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# Thermal Performance of MEMS-Based Heat Exchanger with Micro-Encapsulated PCM Slurry

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## Abstract

**Latent heat thermal energy storage technique has demonstrate to be a better engineering option mainly due to its benefit of supplying higher energy storage density in a smaller temperature difference between retrieval and storage. For this purpose, a micro electro-mechanical system, MEMS-based heat exchanger with microencapsulated PCM (MEPCM) slurry as cold fluid, has been simulated three dimensionally. This work investigates the influence of using MEPCM-slurry on the temperature of the cold and hot fluids. The MEPCM and water properties have been considered temperature dependent. MEPCM-slurry is used with different volume fractions. The result shows that using MEPCM with 25% volume fraction leads to the improvement in fluids temperatures, that is, for hot fluid the rate of temperature reduction increases up to 23.5% and for cold fluid the rate of temperature rise decreases to 9%, compared to using only water in the MEMS.**

## Keywords

**MEMS, Microchannel, MEPCM-Slurry, Latent Heat, Simulate**

## 1. Introduction

Phase change materials (PCMs) are materials with the ability to change phase in a certain temperature range. They absorb or release high energy during melting or solidifying. Their ability to storage high energy indicates their high latent heat. Due to PCMs have inherent low thermal conductivity, their application in the latent heat thermal storage (LHTS) systems has lower heat transfer rates. Different procedures have been offered for the enhancement of PCMs thermal conductivity like dispersing nanoparticles with high thermal conductivity in PCMs [1] and microencapsulating them. A large number of researchers have investigated the performance of different types of heat exchangers used as latent heat thermal storage units, among which MEMS-heat exchanger has higher efficient for micro scales [2]. Fluids used in heat exchangers have significant influence on cooling efficiency rate. Moreover, the fluids individual thermophysical properties are the major key for their cooling ability.

Using encapsulated PCMs improves the performance of the heat exchanger heat storage due to their high la-

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tent heat. At first Tuckerman and Pease [3] offered a microchannel heat exchanger for electronic cooling by using water. They demonstrated that the heat flux rate of 790 W/m$^2$ could be dissipated in that microchannel heat exchanger. Goel *et al*. [4] investigated the convective heat transfer performance of an MEPCM-slurry in volume fraction from 0% - 20% in a circular tube. They showed that MEPCM-slurry affected by Stefan number and the volumetric concentration considerably decreases the wall temperature rise up to 50% compared to water. Sabbah *et al*. [5] studied the influence of MEPCM slurry on the microchannel heat sink. They observed that enhancement of the heat transfer coefficient is significantly affected by MEPCM melting temperature, channel inlet and outlet temperature. Yu *et al.* [6] examined the convective heat transfer of MEPCM with an average of 4.97 µm at volume fraction range of 0% - 20% in rectangular minichannel. The result showed that the 5% suspension has a better effect on cooling performance than water in lower wall temperature and improved heat transfer coefficients. In the presented work, a 3D-dimensional MEMS-heat exchanger has been designed. In this work effect of MEPCM-slurry with octadecane core and polymethylmethacrylat shell on the thermal performance of microchannel has been investigated.

## 2. Methodology

### 2.1. MEMS—Heat Exchanger

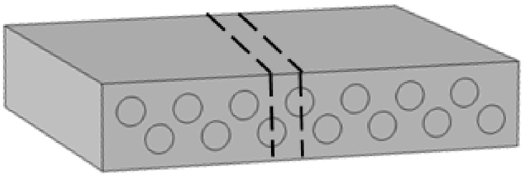
**Figure 1(a)** shows a schematic of MEMS-heat exchanger made of Aluminum, modeled in this study. It consists of 14 circular microchannels with 100 µm diameter. Due to the symmetry of the channel, we modeled only half of the doubled channels as shown in **Figure 1(b)**. The simulations are developed with water and then are repeated with MEPCM-slurry with volume fractions of 5%, 10%, 15%, 20% and 25%.

