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PCMflux as a fully controllable dynamic latent heat storage system

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1. Abstract

The PCMflux concept as a dynamic latent heat storage system avoids a decrease of heat flux while discharging. This drop is typical for state-of-the-art latent heat storage units with locally fixed storage material. In the PCMflux concept, the storage material is physically separated from fixed heat exchanger pipes and moved towards them. The forward velocity of the storage material is directly related to the resulting heat flux of the storage system. Modifying this velocity, the heat flux can be controlled accurately. The correlation of these two factors is described by the dimensionless number K_{Flux}. This number depends on different influence factors such as design parameters and properties of the involved materials. K_{Flux} is developed and discussed. It turns out to be a crucial parameter for both designing and controlling the PCMflux system. This paper focusses on the description of the PCMflux concept and the derivation of K_{Flux} describing the correlation between forward velocity and heat flux.

Keywords: Thermal energy storage, Latent heat, Phase Change Material (PCM), Moving PCM, Separation of heat flux and capacity

2. Introduction

Most renewable energy sources are subject to natural fluctuations. Being able to secure reliable electricity production with a significant share of renewables in the energy mix, storage systems can be used to smooth electricity production. Storing thermal energy using phase change materials (PCM) in combination with e.g. direct steam generating solar thermal power plants is a promising way to do so. Due to the isothermal phase change of both the storage material and the connected water-steam system, only small temperature gradients are necessary for storing heat. That is why high overall efficiencies are expected. The state-of-the-art latent heat storage system shows a conceptual disadvantage: Mainly while discharging, the heat flux of the storage system cannot be kept constant. Due to the poor thermal conductivity of PCMs and the suppression of convection effects, the growing layer of solidified PCM at the heat exchanger causes a significant heat flux drop over time [1–3]. This effect is damped by the implementation of expensive heat transfer structures (HTS). By contrast, the presented PCMflux concept eliminates the heat flux drop without the need of HTS.

3. The PCMflux concept

One challenge in the development of a controllable latent heat storage system is the implementation of moving storage material in order to avoid the establishment of a with time growing crystallized layer of PCM during discharge. Only if the recently frozen PCM is continuously transported out of regions with highest heat transfer, the thermal resistant can be kept constant and therewith the heat rate appears to be constant – without increasing the occurring temperature difference between PCM and heat transfer fluid (HTF). The PCMflux concept addresses this problem by the macroencapsulation of the storage material into containers. These filled containers are separated from the heat exchanger by a thin fluid layer. The separation allows the realization of moveable storage material that can pass the fixed heat exchanger pipes [4]. The containers thereby are moved into one direction for charging and into the other one for discharging the storage. The fluid layer has two main tasks: First of all, it secures thermal contact between the containers and the heat exchanger pipes to avoid a bad dry contact between these components. Secondly, the containers are supposed to float on the fluid in order to minimize parasitics caused by the movement of the storage material. For design details, see Figure 1. If the forward speed of the containers is chosen within a specific range, a quasi-stationary phase change interface inside the containers is established. In this case, exactly as much storage material as changes phase is moved away. This leads to a constant thermal resistance and heat flux. The faster the containers are moved, the higher – until the nominal heat flux of the specific module is reached – the heat flux is. This nominal heat flux and its corresponding nominal velocity strongly depend on a variety of influence factors. The dimensions of the containers and the fins attached to the heat exchanger pipes, see Figure 1, the imposed temperature difference between melting temperature of the PCM and the HTF, the properties of all involved materials such as steel, aluminum, PCM and fluid take on an important role in the course of determining the nominal speed of a specific PCMflux

