

# ONLINE ENTHALPY MEASUREMENT METHOD FOR PHASE CHANGE SLURRIES

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To measure enthalpy densities, respectively overall specific heats, frequently the differential scanning thermal analysis (DSC) is applied. Other useful methods are also available, but all of them have disadvantages. Therefore, an alternative measurement procedure - *the online enthalpy measurement method* - which was presented six years ago, has now been further improved. The quality of the results can be essentially increased by evaluating the experimental data according to a specially developed method. It is analogous to a method of numerical mathematics. The new evaluation procedure is presented and applied to measurements of the enthalpy density of two different phase change slurries, an ice slurry and a water suspension containing micro-encapsulated paraffin wax.

## 1. INTRODUCTION

To measure enthalpy densities of phase change materials (PCM) and phase change slurries (PCS) usually the differential thermal analysis (DTA) or the differential scanning calorimetry (DSC) is applied [1]. Problems occurring, e.g. in the DSC method, are the following:

- 1) To obtain quasi-steady thermal conditions (approximately constant temperature fields in the interior of the sample) by slowly increasing the temperature over the melting range (scanning) - because of the very high enthalpy densities of PCM's and PCS's - hardly adjustable scanning velocities result.
- 2) The samples are small, with a mass of a few milligramms. Because of nonlinear behaviour the results depend on the boundary conditions and therefore also on the sample size. The discrepancy in the results, determined with small samples in experimental apparatuses, which are mainly applied in chemistry, and large quantities of PCS, utilized in practical energy storage systems, can lead to an inappropriate application of the experimentally determined results.

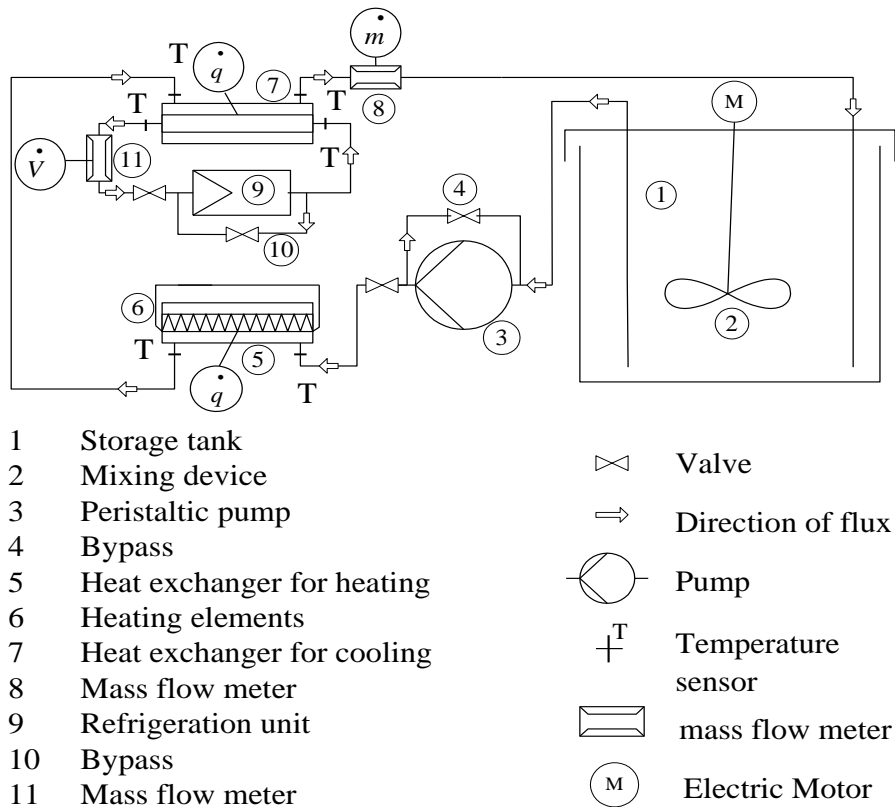
Recently another measuring technique to determine the heat of fusion - the T-history method - was presented [2]. This method is still under development and the evaluation procedure is further improved to increase its accuracy.

## 2. AN ALTERNATIVE METHOD

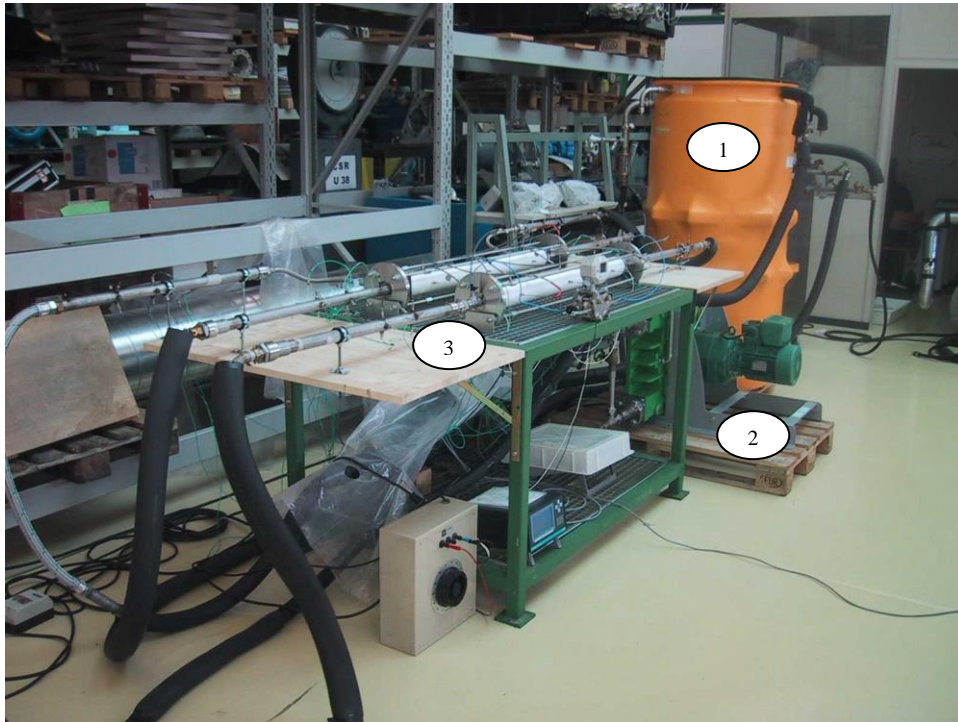
In Ref's [3] and [4] a further alternative method was introduced, which has numerous advantages, but can only be applied to pumpable suspensions (PCS). A small piping circuit contains a pump and a heat exchanger. The circuit must be very well insulated. Temperatures are measured in the cross sections of the inlet and the outlet of the heat exchanger, which very slowly increases the mean temperature of the fluid. This online procedure has the advantage that no samples have to be removed from the well-insulated device. An extraction of material for calorimetric purposes is a source of errors, when it is applied to melting materials. The related evaluation procedures are described in chapters 4 and 5.

