System Analysis of MPCM Slurry Enhanced with Carbon Nanotubes as Heat Transfer Fluid

Hessam Taherian, PhD
Member ASHRAE

Jorge L. Alvarado, PhD, PE
Associate Member ASHRAE

ABSTRACT

Microencapsulated phase change material (MPCM) and carbon-nanotube based nano fluids have both been investigated as heat transfer coefficient enhancers separately. In this paper, we investigate the potential manifold benefit of using a blend of both as a new heat transfer fluid. The effect of percentage of MPCM that undergoes phase change and the composition of the new blend of heat transfer fluid have been investigated. A computer simulation code reveals that the best composition for the MPCM-nanofluid blend depends on the actual percentage of phase change that takes place in the process. Better heat transfer rates can be achieved when high quantity of MPCM undergoes phase change.

INTRODUCTION

Increasing intensity and performance of heat transfer in heat exchanger equipment is one of the most pressing issues in the world today. Information technology applications as well as data centers have seen a growth in processing speed which has resulted in higher dissipation of heat. In HVAC applications, increasing the heat transfer rate can lead to reduction of the required flow rate of heat transfer fluids which consequently saves energy through decreased pumping power.

The introduction of Microencapsulated Phase Change Material (MPCM) in form of slurries as heat transfer fluids has been well accepted among researchers. MPCM slurries consist of a base fluid such as water that contains a relatively low mass fraction of microcapsule filled with phase change material such as octadecane or paraffin wax. The microcapsules vary in size between 1 to 10 μm to avoid breakage during continuous pumping. High effective heat capacity is expected when the phase change undergoes phase change while is flowing under constant heat flux or temperature conditions. Several experimental as well as numerical studies have been published recently (Ravi et al. 2009, Alkan et al. 2009, Alvarado et al. 2007, Chen et al. 2008, Goel et al. 1994, Bai and Lu 2003, Yamagishi et al. 1999 and Mulligan et al. 1996). Improvement in heat transfer coefficient as much as 3 times has been reported.

Use of carbon nanotubes (CNT) dispersed in water has also been under intense investigation recently (Amrollahi et al. 2008, Vadasz 2006, Patel et al. 2008, Hsu et al. 2008, Garg et al. 2009). Most of the literature reports heat transfer enhancement with nano fluids as working fluid, though there is no total agreement among researchers on the magnitude of enhancement. In this paper we propose combining MPCM and CNT to a base working fluid medium in order to quantify the benefits of the anticipated collective effect of additional heat capacity and thermal conductivity enhancement.

ANALYSIS

Transport Properties

Analysis of any heat transfer fluid in a thermal systems needs well defined thermal properties. Density (ρ), specific heat (c_p), thermal conductivity (k) and dynamic viscosity (µ) are the four thermophysical properties that are essential in any convection heat transfer problem. With regards to density, there is minimal discrepancy in the literature. Pak and Cho (1998), compared the density measurement results for Al_2O_3 and TiO_2 in distilled water with those estimated by the simple mixing theory at 298K (536.4R) and up to a volume concentration of 5%, and found that the maximum deviation is 0.6%. Density measurements by Vajjha et al. (2009) showed that for...
nanofluids, the simple mixing equation can be used with minimal deviation.

Equation 1 is postulated based on the conservation of mass principle and by modifying the mixing model for two components (MPCM and CNT) added to the base fluid.

\[ \rho_{mf} = \rho_{np} \Phi_{np} + \rho_{MPCM} \Phi_{MPCM} + \rho_{bf}(1 - \Phi_{np} - \Phi_{MPCM}) \quad (1) \]

The density of the MPCM can be predicted accurately using Equation 2 (Chen et al., 2008). Furthermore, Roy and Avanic (2001) suggested that the suspension density would not change by more than 1-2% for phase change material concentrations of 10-20% as long as the specific gravity of the phase change material was greater than 0.8.

\[ \rho_{MPCM} = \frac{(1 + y) \rho_{f} \rho_{s}}{\rho_{s} + y \rho_{c}} \quad (2) \]

