Convective Heat Transfer of Phase Change Slurries

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1 Introduction

At Fraunhofer UMSICHT a Phase Change Slurry (PCS) has been developed, as medium for thermal energy storages. One of the important fluid properties besides enthalpy and viscosity is the heat exchange. In this paper the determination of heat exchange coefficients of PCS is described and first results are presented in comparison with heat exchange coefficients of water.

Thermal energy storages are used for several purposes. Especially in combination with the increasing amount of renewable energies the ability of shifting energy from peak production to peak demand, becomes more and more necessary. This leads to a better utilization of the renewables and savings fossil fuel, because no potential energy has to be wasted by turning off wind energy plants or solar power plants. Additionally plants efficiency can be raised with thermal storages by operating them constantly at the design point and avoiding part load operation. Compared to electrical energy storages, thermal energy storages offer the advantage of affordable storage solutions, good durability and high efficiencies. [1]

Water, as state of the art medium for thermal energy storages, offers quite good heat exchange and a sufficient thermal energy capacity. But that capacity is limited to the temperature spread of the application the storage is used for and the specific heat capacity of water (4.18 kJ/(kg·K)). Thus sufficient storage capacities are often not to realize due to limited installation space. One solution could be Phase Change Materials (PCM), which are melting at the desired application temperature, for example paraffin [2]. Caused by the phase change, great amounts of thermal energy (up to 240 kJ/kg with technical grade paraffin) are absorbed respectively released during heating and cooling. But because PCM is solid at the cold, it is not pumpable and consequently its heat exchange is limited to conduction, which transports only low amounts of energy. Additionally the solidification disqualifies the material to be used directly in most applications and the energy storage has to be an external storage tank with energy transportation by a separate fluid. A PCS of dispersed paraffin in water solves this problem and combines the raised heat capacity of PCM with the good flowing abilities and heat exchange of water. [3, 4]

To determine the heat exchange by natural and forced convection of paraffin/water dispersions several measurements have been conducted. In this paper these measurements will be presented.

2 Phase Change Slurry

Phase change slurries, are fluids consisting of a dispersed phase, paraffin and water as continuous phase. Due to their immiscibility, paraffin and water always tend to separate. The fine paraffin droplets/particles (1 – 10 µm) are stabilized using a mixture of surfactants, which are adsorbed on the paraffin – water interface forming a dense emulsifiers' film and preventing the droplets coalescence. [5] To create an emulsion (Figure 1), mechanical energy is supplied to break up the droplets using an emulsifying machine (rotor – stator disperser PT1300D of Kinematica AG).

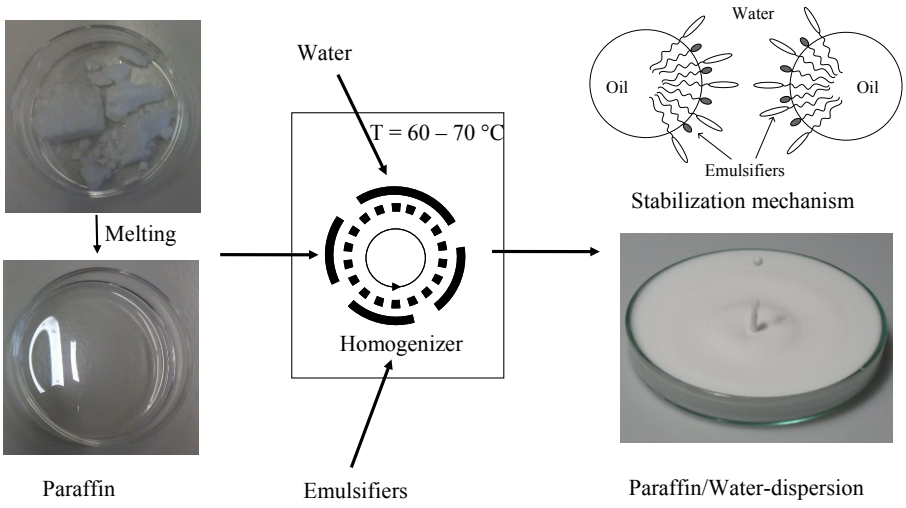

Figure 1: Formation of paraffin/water-dispersion

Measurement equipment:

The phase transition temperature intervals and the heat of fusion of the paraffin/water-dispersions were measured using a differential scanning calorimeter (DSC) apparatus Netzsch DSC 204. The temperature heating rate was 2 K/min and the samples mass between 5 and 10 mg.