## 3. EXPERIMENTAL SET-UP

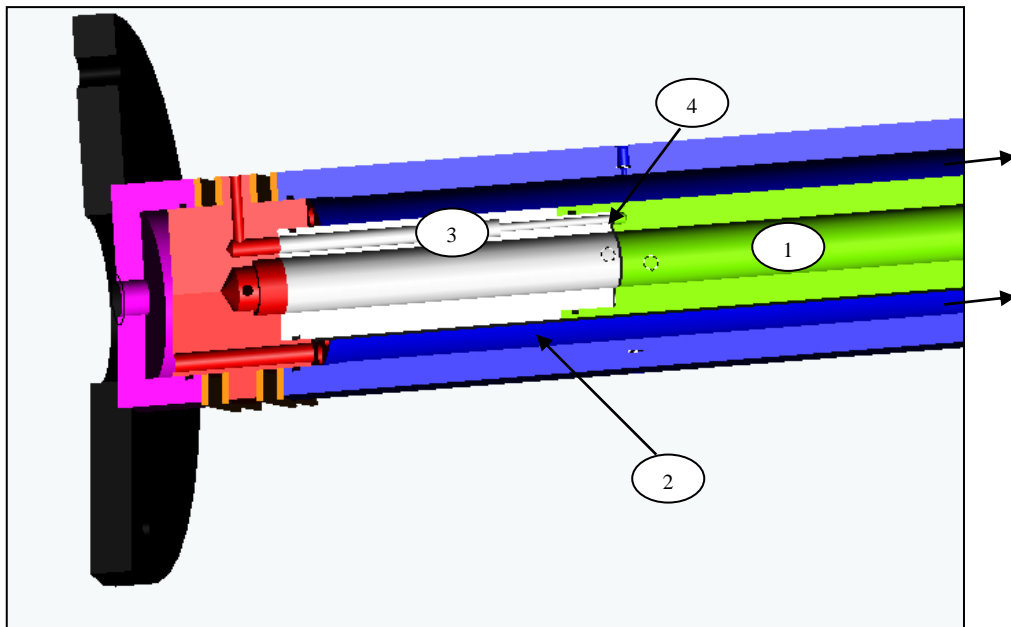
The experimental set-up, with which the enthalpy density of the ice slurry (presented in chapter 7) had been determined, was published in Ref. [4]. The apparatus, described in detail in this chapter, was used to obtain the enthalpy density and specific heat of a PCS with microcapsules (see schematic drawing, FIG. 1, and photography, FIG. 2). The PCS is specified in detail in chapter 8.



**Figure 1:** The experimental set-up for the measurements of the enthalpy density and the overall specific heat of a PCS. It contains two heat exchangers, one for heating and one for cooling.



*Figure 2: The device with the storage tank (1), the peristaltic pump (2,) and the two heat exchangers for heating and cooling (3) - with removed parts of the insulation – are shown.*



*Figure 3: A cross section of the heat exchangers with an aluminium tube (1) are presented. The heating elements are built into the tube and the PCS flows through a concentric slit (2). This has the advantage that the total amount of energy transferred to the heating elements is absorbed by the PCS. Positions of temperature measurements in the wall with thermocouples (3) and on the surface of the fluid domain (4) are shown.*

The components of the experimental device are described in FIG. 1. The apparatus is composed by a storage tank (1), containing 115 liters Phase Change Slurry (PCS), which yields the test fluid. A mixing element (2) in the storage tank guarantees a mixing of the suspension, so that the small microcapsules are homogeneously distributed throughout the fluid. The transport of the fluid is performed by a peristaltic pump (3). It is assumed that this kind of pump does not destruct the microcapsules. Escaping adhesive paraffin wax leads to a clustering of a fraction of capsules. A bypass (4) allows to control the mass flow in the circuit and to adapt it to optimal thermal conditions (see also in chapter 5). In this installation two heat exchangers were mounted. A first one heats the fluid (5) with electrical heating elements (6), and a second was mounted for cooling purposes (7). A cross section of the heat exchanger is shown in FIG. 3. A refrigeration device of type Unistat, containing a refrigerant, is responsible for the cooling of the test suspension. Its small circuit is named secondary circuit. The mass flow in the primary circuit is measured with a mass flow meter Endress and Hauser, Promass 63 F, and in the secondary circuit with a mass flow meter Endress and Hauser, Promag 33. The temperature sensors of type Pt 100 are placed in the fluids at the inlet and outlet of each heat exchanger. Small cylindrical mixing elements are placed in front of each measuring sensor to obtain an uniform temperature profile in the pipe cross section.