With regards to the specific heat of the MPCM slurries, Alisetti and Roy (1999) through numerical analysis, proposed and investigated several functions for the specific heat during phase change process. They found that the exact shape of the function during phase change was not crucial to the analysis of laminar convective heat transfer inside a circular tube as the difference among various models was less than 4%. Equation 3 has been proposed by Mulligan et al. (1996) based on energy balance to calculate the specific heat of MPCM slurries.

\[ C_{p,eff} = C_{p,bf}(1 - \Psi_{MPCM}) + \Psi_{MPCM}C_{p,MPCM} + \frac{k_{MPCM}}{\Delta T} \quad (3) \]

The specific heat of the PCM capsules will be evaluated using Equation 4 (Chen et al. 2008).

\[ C_{p,MPCM} = \frac{(C_{p,c} + y C_{p,a}) \rho_{f} \rho_{s}}{(\rho_{f} \rho_{s} + \rho_{c}) \rho_{MPCM}} \quad (4) \]


\[ C_{p,nf} = \Phi_{np} C_{p,np} + (1 - \Phi_{np}) C_{p,bf} \quad (5) \]

\[ C_{p,nf} = \Phi C_{p,np} + (1 - \Phi) C_{p,bf} \quad (6) \]

However, Zhou and Ni (2008) found that the result of their experiments fits Equation 5 well, and had considerable deviation when using Equation 6. For the mixture of MPCM and nanofluid, an energy balance equation leads to:

\[ C_{p,eff} = \frac{1}{\rho_{eff}} \cdot \left[ \rho_{np} \Phi_{np} C_{p,np} + \rho_{MPCM} \Phi_{MPCM} C_{p,MPCM} + \rho_{bf}(1 - \Phi_{np} - \Phi_{MPCM}) C_{p,bf} + \epsilon \rho_{MPCM} \Phi_{MPCM} \Delta T \right] \quad (7) \]

The thermal conductivity is the most difficult of the properties to model. For MPCM slurries most researchers use Maxwell’s (1954) relation as given in Equation 8.

\[ k_{nf} = k_{bf} \frac{2k_{bf}^2 + k_{MPCM}^2 + 2\varphi(k_{MPCM} - k_{bf})}{2k_{bf}^2 + k_{MPCM}^2 - \varphi(k_{MPCM} - k_{bf})} \quad (8) \]

For nanofluids, in addition to Maxwell’s relation there are other models available in the literature. Equation 9 has been proposed by Hamilton and Crosser (1962):

\[ k_{nf} = k_{bf} \left[ \frac{k_{np}^2 + (n - 1)k_{bf}^2 - (n - 1)\varphi(k_{bf} - k_{np})}{k_{np}^2 + (n - 1)k_{bf}^2 + \varphi(k_{bf} - k_{np})} \right] \quad (9) \]

where \( n = 3/\xi \) and \( \xi \) is called the sphericity and defined as the ratio of the surface areas of a sphere with the volume equal to that of the nanoparticle.

To estimate the combined effect of nanofluid and MPCM slurry, available models for binary mixtures of liquids may be used. Maloka (2007) reviewed several complicated models and proposed a new model. However, according to the study made by Focke (2008), all models deviate by less than 10% from the much simpler “linear blending rule” presented in Equation 10.

\[ k_{eff} = x_Ak_A + x_Bk_B \quad (10) \]

For the dynamic viscosity of suspensions, Einstein’s theory has been presented by Drew (1998) in the form of Equation 11.

\[ \mu_{eff} = \mu_{bf}(1 + 2.5\varphi) \quad (11) \]

Brinkman (1952) and Thomas (1965) proposed Equations 12 and 13, respectively for the effective viscosity of Newtonian suspensions. Both Equations are valid for \( \varphi < 0.25 \).

\[ \mu_{eff} = \mu_{bf} \cdot \frac{1}{(1 - \varphi)^2} \cdot 5 \quad (12) \]

\[ \mu_{eff} = \mu_{bf} \cdot (1 + 2.5\varphi + 10.05\varphi^2) \quad (13) \]