In order to solve this problem following assumptions are adopted: 1) fluid flow is laminar, steady state and incompressible; 2) The viscous dissipation is ignored; 3) The thermophysical properties of water, PCM and MEPCM-slurry are dependent on temperature; 4) External body force and gravitational body force are ignored.
The Governing Equations Are:

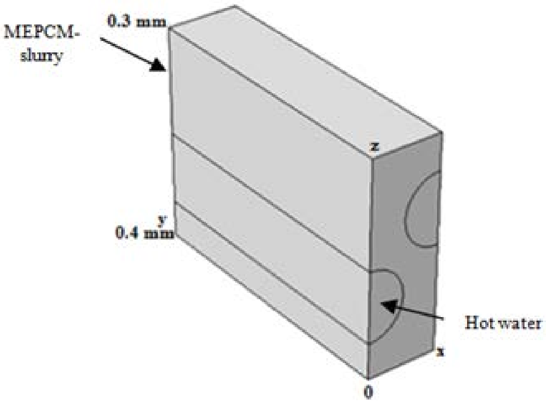
- *Continuity equation*

$$\nabla.(\rho\overline{U}) = 0. \tag{1}$$

$$\overline{U} = ui + vj + wk. \tag{2}$$



(a)



(b)

**Figure 1.** (a) Geometry of the MEMS; (b) MEMS modeled.

- *Momentum equation*

$$\nabla\cdot(\rho\bar{U}\bar{U}) = -\nabla P + \rho\bar{g} + \nabla\cdot\tau + \bar{F} \tag{3}$$

where:
$\bar{F}$ : External body forces ( $\bar{F} = 0$ ).
$\rho\bar{g}$ : The gravitational body force ( $\rho\bar{g} = 0$ ).

- *Energy equation*

$$\nabla\cdot(\rho\bar{U}H) = \nabla\cdot(K\nabla T) + S \tag{4}$$

where:
$H$: The carrier fluid enthalpy.
$S$: volumetric heat source ($S = 0$).
The total enthalpy ( $H$ ) is described by Equation (5).

$$H = h + \Delta H. \tag{5}$$

where:
$H$: sensible enthalpy.
$\Delta$H: MEPCM latent heat.
The sensible heat is calculated by Equation (6).

$$h = h_{\mathrm{ref}} + \int_{T_{\mathrm{ref}}}^{T} c_{\mathrm{p}}\,\mathrm{d}T \tag{6}$$

where
$h_{\mathrm{ref}}$: reference enthalpy.
$T_{\mathrm{ref}}$: reference temperature.

The latent heat of slurry content is calculated by Equation (7).

$$\Delta H = \beta\phi L. \tag{7}$$

where:
$\beta$ : liquid fraction.
$\phi$ : NEPCM mass fraction.
L: PCM latent heat.

The mass ratio of melted PCM to the total mass of PCM is defined as the liquid fraction. The PCM melting temperature ranges from $T_{\mathrm{solidus}}$ to $T_{\mathrm{liquidus}}$. Therefore $\beta$ is described by Equation (8).

$$\beta = 0 \qquad if \quad T < T_{\mathrm{solidus}}$$

$$\beta = 1 \qquad if \quad T > T_{\mathrm{liquidus}}$$

$$\beta = \frac{T - T_{\mathrm{solidus}}}{T_{\mathrm{liquidus}} - T_{\mathrm{solidus}}} \qquad if \quad T_{\mathrm{solidus}} < T < T_{\mathrm{liquidus}}. \tag{8}$$

### 2.2. Numerical Method

The governing equations in the three dimensional system are solved by using CFD software Fluent. The distribution of temperature and velocity are calculated by using finite volume technique with SIMPLE algorithm.

### 2.3. Fluids Properties

In this study, MEPCM-slurry with the core (PCM) and shell made of octadecane and polymethylmethacrylat (PMMA) respectively is mathematically analyzed. The average diameter of ME PCM is 4.9 µm [4]. The core material includes 70% of the MEPCM volume. The PCM latent heat is equal to 244 J/g [7]. The thermophysical properties of octadecane and PMMA are shown in **Table 1** [1] [8] [9].

The density, specific heat and thermal conductivity of microcapsules [4] are defined as Equations (9)-(11)

**Table 1.** The thermophysical properties of MEPCM.

| | Octadecane | PMMA |
|---|---|---|
| Density (kg/m) | $\frac{750}{0.001(\mathrm{T}-319.15)+1}$ | 1190 |
| Specific heat (J/kg·K) | 2000 | 1470 |
| Thermal conductivity (W/m·K) | 0.358 if $T < T_{\text{solidus}}$<br>0.148 if $T > T_{\text{liquidus}}$ | 0.21 |
| $T_{\text{liquidus}}$ | 302 | - |
| $T_{\text{solidus}}$ | 299 | - |

$$\rho_{\mathrm{PCM}} = \frac{10}{7}\left(\frac{d_{\mathrm{C}}}{d_{\mathrm{PCM}}}\right)^{3} \rho_{\mathrm{c}} \tag{9}$$