#### 4. THE BASIC AND SIMPLE EVALUATION TECHNIQUE

Analogous to a method of numerical mathematics the temperature interval, in which the enthalpy density is measured, is discretized. The lowest temperature is denoted  $T_0$  and the highest  $T_n$ . In an experiment a temperature interval is defined by

$$\Delta T_i' = T_i^{(out)} - T_i^{(in)}, \quad (1)$$

with the temperatures measured at the inlet and the outlet of the heat exchanger (see FIG. 4). We define

$$T_i = T_i^{(in)}. \quad (2)$$

The corresponding difference of the enthalpy density at the inlet and outlet is determined with the heating power and mass flow measured at temperature  $T_i$

$$\dot{Q}_i = \dot{m}_i \left[ h_i^{(out)} - h_i^{(in)} \right] = \dot{m}_i \Delta h_i' \quad \Rightarrow \quad \Delta h_i' = R_i = \frac{\dot{Q}_i}{\dot{m}_i} = R = \frac{\dot{Q}}{\dot{m}} = constant. \quad (3a-g)$$

The derivative of the enthalpy density at temperature  $T_i$  is approximated by the difference quotient determined with (1) and (3)

$$\left. \frac{dh}{dT} \right|_{T_i} \cong \frac{\Delta h_i'}{\Delta T_i'}. \quad (4)$$

This is identical with the specific heat at position  $T_i$  (math. and not thermodyn. notation)

$$c_{p_i} = c_p(T_i) = \left. \frac{dh}{dT} \right|_{T_i}. \quad (5a,b)$$

Modern data acquisition systems allow measurements in very short time intervals. But this leads to two kinds of problems:

- 1) The temperature intervals  $\Delta T'_i$  and  $\Delta T'_{i+1}$  will overlap (see FIG. 4b)
- 2) The errors of the temperature sensors may lead to large (relative) deviations of the temperature differences, in the cases that the temperature increments are small. For example, in the heating case some  $\Delta T'_i$ 's may become erroneously zero or even negative.

Therefore, the first procedure is to sort the results with the following rule

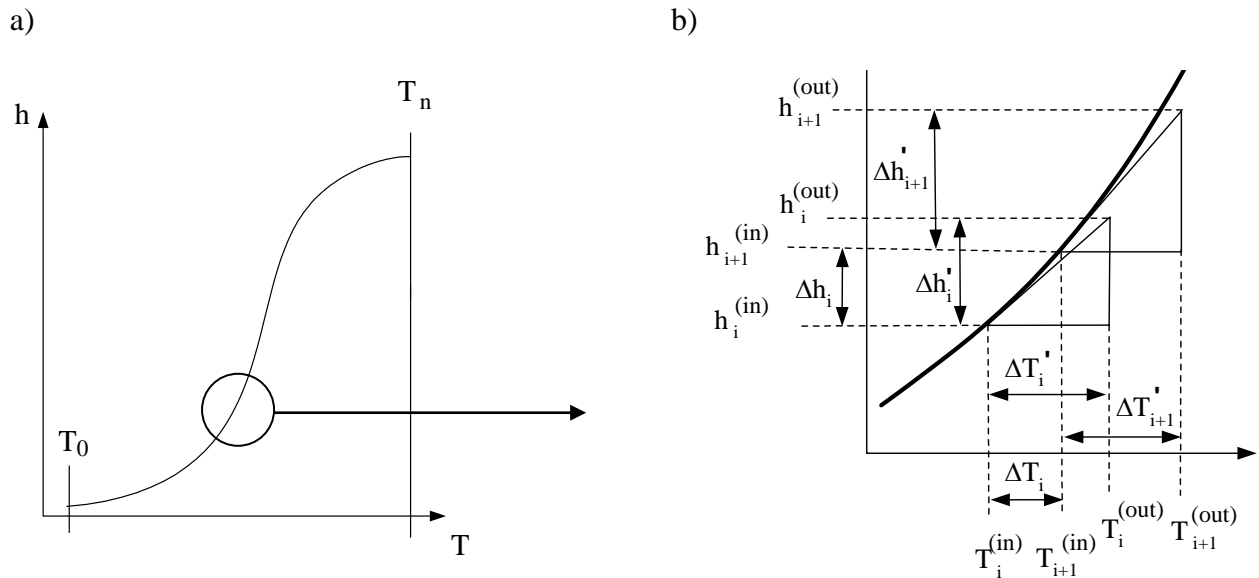
$$T_i < T_{i+1}, \quad \forall i \in \{0, 2, \dots, n-1\}. \quad (6)$$

The enthalpy density is found by integration

$$h = \int_{T_0}^T c_p(y) dy. \quad (7)$$

An overlapping is avoided by only proceeding forward with the reduced step size

$$\Delta T_i = T_{i+1}^{(in)} - T_i^{(in)} = T_{i+1} - T_i. \quad (8a,b)$$



**Figure 4 : The enthalpy density curve of a mixture is a continuous function, which qualitatively is shown in a). Some physical quantities introduced in the model are shown in b).**

A recursive relation is obtained

$$h_{i+1} = h_i + \Delta h_i = h_i + c_{p_i} \Delta T_i = h_i + \frac{\Delta h_i'}{\Delta T_i'} \Delta T_i \quad (9a-c)$$

by substituting (4) and (5b). The integration in the discrete version is a summation process

$$h_k = h_0 + \sum_{i=0}^{k-1} \frac{\Delta h_i'}{\Delta T_i'} \Delta T_i = h_0 + \sum_{i=0}^{k-1} R_i \frac{\Delta T_i'}{\Delta T_i} = h_0 + R \sum_{i=0}^{k-1} \frac{\Delta T_i'}{\Delta T_i}, \quad k \in \{1, 2, \dots, n\}. \quad (10a-c)$$

Equations (3c,e) were applied to derive (10b,c). Equation (10c) is only valid, if the ratio R of heat flux to mass flux is a constant.

The difficulty to obtain a good quality in the resulting enthalpy density function is to choose an accurate heat and mass flux in the heat exchanger. To optimize the evaluation procedure, in the following chapter a theory is presented.

## 5. A SOPHISTICATED EVALUATION METHOD

In numerical mathematics it is known that the calculation of a derivative of a function  $f(x)$  with a simple forward differencing scheme can be performed with an optimal increment  $\Delta x_{opt}$  of the basic variable  $x$ , which depends on the function  $f(x)$  [5]. If  $f$  is nonlinear and the increment  $\Delta x$  too large, the difference quotient is a bad approximation to the differential quotient. Because of this reason small increments seem to be ideal. But different as in pure mathematics, in a numerical analysis a number is always represented by a finite number of digits. Therefore, if the increment  $\Delta x$  is decreasing, at some stage it loses its significance and the result will become also erroneous. From these arguments it can be concluded, that an optimal increment size  $\Delta x_{opt}$  exists. And as in step size regulation procedures the optimal increment is dependent on the function  $f(x)$ . This means it also varies with  $x$ .