The viscosity of paraffin/water-dispersion was investigated with a rotation viscosimeter Bohlin Gemini TM of Malvern Instruments Ltd. using a cone and plate measurement cell. The cone angle is 4°, the diameter is 40 mm and the gap at the cone tip is 30 µm.

The droplet size distribution was measured with a Malvern Mastersizer 2000 instrument by laser diffraction technique. The density was measured by an aerometer (Ludwig Schneider GmbH & Co. KG, Type 10).

Material properties:

The dispersed paraffin is a paraffin blend RT20 from Rubitherm, with the melting point of 21 °C and latent heat of fusion of 130 kJ/kg.

An important property of the paraffin/water-dispersion is the droplets size and size distribution. The droplets size distribution offers information about the emulsion stability. An increase of the droplets size can show a possible destabilization. An emulsion with smaller droplets has an increased stability but presents also a larger degree of subcooling. In Figure 2 can be observed that the paraffin/water-dispersion have a size distribution between 1 and 10 µm.

The DSC melting curves of 30 wt.-% paraffin dispersion are given Figure 3. The melting point is at 21 °C and the solidifying occurs at 18 °C. The melting/solidifying peak areas correspond to fusion heat which for the 30 wt.-% RT 20 dispersion is 35 kJ/kg.

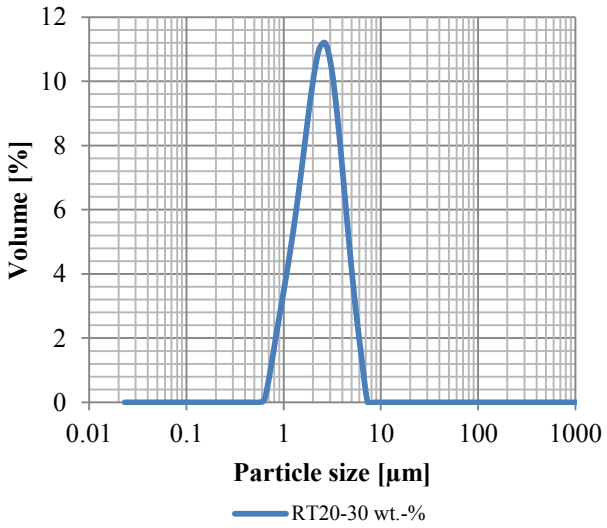

Figure 2: Droplets size distribution

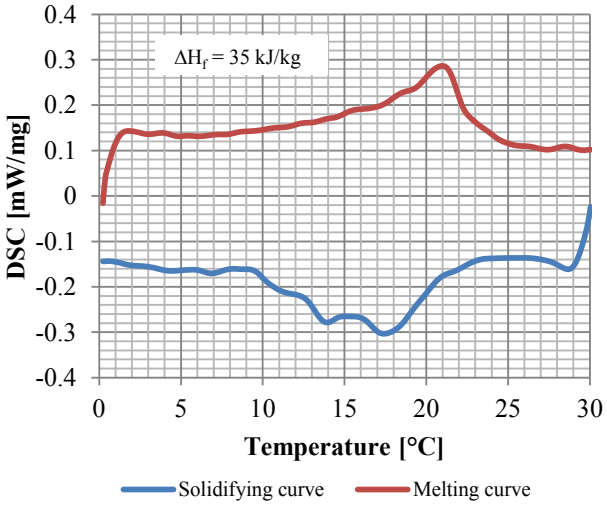

Figure 3: DSC curves of 30 wt.-% dispersion

As presented in Figure 4 the dispersions viscosity first decreases with increasing shear rate and then remains almost constant. The paraffin/water-dispersions are pseudoplastic fluids showing a shear-thinning behavior. At the same time the dispersion viscosity is increasing with decreased temperature, especially during the phase change. The density shows a typical decreasing course with increasing temperature; it varied between 928 and 867 kg m^{-3} at 5 and 70 °C, respectively (Figure 5).