Equations 11-13 can be similarly used for nanofluids and MPCM slurries as long as the assumption of Newtonian behavior holds. In order to estimate the effective viscosity of the mixture of CNT fluid and MPCM slurry, the Refutas method (Maples 1993) which has originally been used for blends of hydcarbons may be used for blends of MPCM slurry and nanofluid. The method is based on calculating Viscosity Blending Index (VBI) of each component of the blend.

\[ VBI = 14.534 \times \ln[\ln(v + 0.8)] + 10.975 \quad (14) \]

then calculating VBN of the blend using Equation (15):

\[ VBI_{blend} = [x_A \times VBI_A] + [x_B \times VBI_B] \quad (15) \]

the kinematic viscosity of the blend can be calculated using Equation (16):

\[ \nu = \exp \left( \frac{VBI_{blend} - 10.975}{14.534} \right) - 0.8 \quad (16) \]
Finally, the dynamic viscosity of the mixture can be calculated with prior knowledge of the mixture’s mass density. The pressure drop can be estimated using the Darcy-Weisbach equation for turbulent flow in pipes.

**Heat Transfer and Pressure Drop of MPCM-CNT Heat Transfer Fluid**

In order to show the enhancing effect of the new heat transfer fluid, a concentric-tube exchanger has been considered as the heat transfer device. Table 1 shows the heat exchanger parameters as well as the heat transfer fluid properties. The results have shown that for 1kW (3412 Btu/hr) only 0.05 L/s (0.79 GPM) of heat transfer fluid flow is required.

Due to the nature of the mixing process, dimensional parameters of multi-walled carbon nanotubes (MWCNT) can only be given within a range rather than a definite fixed value, so median values were considered for computational analysis. The specific heat value for carbon nanotubes was taken from Hepplestone et al. (2006).

The heat exchanger depicted in Figure 1 shows schematic diagram of a concentric-tube heat exchanger.

Which was considered for the analysis. Water flows as the cooling liquid in the outer tube of the heat exchanger. As indicated in Table 1, the volume fractions of CNT in the nanofluid and MPCM in the slurry are considered constant and equal to 1% and 10%, respectively. The design temperatures have been selected in a way that the average inlet fluid temperature is around 27°C (80.6°F) which is the melting point of the phase change material (i.e. octadecane).

At first, a desired temperature drop for water (cooling fluid) was specified. Since both outlet temperature of the heat transfer fluid and heat transfer area are unknown, the simulation starts with an initial guess for the heat transfer fluid outlet temperature. Knowing the average temperature of both fluids, their thermophysical properties can be calculated using the equations shown above. The value for \( C_{P,\text{eff}} \) depends on the temperature drop (or difference) in the heat transfer fluid as seen in Equation 7. Then Nusselt numbers for water and the heat transfer fluid are determined using Dittus-Boelter correlation (Equation 17) for turbulent flow (Winterton 1998).

\[
Nu = 0.023Re^{0.8}Pr^{m}
\]  
(17)

In Equation 17, \( m \) is equal to 0.3 for the fluid that is being cooled and 0.4 for the fluid that is being heated. The overall heat transfer coefficient \( U \) is then calculated using Equation 17 and the corresponding heat transfer coefficients \( (U = 1/h_o + 1/h_i) \). The required heat transfer area is determined using Equation 18 for counter-flow configuration.

\[
A = \frac{Q}{U \cdot LMFD}
\]  
(18)

Using energy balance, the value of the heat transfer fluid outlet temperature can be corrected until convergence is reached. The algorithm briefly described above was incorporated into a computer code which was developed using EES software (Klein 2008) to solve for the heat exchanger design problem to determine required surface area.

