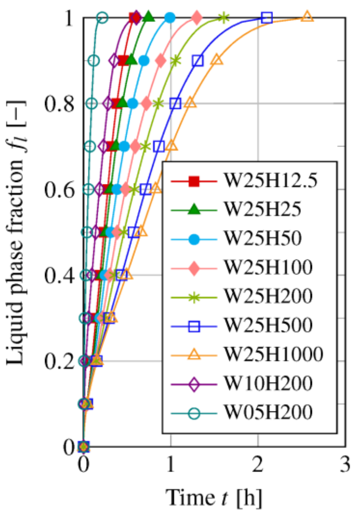

Figure 4: Liquid phase fraction over time

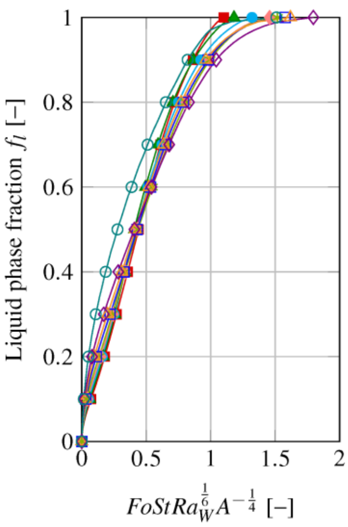

Figure 5: Scaled liquid phase fraction

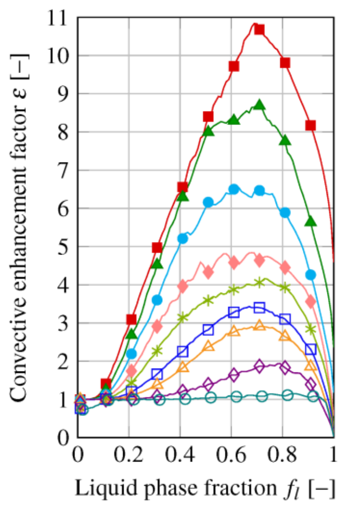

Figure 6: Convective enhancement factor over liquid phase fraction

The impact of natural convection is usually analyzed with the Nusselt number. For the steady flow of a one phase material over a flat plate, for example, it has the significant meaning of being the ratio of the actual heat flux to a hypothetic heat flux by conduction only. However, in this case, the calculation of the Nusselt number wouldn't lead to a similar significant meaning. This is why another parameter, the *convective enhancement factor* is defined as the ratio of convective heat flux to conductive heat flux for the same liquid phase fraction:

$$\epsilon\,(f_l) = \frac{\dot{Q}_{conv}(f_l)}{\dot{Q}_{cond}(f_l)}. \quad (2)$$

To calculate this parameter, two simulations - one with natural convection and one only with conduction - are evaluated at times with equal liquid phase fractions. The result is shown in Figure 6. For the case with the smallest width of 5 mm and height of 200 mm, a small value of ϵ near unity is found, which means that heat transfer is only by conduction. With increasing width, but constant height, the heat transfer enhancement by convection increases significantly up to a maximum value of four for a width of 25 mm. With increasing height at constant width, heat transfer enhancement decreases slightly until a factor of three for a height of 1000 mm. With decreasing height, it increases up to a maximum value of 11 for the smallest height of 12.5 mm. However, since there is also a minimum height needed for natural convection to occur, this trend will eventually reverse at even smaller heights that are not reached here.

5. Conclusions

For a flat plate LHTES concept, the impact of enclosure dimensions on natural convection melting has been investigated with a parameter study of various widths and heights. For large aspect ratios typically found in the flat plate LHTES concept, quantitative results are not available up to now. This study includes a large range of aspect ratios from 0.5 to 40 with Rayleigh numbers from $1.2 \cdot 10^4$ to $1.5 \cdot 10^6$. With dimensional analysis, a proper scaling has been found that allows prediction of the liquid phase fraction evolution over time. The influence of natural convection has been shown by defining a convective enhancement factor that gives the multiple of the heat flux obtained by natural convection compared to a hypothetical conduction only case. This parameter clearly indicates the impact of enclosure dimensions and liquid phase fraction on natural convection. The presented data can be used for design optimization of flat plate LHTES and similar systems considering the effect of natural convection during melting.

6. References

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