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# An Investigation on Heat Transfer Characteristics of Salt Hydrate at Melting Temperature Range

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# An Investigation on Heat Transfer Characteristics of Salt Hydrate at Melting Temperature Range

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This experimental study examines the characteristics of heat transfer for material phase change slurry within melting temperature range. This study is extremely helpful in identifying the phenomena of heat transfer in air handling unit. The fluids used were $CaCl_2 \cdot 9H_2O$ and $Na_2HPO_4 \cdot 149H_2O$. These two fluids are a PCM type of hydrate salt. This research is focused on phase change temperature range that is 15°C to 5°C. Besides that it was also tested at a temperature of 20°C, as a comparison for one phase flow. The heat exchanger used is the double pipe type counter flow. Result of test showed that there was an increase in heat transfer rate when PCM fluid temperature decreased. The same thing also applied for total heat transfer coefficient. The increase seems significant with solid particle being formed in PCM at temperature of 15°C. The heat transfer process in PCM slurry is similar to nano fluid but the concentration of solid particles changes along the heat exchanger, so the Nusselt number equation involves a change in solid mass concentration.

*Keywords*: Phase change material, salt hydrate, heat transfer, secondary refrigerant.

## Nomenclature

| | |
|---|---|
| $A$ | : surface area ($m^2$) |
| $A_i$ | : inside surface area ($m^2$) |
| $A_o$ | : outside surface area ($m^2$) |
| $C_p$ | : specific heat capacity (kJ/kg °C) |
| $D$ | : diameter of pipe (m) |
| $D_i$ | : inside diameter of pipe (m) |
| $D_o$ | : outside diameter of pipe (m) |
| $k$ | : thermal conductivity (W/m K) |
| $L$ | : length of pipe (m) |
| $\dot{m}$ | : mass flow rate (kg/s) |
| $Nu$ | : Nusselt number (-) |
| $Pr$ | : Prandtl number (-) |
| $Q$ | : heat transfer rate (kW) |
| $Re$ | : Reynolds number (-) |
| $T_{c,i}$ | : inlet temperature of cooling fluid (°C) |
| $T_{c,out}$ | : inlet temperature of cooling fluid (°C) |

| | |
|---|---|
| $T_{h,i}$ | : inlet temperature of heating fluid (ºC) |
| $T_{h,out}$ | : inlet temperature of heating fluid (ºC) |
| $U$ | : Overall heat transfer coefficient (W/m$^2$.K) |
| $\gamma$ | : shear rate (1/s) |
| $\mu$ | : dynamic viscosity (Pa.s) |
| $\phi$ | : solid mass concentration (-) |
| $\Delta\phi$ | : delta solid mass concentration (-) |
| $n$ | : behaviour index |

## 1. Inroduction

The use of phase change material in secondary refrigerant is one of the methods that have been being developed to minimize the use of energy in chiller type air conditioning system. In this application, secondary refrigerant can be in the form of two phase solid-liquid. Solid particle is PCM which goes through phase change. With the formation of solid particles in fluid, thus the energy stored is increasing. The process of phase change is able to store or release a huge thermal energy in the form of latent heat. This energy is much greater compared to sensible heat. Ogoshi et.al. used tetra n-butyl ammonium bromide (TBAB) in secondary refrigerant of air conditioning system and there was an increase of efficiency so energy consumption could decrease up to 42%.[1] The most important process in this system is heat transfer taking place in the evaporator and in the air handling unit (AHU) or in the fan coil unit (FCU). From the results of studies, it is shown that the use of PCM slurry is able to increase heat transfer. Wenji et.al. conducted test on heat exchanger by giving heat flux along the outer wall of the pipe and using tetra n-butyl ammonium bromide clathrate hydrate (TBAB CHS) as fluid, it could increase heat transfer coefficient, with the presence of solid particles.[2] Suzuki et.al. used ammonium alum hydrate fluid slurries, and they were tested on double pipe type heat exchanger with inner pipe made of copper, inner surface diameter of 13mm and test section length of 2 m, also producing increase in heat transfer compared to water.[3]