**Results**

In Figure 2, \( \epsilon \) is the percentage of MPCM that has undergone phase change in the process. Figure 2 also shows that when high percentages of phase change material undergoes phase change, an increasing mass fraction of nanofluid in the blend will cause \( C_{P,\text{eff}} \) to drop sharply from 20.1 (4.8) to 4.3kJ/

![Figure 1](image)

**Figure 1** Schematic diagram of a concentric-tube heat exchanger.

<table>
<thead>
<tr>
<th>Table 1. Concentric-Tube Heat Exchanger Analysis Parameters</th>
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<tr>
<td>Inner-Tube Inside Diameter</td>
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<tr>
<td>Inner-Tube Wall Thickness</td>
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<tr>
<td>Outer-Tube Inside Diameter</td>
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<tr>
<td>Water-Side Temperature Raise</td>
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<tr>
<td>Carbon Nanotube Volume Fraction</td>
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<td>MPCM Volume Fraction</td>
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<td>Fluid Flow Rate</td>
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<td>Water Flow Rate</td>
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<td>Fluid Inlet Temperature</td>
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kg·K (1.03 Btu/lb·°F). At low ε values, the effective specific heat is not affected considerably by change in the blend composition. If there is no phase change in the fluid, $C_{p,\text{eff}}$ increases slightly with increasing the amount of CNT.

Figure 3 shows that the effective thermal conductivity of the blend increases by increasing the amount of nanofluid in the blend regardless of the percentage of the MPCM that changes phase. This is expected since higher amount of CNT should result in higher thermal conductivity.

The overall heat transfer coefficient of the heat exchanger almost increases linearly with increasing the amount of nanofluid for cases where a low fraction of phase change happens as shown in Figure 4. As the fraction of material that changes phase increases to a value over 75%, the linearity of the curve is disturbed and the curve exhibits a minimum value. The $U$ value first decreases and then increases again with increasing amount of nanofluid. The $U$ value is at its highest when 100% phase change occurs and no nanofluid is present in the blend. This can be explained by the dominance of $\Delta T$ in the effective specific heat model which reaches a minimum value at 100% phase change.

Figure 5 demonstrates the effect of parameters on the temperature drop of the heat transfer fluid passing through the heat exchanger. As expected, the lowest temperature change happens in the case when 100% phase change takes place, and there is no nanofluid in the blend. This is due to high value of the effective specific heat of the fluid as described above. The change with the fraction of nanofluid in the blend is linear in all cases.

One should expect that the required surface area of the heat exchanger to be lowest when phase change effect is at its highest. This is shown in Figure 6. However, if phase change is less than 50% then it is beneficial to have a high amount of nanofluid in the blend. At low phase change rates, the required
heat transfer area drops by more than 20% when nanofluid-rich blend is used.

No study of heat exchanger is complete without determining the magnitude of pressure drop. Together with the flow rate, it determines the required pumping power to circulate the fluid in the system. Equation 19 was used to determine pressure drop for each flow stream.

$$\Delta P = \frac{f}{D} \left( \frac{V}{2} \right)^2$$  \hspace{1cm} (19)

In Figure 7 we have presented variations of pressure drop with respect to the blend composition and the phase change percentage. As it can be seen in Figure 7, increasing the amount of nanofluid in the blend should decrease pressure drop when phase change percentage is 50% or lower. The trend is inverted when phase change percentage is 75% and more. This is attributed to the change in the effective viscosity of the blend. At the highest phase change percentage, the average fluid temperature is the highest which translates to low dynamic viscosity. From Figure 5 it can be seen that the temperature drop in the heat exchanger can be as 4 times when there is no phase change in MPCM.

A comparison has also been made between new blended MPCM-nanofluid and water. In Figures 2-7, the dashed line demonstrates the value of the variable under study when water is used as heat transfer fluid. In particular, Figure 5 where the temperature drop in water is shown to be higher than in all other cases with the new heat transfer fluid except for the case when there is no phase change. Figure 5 shows that the surface area required for 1kW of heat transfer is higher in the case water. Finally, if more than 50% nanofluid is present in the blend, the pressure drop would always be higher in the heat exchanger than when water is used as the heat transfer fluid.