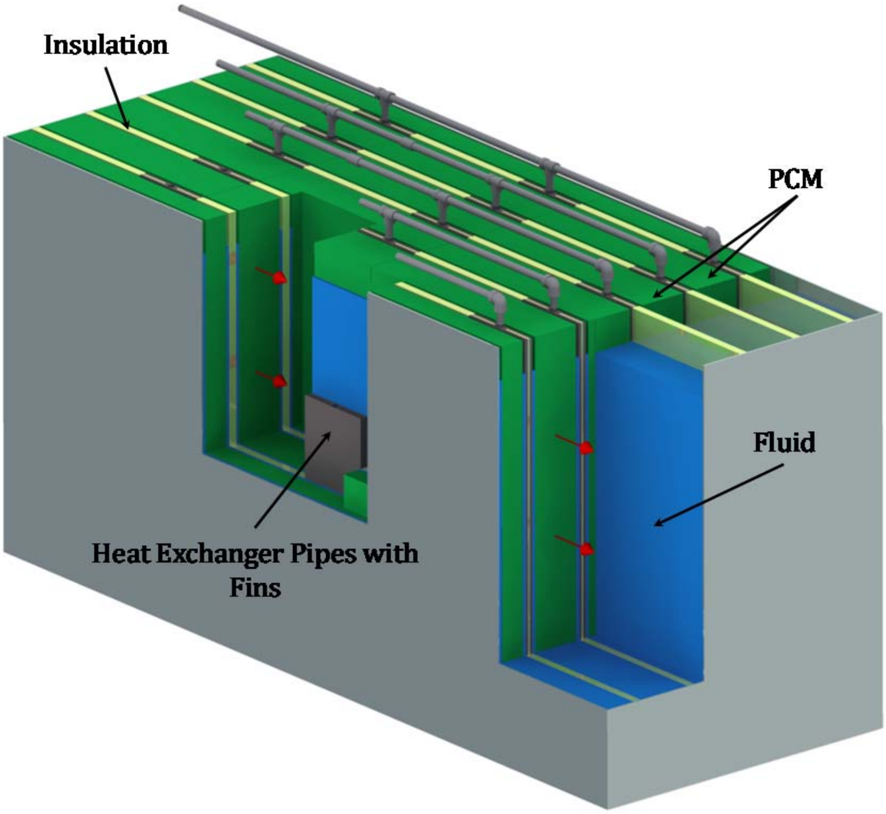

Figure 1. Sectional drawing of the PCMflux concept

configuration. To be able to control the heat flux of this latent heat storage system, the correlation of the forward velocity of the PCM containers and the resulting heat flux of the storage system has to be known. This correlation can be described by a dimensionless number K_{Flux} that is developed according to Buckingham`s Pi Theorem in the next chapter of this paper. K_{Flux} and its meaning for the PCMflux concept is discussed afterwards.

4. Derivation of $\mathbf{K_{Flux}}$

The Buckingham`s Pi Theorem [5] offers a strict methodology to develop dimensionless numbers for specific problems. Following the Buckingham's Pi Theorem, physical equations can be expressed by a set of dimensionless numbers that consist of the physical input variables of a problem. The number of these variables is called n. The number of independent dimensions, the input variables can be combined of, is called k. The necessary amount of dimensionless numbers to describe the problem is calculated via $n - k$. Using a Finite-Difference-Method tool, specifically developed for the PCMflux concept, four input variables ($n = 4$) can be identified. These four variables have a significant influence on the results of the tool. The tool is based on the discretization of the two dimensional heat conduction equation in enthalpy form and specialized on the modelling of PCM, for details see [6,7]. These four input variables are the forward velocity of the containers v, the density ρ_{PCM} and the heat of fusion L of the storage material and the inner heat exchanger pipe surface related heat flux $\dot{q}$. The dimensions of these four input variables can be expressed with the three basic units ($k = 3$) length m, mass kg and time s. For details see Table 1. According to Buckingham`s Pi Theorem, one dimensionless number ($n - k = 1$) is necessary to describe the correlation between forward velocity and heat flux within the PCMflux concept. This dimensionless number K_{Flux} therefore generally can be written as:

$$K_{Flux} = {\rho_{PCM}}^{a} \cdot v^{b} \cdot L^{c} \cdot \dot{q}^{d} \tag{1}$$

Table 1. Input variables and their dimensional analysis for the Buckingham`s Pi Theorem