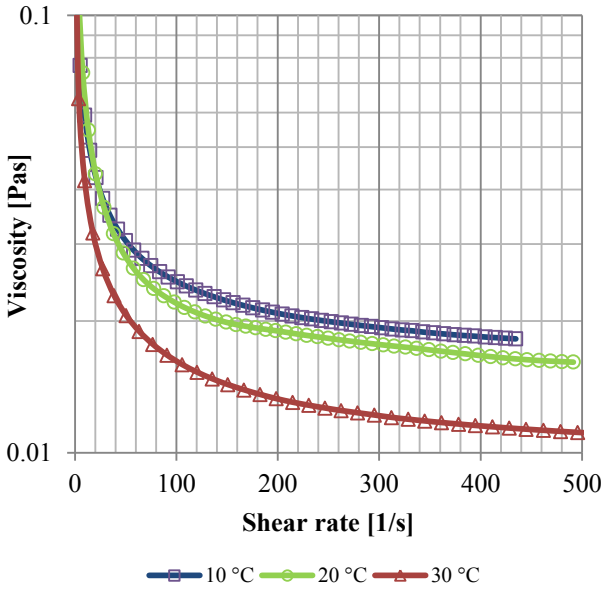

Figure 4: Viscosity of 30 wt.-% paraffin dispersion at different temperatures

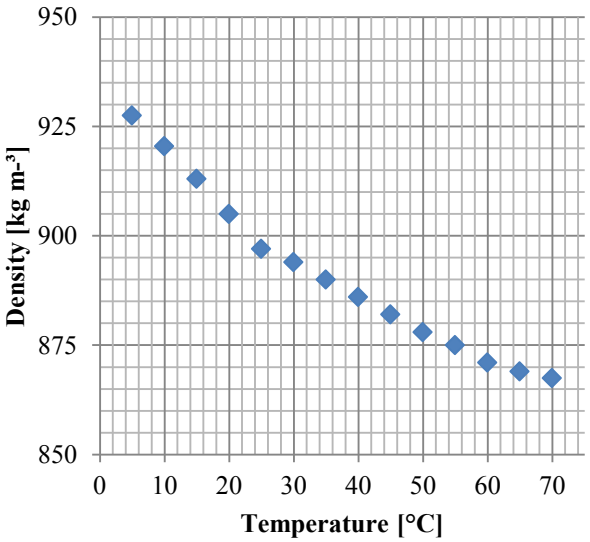

Figure 5: Density of 30 wt.-% paraffin dispersion depending of temperature

3 Methods

3.1 Natural Convection

3.1.1 Set-Up and Procedure

For measurements of heat exchange through natural convection, a fin-tube heat exchanger in a vessel is used. The set-up of the experiment is depicted in Figure 6. Fin-tubed heat exchangers are commonly used for thermal energy storages, so the test set-up is application oriented. Before measurements of PCS were conducted, heat exchange coefficients of water inside the vessel have

been measured for comparisons. The fluid volume is about 50 l. The volume flow of water through the heat exchanger is about 200 l/h with small variations. Pipes and vessel are insulated to reduce heat losses.