Alvarado et al. (2007) experimentally determined the effective thermal conductivity of nanofluid containing 1% carbon nanotube in water at 20°C (68°F) as 0.85 W/m·K (0.49 Btu/ft·hr·°F). The current theoretical model under predicts the value of $k_{\text{eff}}$ as can be seen in Figure 2. Yamagishi et al. (1999) showed that the friction factor $f$ can be determined using the same correlations as for water. Currently, experiments are being conducted to validate the results shown above. Recent experimental results for CNT-nanofluid alone reveal that higher pressure drop could be observed once it is mixed with MPCM slurry. Also, heat transfer coefficient values for a MPCM-CNT blend could be more sensitive to heat transfer area (specifically heat transfer length) based on recent heat transfer results of CNT-nanofluids and MPCM slurry as shown in Figure 8 for an MPCM slurry with mass concentration of 11% at a uniform heat flux of 13.6 kW/m² (4311.2 Btu/hr·ft²) and a flow rate of 0.09 lit/s (1.43 GPM). There is no CNT

![Figure 6](image1.png)  
*Figure 6* Required heat transfer surface as a function of fluid blend composition.

![Figure 7](image2.png)  
*Figure 7* Effect of fluid blend variables on pressure drop in the heat exchanger.

![Figure 8](image3.png)  
*Figure 8* Experimental results for 11% MPCM slurry with no CNT.
present in the slurry. Figure 8 indicates that wherever there is change in phase, the heat transfer coefficient increases significantly. A full comparison between the results shown above and experimental results will be presented during the conference and will appear in an ASHRAE publication in the future.

SUMMARY AND DISCUSSION

A computer tool was developed to investigate the potential benefits that can be obtained by blending CNT nanofluid with MPCM slurry with the purpose of introducing a novel heat transfer fluid. The model was based on the theoretical correlations available in the literature. The effect of variable blending composition was studied ranging from just 100% MPCM to 100% nanofluid. The effect of the percentage of MPCM that actually changes phase in the process was found to be quite significant in a manner that it can inverse trends in some cases. Using blended fluid has been proved to have advantages over using water as heat transfer fluid in most cases. It has also shown that heat transfer process can be improved when high amount of material undergoes phase change. The tool can be used to find a theoretical optimum blend composition using CNT and MPCM. Once all the heat transfer and pressure drop experimental results for each individual fluid have been fully characterized, a full and comprehensive comparison between the analytical and experimental results can be obtained.

NOMENCLATURE

\[ A = \text{Heat transfer surface area, } m^2 \]
\[ C_p = \text{Specific heat, J/kg-K} \]
\[ CNT = \text{Carbon nanotube} \]
\[ k = \text{Thermal conductivity, W/m-K} \]
\[ LMTD = \text{Logarithmic mean temperature difference, K} \]
\[ MPCM = \text{Microencapsulated phase change material} \]
\[ n = \text{Factor corresponding to nanoparticle shape} \]
\[ Nu = \text{Nusselt number} \]
\[ Pr = \text{Prandtl number} \]
\[ Q = \text{Heat transfer rate, W} \]
\[ Re = \text{Reynolds number} \]
\[ U = \text{Overall heat transfer coefficient, W/m}^2\text{K} \]
\[ VBI = \text{Viscosity Blending Index} \]
\[ x = \text{Mass fraction of the component in blend} \]
\[ y = \text{Core-shell weight ratio} \]

Greek Symbols

\[ \omega = \text{Kinematic viscosity, Centistokes} \]
\[ \phi = \text{Volume fraction} \]
\[ \Psi = \text{Mass fraction} \]
\[ \xi = \text{Sphericity index of nanotubes} \]

Subscripts

\[ A = \text{Component A} \]
\[ B = \text{Component B} \]
\[ bf = \text{Base fluid} \]
\[ c = \text{Core} \]
\[ eff = \text{Effective} \]
\[ MPCM = \text{Microencapsulated Phase Change Material} \]
\[ nf = \text{Nanofluid} \]
\[ np = \text{Nanoparticle} \]
\[ s = \text{Shell} \]
\[ wf = \text{Working fluid} \]

REFERENCES