Quantity	Numerical mathematics	Enthalpy measuring method
Function	$f(x)$	$h(T)$
Variable	$x$	$T$
Increment	$\Delta x$	$\Delta T$
Optimal value	$\Delta x_{opt}$	$\Delta T_{opt}$
Error toward small increments	Finite number of digits	Errors of temp. measurements
Error toward large increments	Nonlinearity of $f(x)$	Nonlinearity of $h(T)$

**Table 1: Analogy between the forward differencing scheme to approximate a differential quotient in numerical mathematics and the online enthalpy measuring method.**

These ideas can be directly applied to optimally evaluate the enthalpy density function. Instead of the finiteness of the number of digits, now, the errors of the temperature measurements lead to a loss of significance of small temperature increments (see also Table 1).

Let us assume that the error of a measurement, which is performed with a temperature sensor, is denoted by  $e_T$ . Then a measured temperature increment has the following numerical value

$$\Delta \tilde{T}_i' = \left[ T_i^{(out)} + e_{T_i^{(out)}} \right] - \left[ T_i^{(in)} + e_{T_i^{(in)}} \right] = \left[ T_i^{(out)} - T_i^{(in)} \right] + \left[ e_{T_i^{(out)}} - e_{T_i^{(in)}} \right]. \quad (11a,b)$$

The following abbreviation

$$\Delta e_i' = e_{T_i^{(out)}} - e_{T_i^{(in)}} \quad (12)$$

is introduced. The following relation for the error of the overall specific heat is obtained

$$\varepsilon(\Delta T_i') = \frac{\Delta h_i'}{\Delta \tilde{T}_i'} - \frac{dh(T)}{dT} \Big|_{T_i}. \quad (13)$$

If we assume that the errors of the heat and mass flux measurements are negligible, then no error must be taken into consideration in the enthalpy density. With equation (11b) and (12) it follows that

$$\varepsilon(\Delta T_i') = \frac{\Delta h_i'}{\Delta T_i' + \Delta e_i'} - \frac{dh(T)}{dT} \Big|_{T_i}. \quad (14)$$

After a division of the nominator and denominator with the temperature increment it follows

$$\varepsilon(\Delta T_i') = \frac{\Delta h_i'}{\Delta T_i'} \frac{1}{1 + \frac{\Delta e_i'}{\Delta T_i'}} - \frac{dh(T)}{dT} \Big|_{T_i}. \quad (15)$$

With the condition

$$\left| \frac{\Delta e_i'}{\Delta T_i'} \right| \ll 1, \quad (16)$$

the following relation for the error of the overall specific heat is obtained

$$\varepsilon(\Delta T_i') = \frac{\Delta h_i'}{\Delta T_i'} \cdot \left\{ 1 - \frac{\Delta e_i'}{\Delta T_i'} + O\left[ \left( \Delta T_i' \right)^{-2} \right] \right\} - \frac{dh}{dT} \Big|_{T_i}. \quad (17)$$

The principle law of differential calculus (the law of the mean) states that

$$h_i^{(out)} = h_i^{(in)} + \frac{dh}{dT}\bigg|_{T_i} \cdot \Delta T_i' + \frac{1}{2} \frac{d^2h}{dT^2}(\xi) (\Delta T_i')^2. \quad (18)$$

with

$$\xi \in ] T_i^{(in)}, T_i^{(out)} [. \quad (19)$$

From equation (18) it follows that

$$\frac{h_i^{(out)} - h_i^{(in)}}{\Delta T_i'} - \frac{dh}{dT}\bigg|_{T_i} = \frac{\Delta h_i'}{\Delta T_i'} - \frac{dh}{dT}\bigg|_{T_i} = \frac{1}{2} \frac{d^2h}{dT^2}(\xi) \cdot \Delta T_i'. \quad (20a,b)$$

Combining equations (17) and (20a,b), the result is

$$\varepsilon(\Delta T_i') = \frac{1}{2} \frac{d^2h}{dT^2}(\xi) \Delta T_i' - \frac{\Delta h_i' \Delta e_i'}{(\Delta T_i')^2}. \quad (21)$$

The maximal error of the temperature measurements is denoted by

$$\varepsilon_T = \max_i |e_{T_i}^\chi| \quad \Rightarrow \quad \Delta e_i' \leq 2\varepsilon_T, \quad \chi \in \{(in), (out)\}, \quad (22a,b)$$

because of the definition of  $\Delta e_i'$  (equation (12)). Now, with the knowledge of the inequality of Schwarz, from (21) the following upper bound is derived

$$\varepsilon(\Delta T_i') \leq \frac{1}{2} \left| \frac{d^2h}{dT^2}(\xi) \Delta T_i' \right| + 2 \left| \Delta h_i' \right| \frac{\varepsilon_T}{(\Delta T_i')^2}. \quad (23)$$

Up to first order the enthalpy density increment is

$$\Delta h_i' = \left\{ h_i^{(in)} + \frac{dh}{dT}\bigg|_{T_i} \Delta T_i' + O[(\Delta T_i')^2] \right\} - h_i^{(in)} = \frac{dh}{dT}\bigg|_{T_i} \Delta T_i' + O[(\Delta T_i')^2]. \quad (24a,b)$$