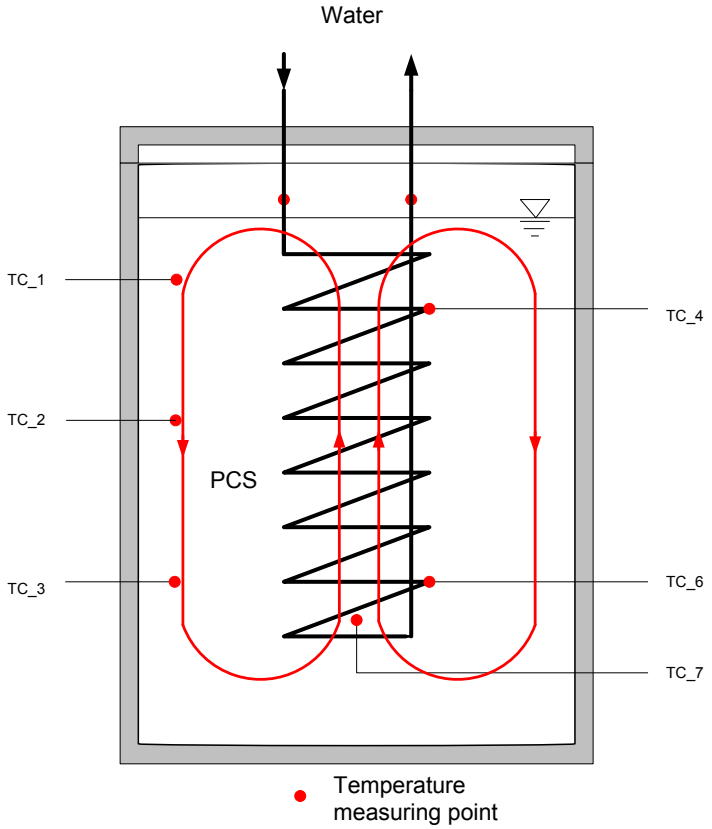

Figure 6: Fin-tube heat exchanger in vessel

Six thermocouples are placed in the vessel. Two of them are in direct contact with the heat exchanger, to measure its outside wall temperature, so calculation of the inner alpha and heat conduction can be evaluated. One thermocouple is located at the bottom between the heat coils. Three thermocouples are mounted in the circulation flow of the natural convection stream. Measurements are conducted at different temperatures, to determine heat exchange coefficients. Before each measurement the vessel is tempered and manually stirred to achieve a homogeneous constant temperature. Afterwards the heat exchanger is heated or cooled, to get a sufficient temperature difference between heat exchanger and vessel temperature. The volume flows are kept very low, so quasi stationary conditions are achieved. The temperature program for heating is depicted schematically at Figure 7.

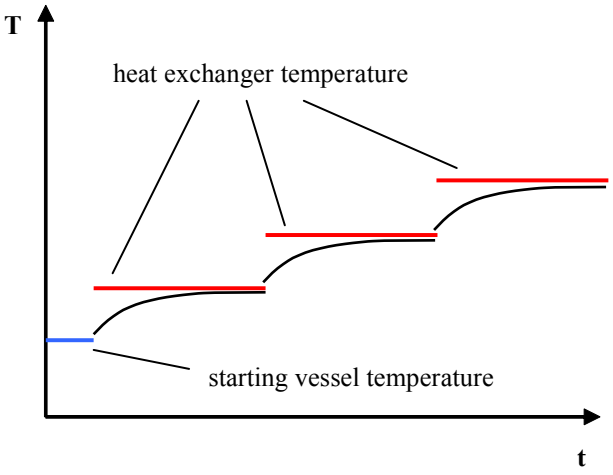

Figure 7: Schematic depiction of heating temperature program

3.1.2 Analysis

The volume flow and inlet and outlet temperature of the water are measured. According to Equation 1 [6] the heat flow is calculated.

$$\dot{Q} = \dot{m}_w \cdot c_{p,w} \cdot \Delta T_w = \frac{1}{R_{Th}} (T_{Fl} - T_{St}) = k \cdot A \cdot (T_0 - T_\infty) \quad \textbf{1}$$

Equation 1 can be resolved to k (Equation 2), which determines the overall heat exchange. With the mean logarithmic temperatures from water flow ($T_{Fl} = T_0 = T_{lm,w} = \frac{T_{w,o} - T_{w,i}}{\ln(T_{w,o}) - \ln(T_{w,i})}$) and storage vessel ($T_{St} = T_\infty = T_{lm,PCS} = \frac{T_{St,3} - T_{St,2}}{\ln(T_{St,3}) - \ln(T_{St,2})}$), values of k are calculated for different temperatures and heat flows. The heat exchange area (A) of 1.8 m² is given by the manufacturer of the heat exchanger. [7]

$$k = \frac{\dot{m}_{water} \cdot c_{p,w} \cdot \Delta T_w}{A \cdot (T_0 - T_\infty)} \quad \textbf{2}$$