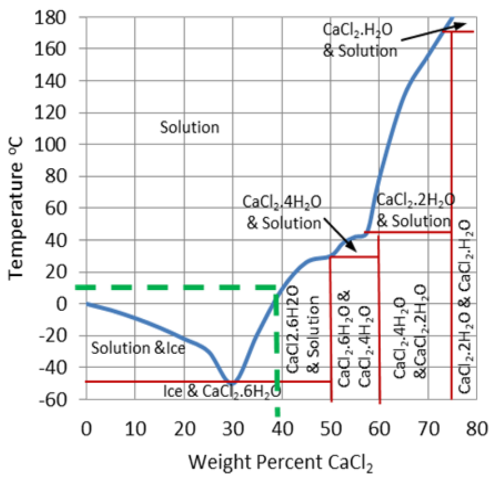
Hydrate salt is included in PCM inorganic group which has a number of advantages: high thermal conductivity and high latent heat.[4,5] From previous studies, there were several hydrate salts which were suitable for application as secondary refrigerant, among others are from calcium chloride ($CaCl_2$), and disodium hydrogen phosphate ($Na_2HPO_4$). Hydrate salt from $CaCl_2$ with a composition of 40% $CaCl_2$ and 60% water, has latent heat of 315.57kJ/kg.[6] Hydrate salt from $Na_2HPO_4$ with a composition of 5.08% $Na_2HPO_4$ and 94.92% water also has a high latent heat at 205.94kJ kg$^{-1}$.[7]

## 2. Materials and Experiment Apparatus

### 2.1. *Materials*

PCM tested was hydrate salt from calcium chloride ($CaCl_2$) and disodium hydrogen phosphate ($Na_2HPO_4$). Hydrate salt from $CaCl_2$ has a composition of 40% $CaCl_2$ and 60% water. While hydrate salt from $Na_2HPO_4$ has a composition of 5.03% $Na_2HPO_4$ and 94.97% water.

(a) $CaCl_2$ + water




(b) $Na_2HPO_4$ + water

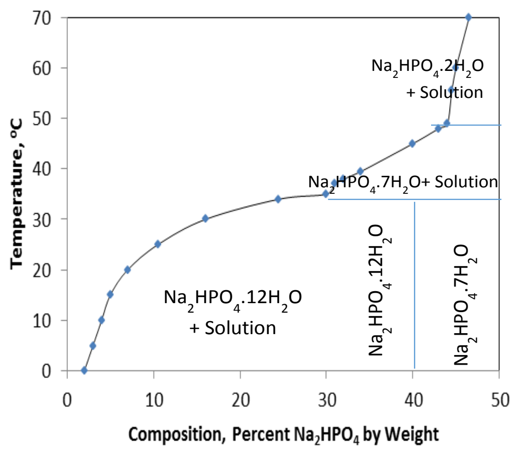



Fig. 1. Phase diagram of salt hydrate.[8]

The selection of composition based on phase change seen from phase change curve, as shown in

Fig. 1. $CaCl_2$ used is the one available in the form of calcium chloride dehydrate ($CaCl_2.2H_2O$) compound. The compound formed of hydrate salt from $CaCl_2$ is $CaCl_2{\cdot}9H_2O$. While the compound formed of hydrate salt from $Na_2HPO_4$ is $Na_2HPO_4{\cdot}149H_2O$.

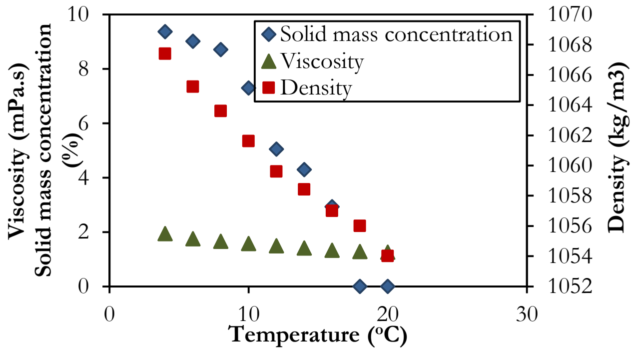



Fig. 2. Fluid characteristics of salt hydrate from $Na_2HPO_4$.[9]