$$c_{\mathrm{pPCM}} = \frac{\left(7c_{\mathrm{pc}} + 3c_{\mathrm{psh}}\right)\rho_{\mathrm{c}}\rho_{\mathrm{sh}}}{\left(3\rho_{\mathrm{c}} + 7\rho_{\mathrm{sh}}\right)\rho_{\mathrm{PCM}}} \tag{10}$$

$$\frac{1}{k_{\mathrm{PCM}} d_{\mathrm{PCM}}} = \frac{1}{k_{\mathrm{c}} d_{\mathrm{c}}} + \frac{d_{\mathrm{PCM}} - d_{\mathrm{c}}}{k_{\mathrm{sh}} d_{\mathrm{PCM}} d_{\mathrm{c}}} \tag{11}$$

where
*d*: diameter.
*c*: PCM particles (core).
sh: PMMA (shell).
PCM: MEPCM particle (core + shell).

Equations (12)-(15) are used to calculate the density, specific heat [6], viscosity [4], and thermal conductivity [10], of MEPCM-slurry.

$$\rho_{\mathrm{f}} = c\rho_{\mathrm{np}} + (1-c)\rho_{\mathrm{w}} \tag{12}$$

$$c_{\mathrm{pf}} = \varphi c_{\mathrm{pnp}} + (1-\varphi)c_{\mathrm{pw}}. \tag{13}$$

$$\mu_{\mathrm{f}} = \mu_{\mathrm{w}}\left(1 - c - 1.16c^{2}\right)^{-2.5}. \tag{14}$$

$$k_{\mathrm{f}} = \frac{2k_{\mathrm{w}} + k_{\mathrm{np}} + 2c\left(k_{\mathrm{np}} - k_{\mathrm{w}}\right)}{2 + \frac{k_{\mathrm{np}}}{k_{\mathrm{w}}} - c\left(\frac{k_{\mathrm{np}}}{k_{\mathrm{w}}} - 1\right)} \tag{15}$$

where
*W*: water.
$c$ : volume fraction.
$\phi$ : mass fraction of NEPCM.

The following relation is used to measure $\phi$ Equation (16).

$$\phi = \frac{c_{\mathrm{pnp}}}{\rho_{\mathrm{w}} + c(\rho_{\mathrm{np}} - \rho_{\mathrm{w}})}. \tag{16}$$

## 3. Results and Discussion

Simulations were carried out first with pure water, and then were repeated with MEPCM-slurry with volume fractions of 5%, 10%, 15%, 20% and 25%. Considering that, the inlet velocity ($V_{in}$) is equals to 1 m/s and inlet temperatures of cold and inlet fluid are 298 and 300 K respectively.

### 3.1. The Mean Temperatures of Hot and Cold Fluids

**Figure 2** shows the mean temperature of cold and hot water versus channel length. **Figure 3** shows the mean temperature of hot water and MEPCM-slutty at the volume fraction of 5% versus channel length. The results show that using MEPCM-slurry reduces the rate of temperature rise of cold flow, moreover increases the rate of temperature reduction of hot flow compared to using only water. It can be seen that hot water temperature decreases without significant increasing in MEPCM-slurry temperature. In this way, it can be found that PCMs have capability of energy storage due to its high latent heat. In addition, Sabbah *et al*. [5] indicated the significant influence of the channel inlet and outlet temperature on the heat transfer coefficient in the microchannels. The mean flow temperature is described by Equation (17).

$$T_{\mathrm{m}} = \frac{\int_{A_c} \rho v c_{\mathrm{p}} T \mathrm{d}A_{\mathrm{c}}}{\int_{A_c} \rho v c_{\mathrm{p}} \mathrm{d}A_{\mathrm{c}}} \tag{17}$$

where

$A_{\mathrm{c}}$ : channel cross-sectional area ($\mathrm{m}^2$).