3.2 Forced Convection

3.2.1 Set-Up and Procedure

The investigation on forced convection was carried out in a double tube heat exchanger, which is schematically depicted in Figure 8. The entire heat transfer loop consists of a temperature controlled PCS reservoir and a pump, which are combined in a device (Tool-Temp TT 162 E). The PCS in reservoir can be heated up by an electrical heater (16 kW) and cooled down by chilled water (8 °C) supplied by a cold water system. The flow rate was adjusted by a valve and measured by a coriolis flow meter (Endress+Hauser type 4y) with an accuracy of 0.5 %. Temperatures of PCS and water were measured with ice/boiling water calibrated Pt 100 (type B). The chilled water delivered a constant inlet temperature of 8 °C.

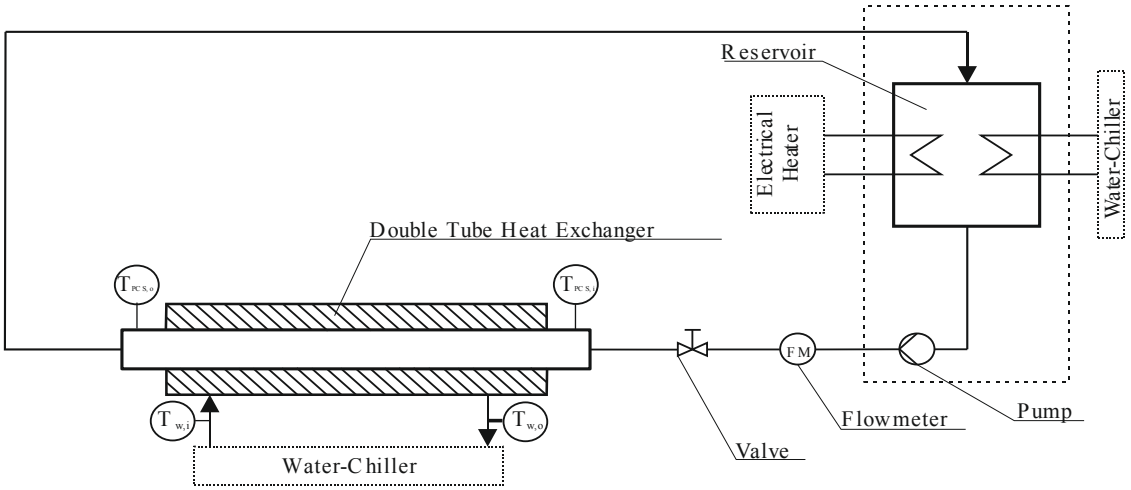

Figure 8: Schematic experimental apparatus for measuring the heat transfer of the PCS in the double tube heat exchanger.

The double tube heat exchanger is detailed displayed in Figure 9, the inner diameter of the inner and outer copper tubes are 6 and 13 mm, respectively; and the tube walls have a thickness of 1 mm. In addition, the heat exchanger is equipped with a suitable insulation to the environment.

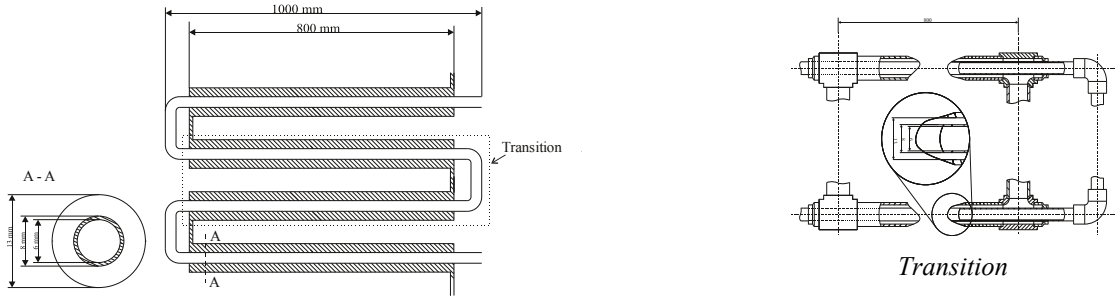

Figure 9: Illustration of the double tube heat exchanger (left), detailed image magnification of the transition area

The double tube heat exchanger is designed out of four identical 800 mm-heat transfer sections. The transition between these heat transfer sections is illustrated in detail in Figure 9 on the right side.