Substituted into (23) leads to

$$\varepsilon(\Delta T_i') \leq \frac{1}{2} \left| \frac{d^2h}{dT^2}\bigg|_{T_i} \Delta T_i' \right| + 2 \left| \frac{dh}{dT}\bigg|_{T_i} \frac{1}{\Delta T_i'} \right| \varepsilon_T, \quad (25)$$

because the temperature intervals are assumed to be very small, and one can set

$$\xi \cong T_i. \quad (26)$$

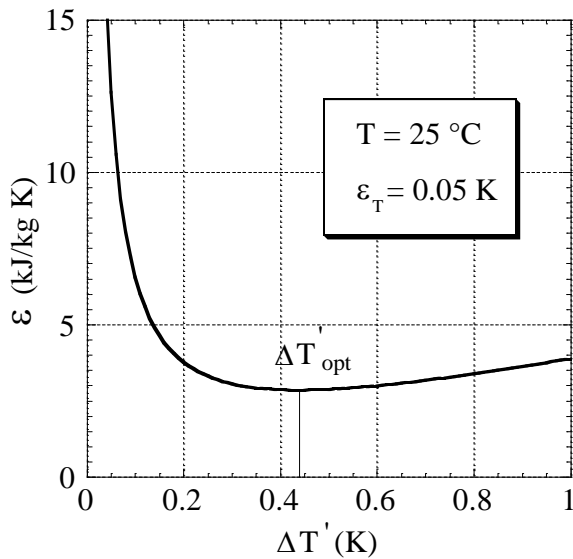


In FIG. 5, for the PCS which is described in chapter 8, the error  $\varepsilon$  is shown. The function has a minimum, which defines the optimal temperature difference  $\Delta T'_{opt}$  for the evaluation of the enthalpy density function. It is calculated with the derivative of the error (equation (25))

$$\frac{d\varepsilon(\Delta T'_i)}{d\Delta T'_i} = \frac{1}{2} \left| \frac{d^2 h}{dT^2} \right|_{T_i} - 2 \left| \frac{dh}{dT} \right|_{T_i} \frac{\varepsilon_T}{(\Delta T'_{i_{opt}})^2} = 0. \quad (27)$$

This condition leads to the optimal value

$$\Delta T'_{i_{opt}} = 2 \sqrt{\frac{\left| \frac{dh}{dT} \right|_{T_i} \varepsilon_T}{\left| \frac{d^2 h}{dT^2} \right|_{T_i}}}. \quad (28)$$



**Figure 5: The upper bound for the error of a measurement of the specific heat of a PCS at 25 °C.**

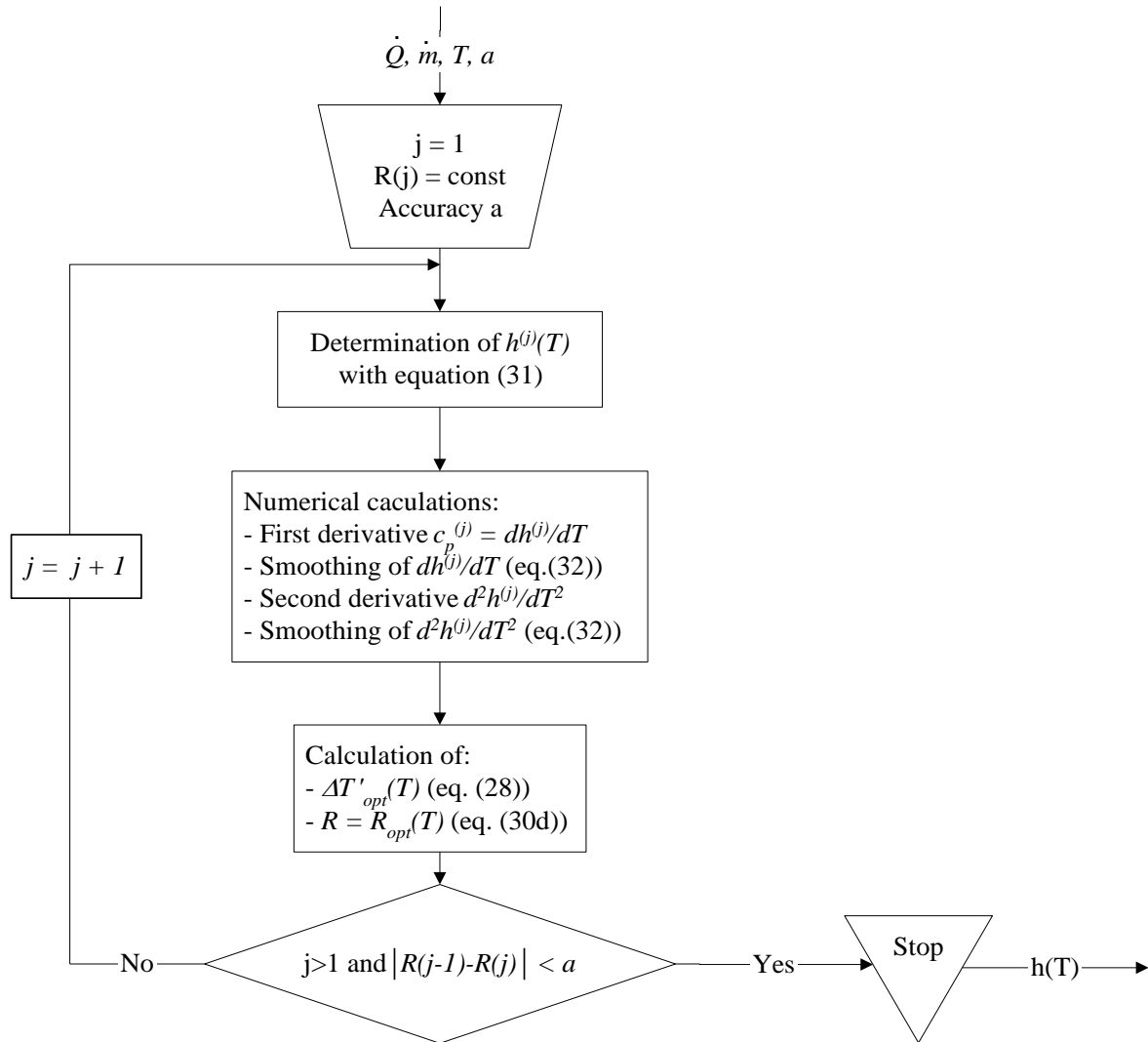
In FIG. 5, for the PCS at a temperature of 25 °C, an upper bound of the error  $\varepsilon$  is shown. The maximal error of the temperature sensor is assumed to be  $\varepsilon_T = 0.05$  K. In this particular case the optimal value is approximately  $\Delta T'_{i_{opt}} = 0.44$  K. For each single temperature  $T$  another optimal value results (see chapter 8).