**Figure 4** shows the mean temperature of hot water when MEPCM-slurry in 5%, 10%, 15%, 20% and 25% of volume fractions is used as cold fluid. As a result the increase of the rate of the hot water temperature reduction is observed for all MEPCM volume fractions. **Figure 5** shows the mean temperature of MEPCM-slurry as cold fluid in various volume fractions. From Results, It can be seen that MEPCM-slurry in all of its volume fractions

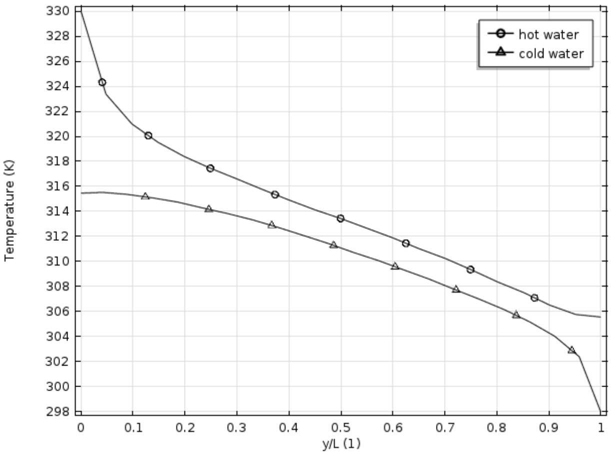


**Figure 2.** Mean temperature of cold and hot water.

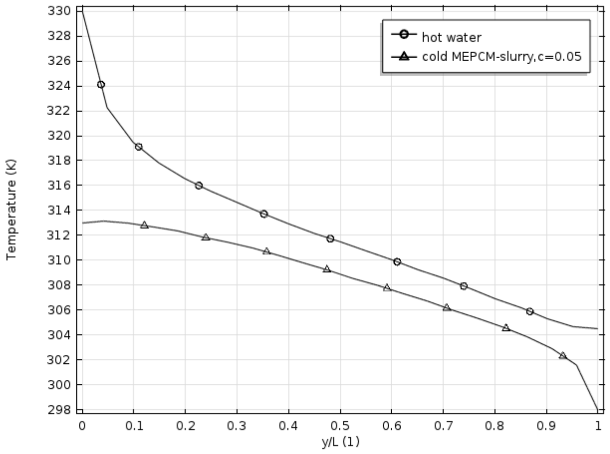


**Figure 3.** Mean temperature of MEPCM-slurry and hot water.

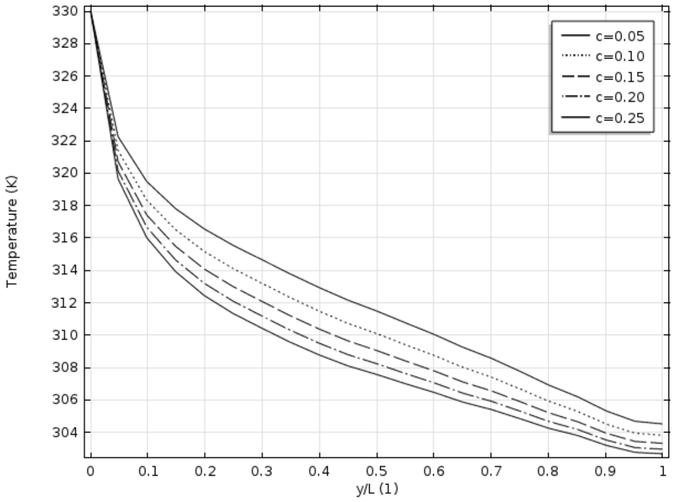


**Figure 4.** Mean temperature of hot water by using MEPCM-slurry as cold fluid in various volume fractions.

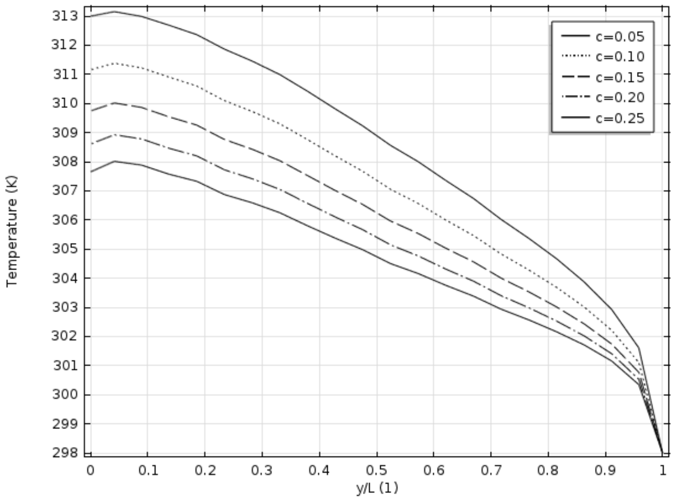


**Figure 5.** Mean temperature of MEPCM-slurry in various volume fractions.

reduces the rate of temperature rise of cold fluid. To illustrate, consider the list of data in **Table 2**. The results show that increasing volume fraction of MEPCM reduces the temperature of both hot and cold fluids. The best performance of thermal storage in MEMS-heat exchanger is observed at the volume fraction of 25%. It should be noted that MEPCM particles must be less than 25% to be considered Newtonian [11].