3.2.2 Analysis

The heat transfer coefficient (α_{PCS}) of forced convection can be obtained from inlet and outlet temperatures, mass flow rate, heat transfer surface area, and the heat transfer rate inside the double tube heat exchanger.

The heat transfer rate ($\dot{Q}$) between both fluids (PCS and water) is described by

$$\dot{Q} = k \cdot A_{lm} \cdot \Delta T_{lm}\,, \tag{3}$$

where k is the overall heat transfer coefficient, A_{lm} the mean heat transfer surface (A_{lm} = 0.0699 m^2) and ΔT_{lm} is the log mean temperature difference.

$$\Delta T_{lm} = \frac{\left(T_{PCS,i} - T_{w,o}\right) - \left(T_{PCS,o} - T_{w,i}\right)}{\ln\left(\dfrac{T_{PCS,i} - T_{w,o}}{T_{PCS,o} - T_{w,i}}\right)} \tag{4}$$

Here the subscripts ‘i’ and ‘o’ denote the inlet and outlet temperatures of PCS and water (w), respectively. The overall heat transfer coefficient can be defined as

$$\frac{1}{kA_{lm}} = \frac{1}{\alpha_{PCS} A_i} + \frac{\ln\left(d_o / d_i\right)}{2\pi\lambda_c s} + \frac{1}{\alpha_w A_o}, \qquad 5$$

where λ_c is the thermal conductivity of copper (401 W m^{-1} K^{-1}) [6], s is the wall thickness of the inner tube and the subscripts 'i' and 'o' denote the inner and outer parameters of the inner tube, respectively. Assuming an ideal insulation, the heat transfer rate ($\dot{Q}$) can be substituted by

$$\dot{Q} = \dot{m}_w \cdot c_{p,w} \cdot \left(T_{w,o} - T_{w,i}\right), \qquad 6$$

to determine k from Equation 3. In Equation 4, $\dot{m}_w$ and $c_{p,w}$ are the mass flow and the specific heat capacity of water, respectively. Moreover, α_w can be expressed using the Dittus-Boelter equation [8]:

$$Nu = \frac{\alpha_w \cdot D_h}{\lambda_w} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3} \qquad 7$$

Here Nu, Pr, and Re are the Nusselt, Prantl, and Reynolds number, respectively; and D_h is the hydraulic diameter of the annular gap ($D_h = D_i - d_a$). Subsequently, α_{PCS} can by calculated as the only unknown parameter in Equation 5.

4 Results and Discussion

4.1 Natural Convection

The heat transfer coefficients of natural convection are displayed in Figure 10 plotted versus the corresponding heat per heat transfer surface ($q = \dot{Q}/A_{lm}$). The values of q comply with the data of the heat exchanger manufacturer for the applied temperature differences and volume flows.