In the pure solid and liquid phases the enthalpy function is linear and the second derivative zero. It is clear that in these regions large temperature increments lead to the best results. This is in agreement with the main result (28). In the melting region smaller temperature increments are required.

If the simple evaluation method, with an ideal choice of the mass and heat flow, respectively a ratio

$$R_i = \text{constant} \quad (29a,b)$$

is applied, then the requirement (28) is approximately fulfilled. In the melting range the heat absorption of the material is much higher and the temperature increases slower. This causes de-



**Figure 6: Flux diagram for the iterative experimental determination of the enthalpy density with a loop with index  $j$  for an optimization of the results. In this diagram further loops with counting index  $i$  have been neglected.**

sired smaller temperature increments in temperature regions, where the enthalpy density curve is steeper (see also chapter 7).

Furthermore, it follows

$$R_i = \Delta h'_i = c_{p_i} \Delta T'_i \quad \Rightarrow \quad R_{i_{opt}} = \Delta h'_{i_{opt}} = c_{p_i} \Delta T'_{i_{opt}}. \quad (30a-d)$$

From equation (10b) and (30c,d) one concludes that

$$h_k = h_0 + \sum_{i=0}^{k-1} R_i \frac{\Delta T_i}{\Delta T'_i} \quad \Rightarrow \quad h_0 + \sum_{i=0}^{k-1} R_{i_{opt}} \frac{\Delta T_i}{\Delta T'_{i_{opt}}} \quad k \in \{1, 2, \dots, n\}. \quad (31)$$

A serious problem remains, namely that an evaluation of the enthalpy density curve has to be performed with an optimal heat to mass flow relation. But to determine the optimal value the enthalpy density curve already must be known. Therefore, an iterative process - as shown in FIG. 6 - is the solution. One starts with a guess of a ratio  $R$ , which is kept constant during the first measurement. Then a first approach to the enthalpy curve is obtained. From this the optimal value  $\Delta T_{i_{opt}}$  and  $R_{i_{opt}}$  are calculated. Now the experiment is repeated, but by adjusting it to the calculated function  $R_{opt}(T)$ . The process will converge toward a definite enthalpy density curve after a low number of experimental iteration processes.

The applied smoothing process is described by the following formula

$$S(f(x_i)) = \frac{1}{m} \sum_{l=0}^{m-1} f(x_{i+l}), \quad i \in \{1, n - m + 1\}. \quad (32)$$

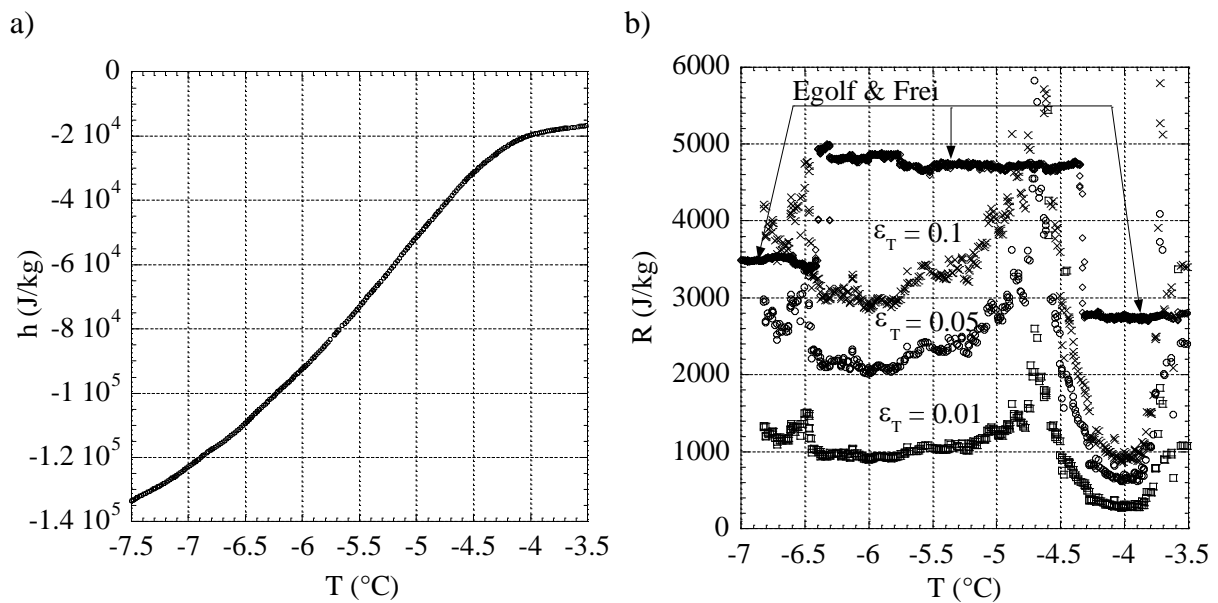
The following procedures were performed for the first and second derivative

$$SDh \quad \text{and} \quad SDDh, \quad D = \frac{d}{dT} \quad (33a-c)$$

and with a smoothing operation  $S$  as defined in equation (32).

## 7. ENTHALPY DENSITY OF AN ICE SLURRY

In FIG. 7a the experimentally determined enthalpy density curve of a ten mass percent talin/water ice slurry, as it was measured by the EUREKA FIFE group [4], is presented. These results are in good agreement with a physical-properties model published in this reference.