### 3.2. Inlet Velocity

**Figure 6** shows the mean temperature of hot water in various inlet velocities, $V_{in}$ = 0.5, 1, 1.5 and 2 m/s versus channel length. MEPCM-slurry in 25% of volume fraction is used as cold fluid. The results show that in all inlet velocities the rate of temperature reduction of hot water increases. Besides, it can be seen that higher inlet velocity leads to lower water temperature. **Figure 7** shows the mean temperature of MEPCM-slurry at the volume fraction of 25% and in various inlet velocities. The results show that the rate of temperature rise of MEPCM-slurry is decrease for all inlet velocities. In addition, it can be seen that higher inlet velocity leads to lower MEPCM-slurry temperature. As a result, inlet velocity is one of the important factors for enhancement of thermal performance of MEMS-heat exchanger.

**Table 2.** List of fluids temperature.

| MEPCM volume fraction | $T_{out}$ (K) hot water | $T_{out}$ (K) cold fluid |
|---|---|---|
| 0% | 305.57 | 315.52 |
| 5% | 304.52 | 313.15 |
| 10% | 303.82 | 311.38 |
| 15% | 303.32 | 310 |
| 20% | 302.96 | 308.92 |
| 25% | 302.68 | 308 |

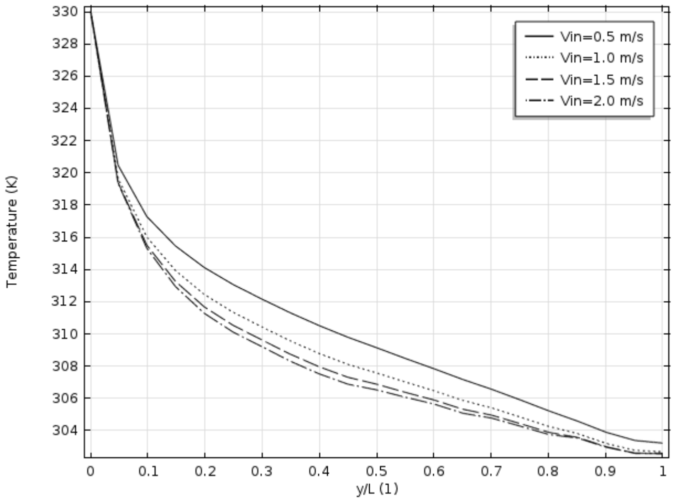


**Figure 6.** Mean temperature of hot water in various inlet velocities by using MEPCM-slurry as cold at the 25% of volume fraction.

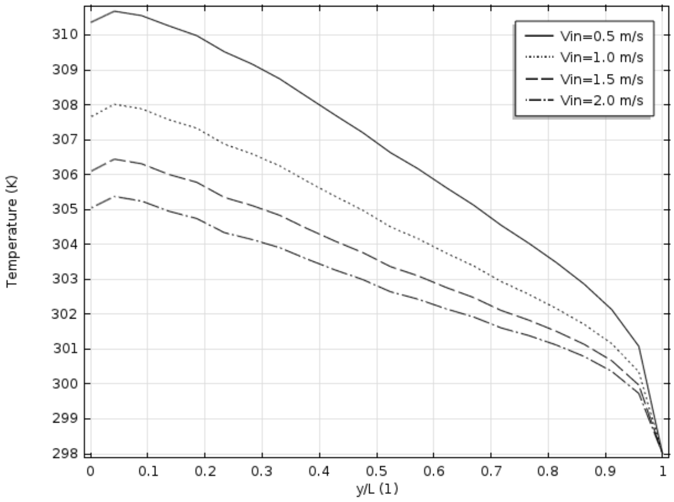


**Figure 7.** Mean temperature of MEPCM-slurry at the 25% of volume fraction in water in various inlet velocities.

## 4. Conclusions

- Using MEPCM-slurry instead of water reduces The MEMS temperature due to high-energy storage capability of PCM.

- Increasing volume fraction of MEPCM-slutty and inlet velocity are the most important factors for the thermal performance enhancement of the MEMS-heat exchanger.
- An improvement of 23.5% can be achieved by using MEPCM-slurry as cold fluid at the volume fraction of 25%, compared to using only water in MEMS-heat exchanger.

Considering the temperature dependent of fluids properties, the achieved results are accurate and more similar to the real situation.

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