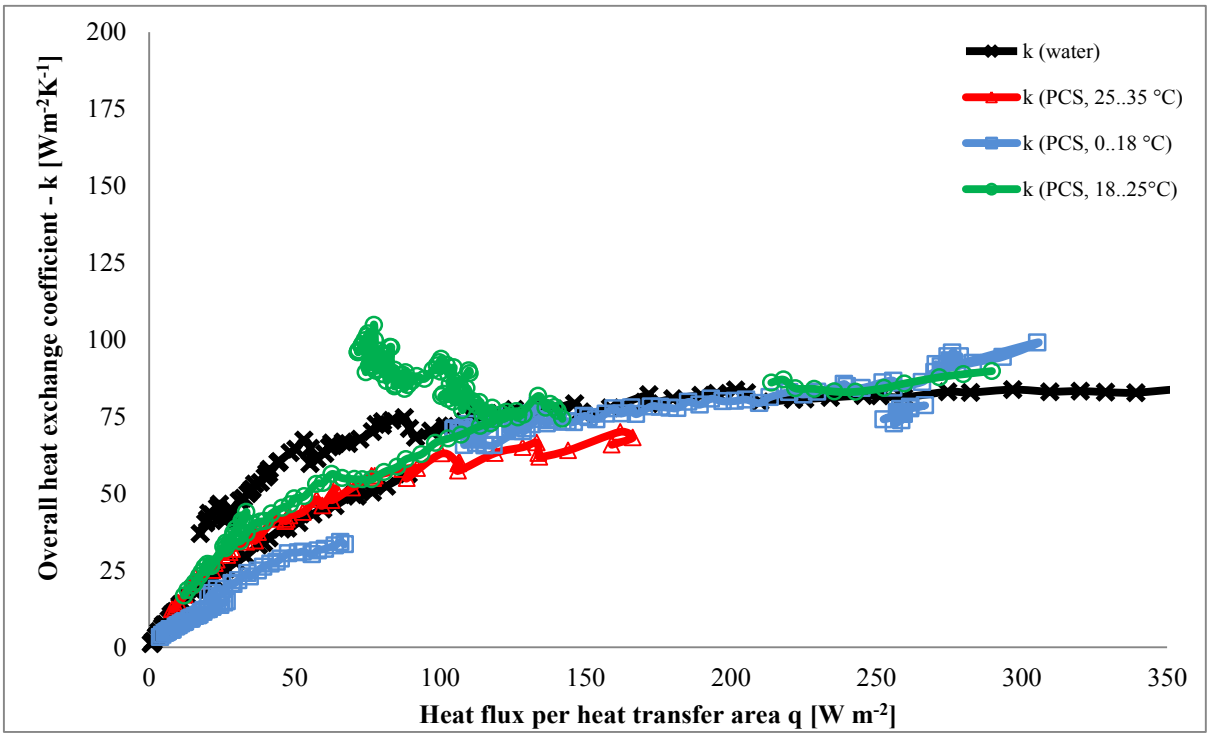

Figure 10: Overall heat transfer coefficients of PCS for natural convection as a function of the heat flux per heat transfer area

It can be observed, that the values of the overall heat exchange coefficient k are nearly equal for water and PCS. The deviations of the curves can be explained by fluctuations of the volume flow.

During the phase change of the PCS an increasing heat exchange is noticed. This phenomenon has been confirmed through several measurements. An explanation could be the great density change during the phase change. Another option is an increased absorption respectively desorption of heat caused during the phase change.

4.2 Forced Convection

The heat transfer coefficients of forced convection are displayed in Figure 11 in accordance with the corresponding heat per heat transfer surface ($q = \dot{Q}/A_{lm}$). The applied heat transfer fluids were chilled water in the outer tube and PCS (30 wt.-% RT20) in the inner tube. The chilled water was supplied with an inlet temperature of 8 °C at flow rates of 100, 200 and 300 L h^{-1}. The PCS was circulated in a closed heat transfer loop at flow rates between 100 to 350 L h^{-1}, the inlet temperature of PCS was set at 40 °C. The outlet temperature of PCS was always superior to the freezing point of the paraffin (20 °C) [3]; thus, PCS was always present in emulsion-state.