Input Variable	**SI-Unit**	**Expressed by Basic Units**	
$\boldsymbol{\rho_{PCM}}$	$\frac{kg}{m^3}$	$\frac{kg}{m^3}$	**k = 3** (m, kg, s)
$\boldsymbol{v}$	$\frac{m}{s}$	$\frac{m}{s}$	
$\boldsymbol{L}$	$\frac{J}{kg}$	$\frac{m^2}{s^2}$	
$\boldsymbol{\dot{q}}$	$\frac{W}{m^2}$	$\frac{kg}{s^3}$	

Knowing that all dimensions in equation (1) have to vanish, equation (2) can be developed as follows:

$$[\rho_{PCM}]^a \cdot [v]^b \cdot [L]^c \cdot [\dot{q}]^d = \left(\frac{kg}{m^3}\right)^a \cdot \left(\frac{m}{s}\right)^b \cdot \left(\frac{m^2}{s^2}\right)^c \cdot \left(\frac{kg}{s^3}\right)^d = 1 \tag{2}$$

Solving equation (2) for the factors a, b, c and d, the equation is transferred into a set of equations, see set (3). Each equation of this system is a result of balancing one of the basic dimensions according to equation (2) in order to lead their specific combinations to zero.

$$\begin{array}{rr} \text{Lenght:} & -3a + b + 2c = 0 \\ \text{Mass:} & a + d = 0 \\ \text{Time:} & -b - 2c - 3d = 0 \end{array} \tag{3}$$

The set of equations (3) only contains three equations for four variables. Choosing for example a = 1 and solving the system of equations, leads to one possible solution a = b = c = 1 and d = -1. This results into the definition of K_{Flux}, see equation (4).

$$K_{Flux} = \rho_{PCM}{}^1 \cdot v^1 \cdot L^1 \cdot \dot{q}^{-1} = \frac{\rho_{PCM} \cdot v \cdot L}{\dot{q}} \tag{4}$$

If the value for K_{Flux} is known, the PCMflux system can be designed and calculated analytically. Equation (4) describes the correlation of the forward velocity v and the resulting heat flux $\dot{q}$. However, it does not offer a possibility to calculate K_{Flux} directly without knowing at least one corresponding pair of v and $\dot{q}$. These pairs strongly depend on various design and material aspects, such as the width of the PCM containers, the involved materials and the imposed temperature difference ΔT between HTF temperature and melting temperature of the storage material. Being able to calculate an absolute value for K_{Flux} is therefore crucial for both

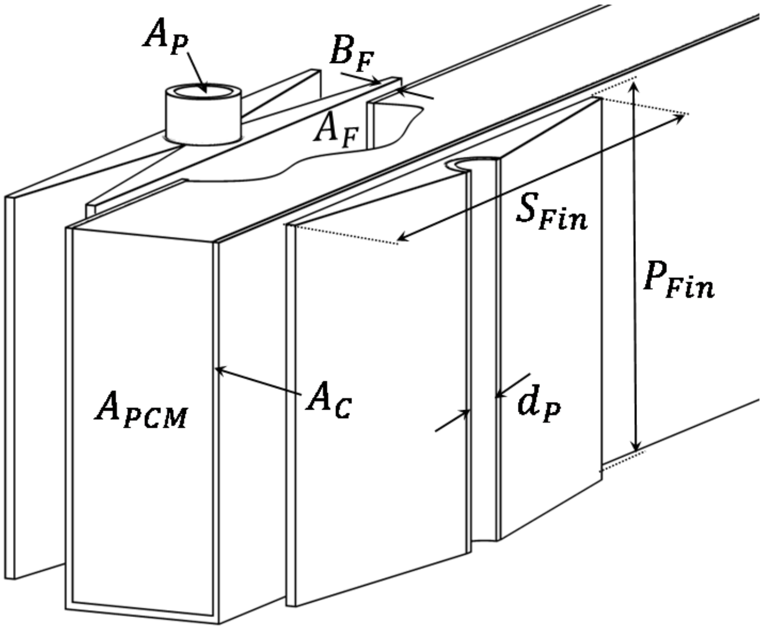

Figure 2. Sketch of the main construction parameters of a PCMflux module

designing and optimizing the PCMflux configuration. After expanding equation (4) by the inner heat exchanger pipe surface A_p and the cross sectional area of the PCM in the container A_{PCM}, see Figure 2, both the numerator and the denominator of K_{Flux} can be interpreted as different and separately calculable heat flows:

$$K_{Flux} = \frac{\rho_{PCM} \cdot v \cdot L}{\dot{q}} = \underbrace{\frac{\overbrace{A_{PCM} \cdot v \cdot L \cdot \rho_{PCM}}^{\dot{Q}_L}}{\dot{q} \cdot A_P}}_{\Xi} \cdot \left(\frac{A_P}{A_{PCM}}\right) \tag{5}$$

The heat flow that is symbolized by the numerator of the first factor of equation (5), $\dot{Q}_L$, describes the heat flow that is necessary to melt or freeze the storage material. Whereas the denominator of the first part of equation (5), $\dot{q} \cdot A_P$, stands for the whole heat flow passing the heat exchanger pipes. This heat flow contains several part-flows, such as the sensible heating or cooling of the container and storage material and, again, the heat flow necessary for the phase change of the PCM. The ratio Ξ, see equation (5), therefore describes the relation of stored latent heat and sensible heating and cooling effects. If, theoretically, the whole PCMflux system was operated at the exact melting temperature only without overheating and undercooling some degrees, Ξ would have the value $\Xi = 1$ and K_{Flux} could be calculated just by A_P and A_{PCM}, see equation (5). Ensuring a complete phase change of the whole storage material, the PCM is approximately heated up or cooled down to the temperature that is imposed at the heat exchanger pipe. In this case, the heat flow that is necessary for the sensible temperature change of the container material $\dot{Q}_{s,c}$ and the one for the sensible heating or cooling of the storage material $\dot{Q}_{s,PCM}$ is calculated via equations (6) and (7).

$$\dot{Q}_{s,c} = A_C \cdot c_c \cdot v \cdot \rho_C \cdot \Delta T \tag{6}$$

$$\dot{Q}_{s,PCM} = A_{PCM} \cdot c_{PCM} \cdot v \cdot \rho_{PCM} \cdot \Delta T \tag{7}$$

In these equations, c_c and c_{PCM} describe the specific heat capacities of the container and storage material, ρ_C and ρ_{PCM} the densities of the container material and PCM and A_C the cross sectional area of the container walls, see Figure 2. Summing up equations (6), (7) and $\dot{Q}_L$ results into the value for $\dot{q} \cdot A_P$, the denominator of the first factor of equation (5).

$$\dot{q} \cdot A_P = \dot{Q}_{s,c} + \dot{Q}_{s,PCM} + \dot{Q}_L \tag{8}$$

Inserting equations (6) – (8) into equation (5), the forward velocity v of the PCM containers can be cancelled. Rearranging leads to the final equation for the calculation of K_{Flux} containing known design parameters and material properties only:

$$K_{Flux} = \frac{A_P \cdot L \cdot \rho_{PCM}}{A_{PCM} \cdot \rho_{PCM} \left(L + c_{PCM} \cdot \Delta T\right) + A_C \cdot \rho_C \cdot c_C \cdot \Delta T} \tag{9}$$