**Figure 7: The enthalpy density of an ice slurry (a) and the ratio  $R$  applied by Egolf and Frei in 1999 (b). The remaining curves show the optimal functions, evaluated with the present theory for three maximal sensor errors (parameter  $\varepsilon_T$ ) in the figure.**

The ratio  $R$  of the experiments of Egolf and Frei [4] was evaluated and is shown in FIG. 7b. It can be seen that they, after repeating their measurements several times, intuitively increased  $R$  in the melting domain toward an optimal evaluation as proposed in this article. The best possible ratio  $R$ , as calculated with the present theory, is also shown for comparison. The results depend on the choice of the quality of the temperature sensors, respectively on their measuring errors  $\varepsilon_T$ . For large values condition (16) may be violated. It is seen that Egolf and Frei increased the heating power to a slightly too high value at low temperatures ( $-6.5^\circ\text{C}$ ,  $-5.0^\circ\text{C}$ ). On the other hand the quantity of approximately  $5000 \text{ J/kg}$  was a quite good choice above the temperature  $-5.0^\circ\text{C}$  and the reduction at  $-4.3^\circ\text{C}$  was a correct guess. If the experiment had been repeated a second time, it should have been performed by following for example one of the three  $R(T)$  relations, which are proposed in this figure. This then would lead to an even better evaluation of the enthalpy density curve. But there remains a problem. At the inflection point, at approximately  $-4.7^\circ\text{C}$ , the curvature of the enthalpy density curve vanishes. Locally, namely at this single temperature, the curve has some properties of linearity. This leads to a vanishing upper boundary in the optimization process, and the result for  $\Delta T_{opt}$  and  $R_{opt}$  is infinite. For practical applications it is proposed to restrict  $R_{opt}$  at this point.

The evaluation procedure of the results  $R_{opt}$  were the following. First a sorting process, similar to equation (6) was applied. To sort the intervals, here the arithmetic mean temperatures were calculated

$$\bar{T}_i = \frac{T_i + T_{i+1}}{2}, \quad \forall i \in \{0, 2, \dots, n-1\} \quad (34)$$

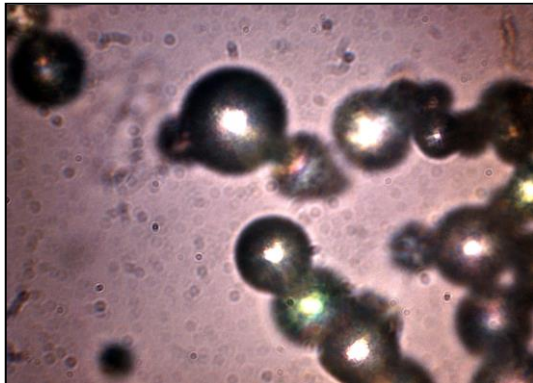
and then the criteria

$$\bar{T}_i < \bar{T}_{i+1}, \quad \forall i \in \{0, 2, \dots, n-1\} \quad (35)$$

was applied. Because a very high sampling rate was performed, the smoothing was also applied with a large number  $m=100$ .

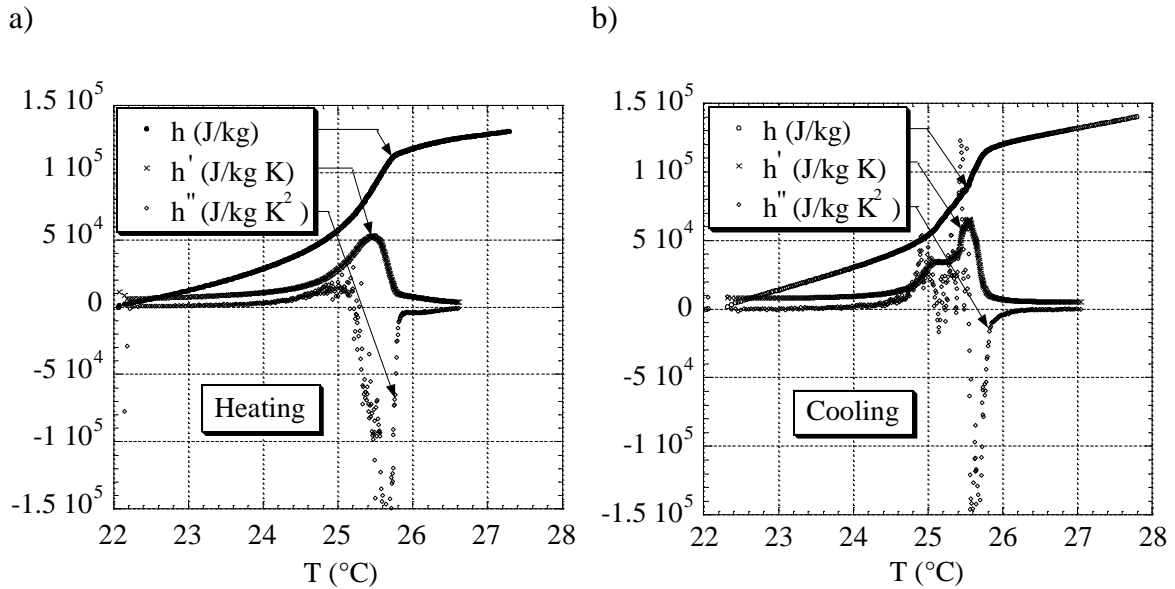
## 8. ENTHALPY DENSITY OF A SUSPENSION WITH MICROCAPSULES

In an experimental work of Schneider and Sari a PCS with thirty five mass percent microencapsulated paraffin wax (octadecane) was experimentally investigated [6]. The experimental data sets of the enthalpy density were taken as a basis for the following evaluations.