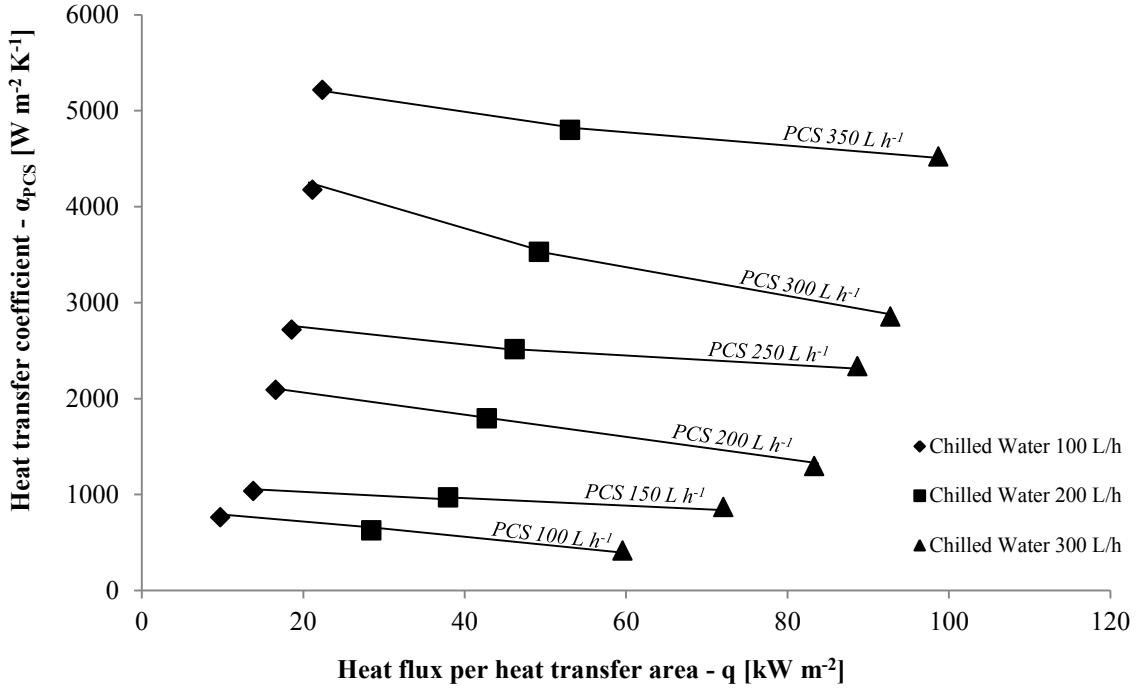

Figure 11: Heat transfer coefficient of PCS for forced convection as a function of the heat flux per heat transfer area

As shown in Figure 11, the heat transfer coefficients at the inner tube are strongly dependent on the flow rate of PCS, which might be related to the flow properties at the inner tube. Laminar flow occurs over the entire flow range; the Reynolds number varied between about 450 and approximately 1500 at 100 respectively 350 L h^{-1}.

5 Conclusion and Outlook

The overall heat exchange values of PCS and water for natural convection are almost equal. Except for the phase change region the differences are within the uncertainty of measurement for a testing set-up, which is application oriented. The results for natural convection apply only for exactly this geometry, but they are helpful for a comparison between heat exchange ability of water and PCS at natural convection.

Heat transfer coefficients of forced convection are determined at a standardized test set-up. Alpha values for the PCS have been determined for laminar flow and within the emulsion state of the PCS.

Further investigations will focus on the heat transfer inside the phase transition area of paraffin. To this end, an additional test section will be designed, in order to determine local heat transfer coefficients along circular ducts; because [9] denoted that the log mean temperature difference method is not suitable for heat transfer determination inside the phase transition area. Nevertheless, the log mean temperature difference method delivered appropriate results for the experiments in this article, due to the fact that we measured heat transfer coefficients only above the phase transition area of the investigated paraffin (RT-20).

6 Acknowledgement

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NOMENCLATURE

Symbols

A	Area
c_p	Specific heat capacity
d	Diameter
k	Overall heat transfer coefficient
$\dot{m}$	Mass flow
Nu	Nusselt number
Pr	Pandtl number
$\dot{Q}$	Heat flux
q	Heat flux per heat transfer surface
Re	Reynolds number
T	Temperature
α	Heat transfer coefficient
Δ	Difference
λ	Thermal conductivity

Subscripts

c	Copper
h	Hydraulic
i	Inlet, inner
lm	Log mean
m	mean
o	Outlet, outer
PCS	Phase change slurry
w	Water
Th	Thermal
Fl	Fluid
St	Storage

Abbreviations

FM	Flow meter
PCS	Phase change slurry / slurries

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