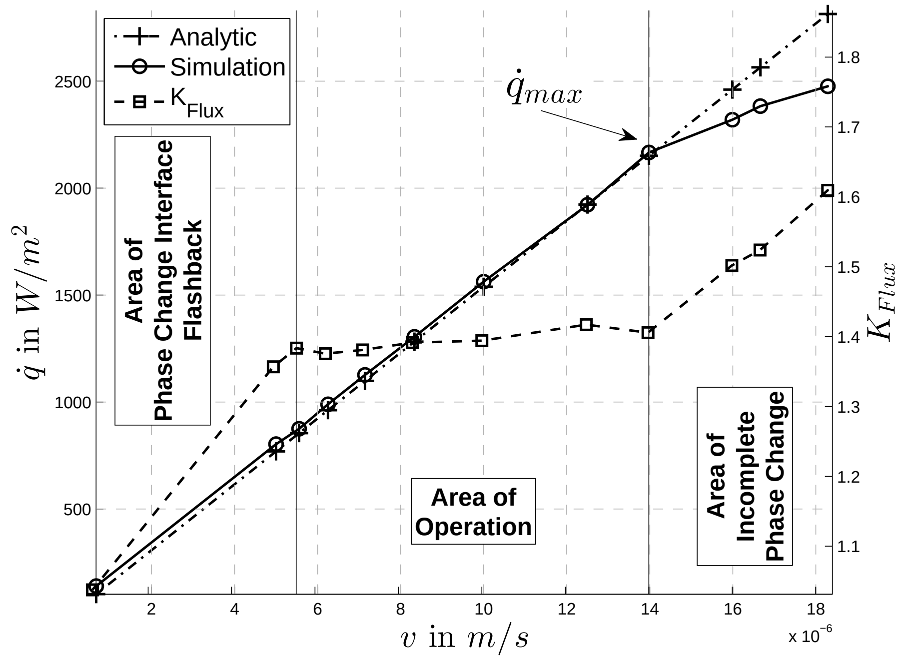

Figure 3. Analytic and simulation results of the forward velocity and the resulting heat flux together with $\boldsymbol{K_{Flux}}$ for an exemplary and non-optimized PCMflux module configuration. $\boldsymbol{\Delta T = 10K}$, $\boldsymbol{A_{PCM} = 0.04m^2}$, $\boldsymbol{A_P = 0.064\, m^2}$, $\boldsymbol{A_C = 0.002\, m^2}$, $\boldsymbol{\rho_{PCM} = 2017.5\, kg/m^3}$, $\boldsymbol{\rho_C = 7872\, kg/m^3}$, $\boldsymbol{c_{PCM} = 1421\, J/kgK}$, $\boldsymbol{c_C = 481\, J/kgK}$, $\boldsymbol{L = 108\, kJ/kg}$, also see [7].

5. Discussion of K_{Flux}

According to K_{Flux}, the forward velocity of the PCM container v and the heat flux at the inner heat exchanger pipe surface $\dot{q}$ are correlated linearly. This fact is validated by the simulation tool and exemplarily shown in the “Area of Operation” in Figure 3. The characteristic curve (the relation of v and $\dot{q}$) in the corresponding area can be well approximated by a straight line. This fact is supported by nearly constant values of K_{Flux} in that area. The values of K_{Flux} in Figure 3 are calculated from the corresponding simulation results (v and $\dot{q}$) that are also displayed in Figure 3 with the help of the “Simulation” curve. The values of K_{Flux} calculated after this manner are very close to the theoretical one of $K_{Flux} = 1{,}403$ according to equation (9), see Figure 3 and the data given in its caption. K_{Flux} describes the slope of the characteristic curve in the area of operation. This correlation can easily be seen after rearranging the definition equation of K_{Flux}, see equation (10).

$$\dot{q} = \frac{\rho \cdot L}{K_{Flux}} \cdot v \tag{10}$$

That is why K_{Flux} also describes the sensitivity of the heat flux reacting on changes of the forward velocity. The smaller K_{Flux}, the steeper the characteristic curve in the area of operation is. This results in bigger changes of the heat flux compared to the same variation of v at a configuration with a bigger K_{Flux}. K_{Flux} is calculated for each specific module configuration

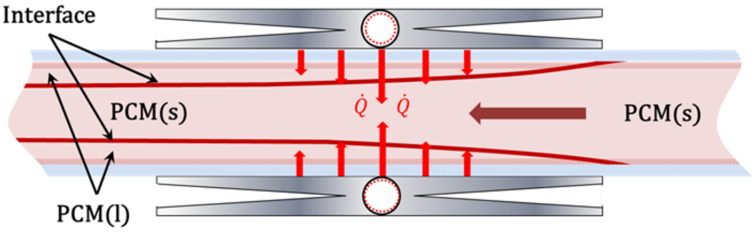

Figure 4. Position of the phase change interface in the area of Incomplete Phase Change in case of charging