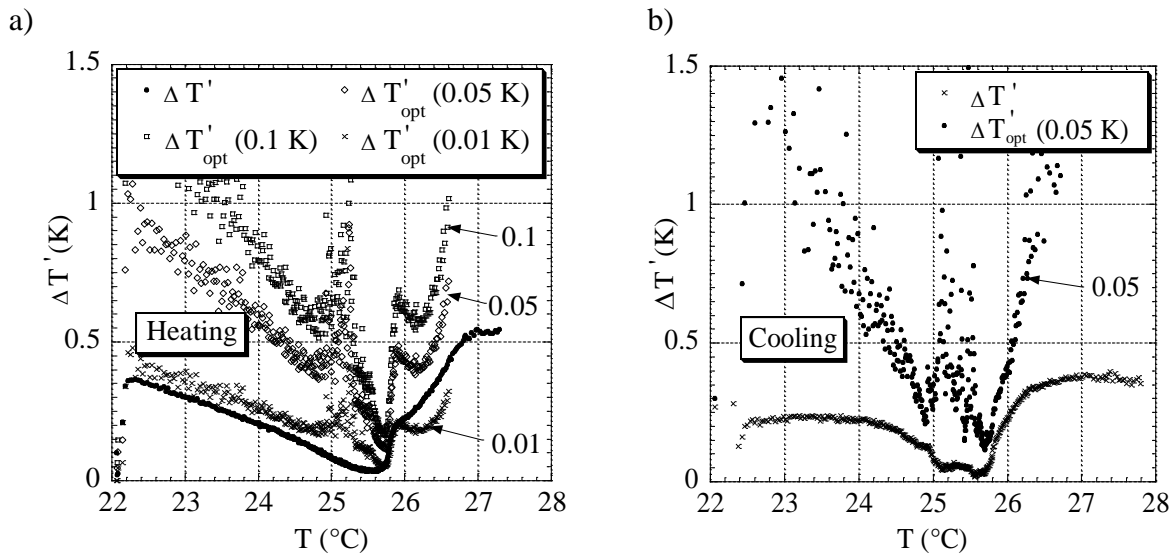


**Figure 8: Microencapsulated technical grade Paraffin (Octadecane Type TH 83). The shells are produced with polyoxymethylene urea, the water content is less than four percent, the content of formaldehyd less than 0.01 % and the volatile behaviour less than 2%. The diameters of the spheres are between 10 and 35 micrometers. Cyclic tests of melting freezing were performed with 200 000 periods.**

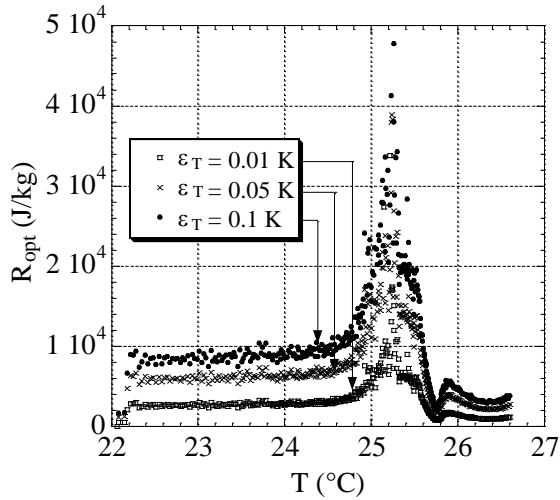
The enthalpy density of the PCS shown in FIG. 8, measured in the two heat exchangers, are presented in FIG. 9. The two obtained functions are very similar. The first and second derivatives are shown. They were numerically calculated by an application of the smoothing procedure according to equations (33a,b) with  $m=30$ . FIG. 10 shows the evaluated temperature increments  $\Delta T'$  in the first step, obtained with a constant ratio  $R$ . Then after the smoothing procedure was applied to the first and second derivative of the enthalpy density with equation (28) the optimal values  $\Delta T'_{opt}$  were calculated. These calculations were performed for three different temperature sensor errors.



**Figure 9:** The enthalpy density function  $h$  and its first  $h'$  and second derivative  $h''$  as a function of the temperature are shown. After the first and second derivative were numerically calculated a data smoothing process was applied. The enthalpy density determined with heating (a) and cooling (b) are almost identical.



**Figure 10:** The temperature increments  $\Delta T'$  as obtained with a constant ratio  $R$ . Furthermore, the optimal temperature differences  $\Delta T'_{opt}$  are shown for different sensor errors  $\epsilon_T$ , which vary between 0.01 K and 0.1 K. These errors are indicated in parentheses.



In FIG. 11, by applying equation (30d), the ratio  $R_{opt}$  was calculated. It is seen that when the errors of the temperature sensors are small, the adjusted heat flow in a second experiment can be chosen smaller. A second run (improvement) of the experiment was not performed yet.

*Figure 11: The first calculations of  $R_{opt}$  which defines the heat and mass flow ratio as a function of  $T$  for a second improved enthalpy density measurement.*

## 9. CONCLUSIONS AND OUTLOOK

To measure enthalpy densities the “*Online method*” has great advantages, e.g. no material probes have to be removed from the well-insulated testing device. To obtain results of reasonable quality in the piping system, a constant heat and mass flow may be chosen. But a basic understanding of the procedure is necessary to improve the results. This is given by a small theory, which is presented in this article and named sophisticated evaluation method (see chapter 5). With simple numerical calculation schemes for differentiation and smoothing of data sets of a PCS with microencapsulated paraffin wax, the heat and mass flow ratio  $R$  for an improved measurement series is determined. In future experiments - with a product which is produced by *BASF Ludwigshafen* - the enthalpy density measurements shall be iteratively repeated till convergence occurs. This will lead to the highest possible quality of results obtainable with this measuring technique. For the evaluation of the data a Delphi program was developed, which performs the derivatives and smoothing operations. It is distributed free to interested scientists.

## NOMENCLATURE

### Standard

$c_p$	specific heat	(J/kg K)
$D$	operator for derivation	( $K^{-1}$ )
$e$	maximal error	(K)
$f$	mathematical function $\in C^2$	(-)
$h$	enthalpy density	(J/kg)
$\dot{m}$	mass flow	(kg/s)
$\dot{Q}$	heat flow	(W)
$R$	ratio of heat to mass flow	(J/kg)
$S$	smoothing operator	(-)
$T$	temperature	(°C)
$T_i$	discretized temperature	(°C)
$x$	space co-ordinate downstream	(m)

## Greek

$\Delta$	increment	(-)
$\varepsilon$	error	(J/kg K)
$\xi$	intermediate value	(K)

## Indices

$i$	discretization index
$in$	inlet
$j$	number of experiment
$opt$	optimal value
$out$	oulet

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