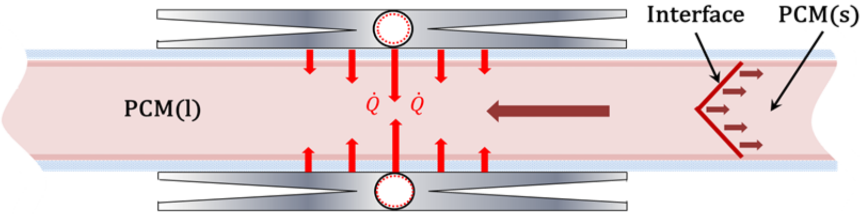

Figure 5. Position of the phase change interface in the area of Flashback in case of charging

via equation (9). Only design and material parameters are necessary for that. Knowing K_{Flux} immediately leads to the corresponding pairs of v and $\dot{q}$ for the considered module configuration in the operational area. This is how the heat flux of the PCMflux concept can be controlled. The requested heat flux is adjusted by the modification of the forward velocity v. All of this can be described with the help of K_{Flux}.

In the areas “Area of Phase Change Interface Flashback” and “Area of Incomplete Phase Change”, K_{Flux} leaves its constant value and therefore the relation between v and $\dot{q}$ cannot be described by the K_{Flux} calculated via equation (9) anymore, see Figure 3. The turning points of the K_{Flux} curve indicate the limits of v. If it is chosen too small, the phase change interface moves contrary to the velocity vector of the PCM container. This state is called a flashback of the phase change interface. On the other hand, if v is too big, the storage material does not have enough time to change phase completely. The storage shall always be operated in a way that the whole storage material is utilized to store heat. Additionally, the flashback only happens at very small velocities that practically will not be used while operation. That is why the knowledge of the correlation of v and $\dot{q}$ in the area of operation is enough for operating the system. For the determination of the nominal power $\dot{q}_{max}$ of a specific PCMflux configuration as the upper turning point, additional influence factors like the width of the fluid layer B_F, the heat exchanging area A_F, the length and width of the fins S_{Fin} and P_{Fin} and their specific shapes, see Figure 2, have to be taken into account. Due to a variety of dependencies between these influence factors, determining the nominal velocity and heat flux is done via an iteration process. The exact procedure together with all assumptions in order to calculate the nominal pair of heat flux and forward velocity analytically, is described in detail in reference [7]. Figure 4 and Figure 5 visualize the different positions of the phase change interface in the areas of Incomplete Phase Change and Flashback in the case of charging the storage.

K_{Flux} turns out to be a very important parameter both for designing and operating the PCMflux concept. With the help of K_{Flux}, the nominal power of the system can be calculated, see [7]. Moreover, the correlation between the forward velocity of the PCM containers and the resulting heat flux in the whole area of operation is given by K_{Flux}. This leads the heat flux of the PCMflux system to be accurately controllable. While the phase change interface is locally fixed in areas close to the heat exchanger pipes by the establishment of a quasi-stationary state, the value of K_{Flux} stays constant. As soon as it significantly changes its value, the area of operation is left and the forward velocity has to be adjusted to ensure a reliable operation. K_{Flux} therewith additionally is an indicator that can be used to keep the system within the operational area.

6. Conclusion

In this paper, the PCMflux concept as a dynamic latent heat storage system is described. This concept allows the separation of heat flux and capacity by the implementation of moveable storage material. The storage material thereby is macroencapsulated into containers. These containers are transported towards fixed heat exchanger pipes floating on a heat conductive fluid layer. Due to the physical separation of heat exchanger and storage material, the heat flux within the PCMflux concept can be controlled accurately. This is why the concept appears to be a promising way to improve the performance of latent heat storage systems at possibly lower specific costs. Depending on the forward velocity of the storage material, different heat fluxes are achieved. The correlation between this velocity and the resulting heat flux can be described by the dimensionless number K_{Flux}. The paper outlines the derivation of K_{Flux} and discusses its crucial relevance for the PCMflux concept. In a next step, the feasibility of the PCMflux concept will be shown experimentally. Of particular importance thereby will be the examination of the heat transfer over the fluid layer.

7. Acknowledgements

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8. References

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