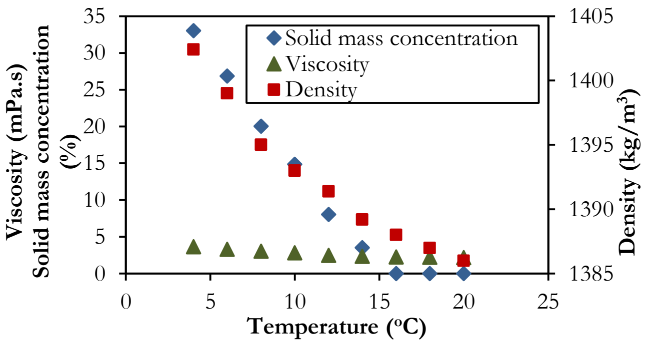



Fig. 3. Fluid characteristics of salt hydrate from $CaCl_2$.[9]

Supporting data for these both hydrate salt are viscosity, density and solid mass concentration. In Figure 2, viscosity density and solid mass concentration of hydrate salt from $Na_2HPO_4$ several temperatures are shown. While Figure 3 has shown of viscosity density and solid mass concentration of hydrate salt from $CaCl_2$ several temperatures.[10] Specifically for the viscosity of these both hydrate salts were tested using a rotary viscometer to obtain the effect of shear rate and temperature to viscosity.

## 2.2. *Heat Transfer Characteristics Test*

To determine the characteristics of hydrate salt fluid heat transfer, a test on testing equipment was conducted with a scheme shown in Fig. 4. Heat exchanger used was double pipe counter flow type. Material from both pipes used was copper with inner diameter of 9.3 mm for inner pipe, and 25.4 mm for outer pipe, and pipe length of 3.2 m. Temperature was measured using thermocouple type K and data logger Lutron type BTM-4208SD. Flow rate was measured using Omega flow meter type FMG92.

Data was taken by varying the temperature and flow speed of hydrates salt. Temperature variations were 20, 15, 10, and 5°C. Temperature chosen was temperature prior to phase change and at phase change process. While the variations of flow speed were 3, 6, 9, and 12 lpm. While the water temperature is varied to obtain a constant temperature difference between water and hydrate salt at the inlet section of the heat exchange. The temperature difference of these both fluids is 30°C.

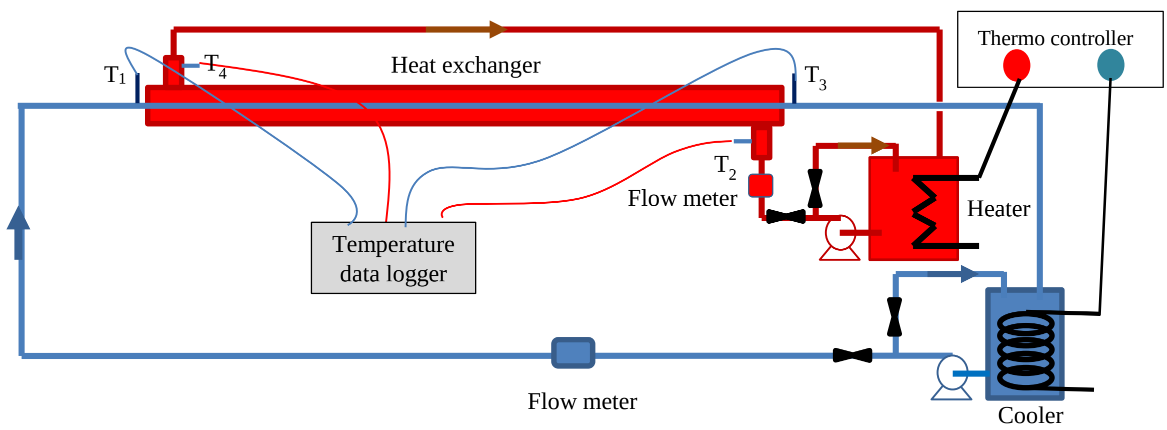
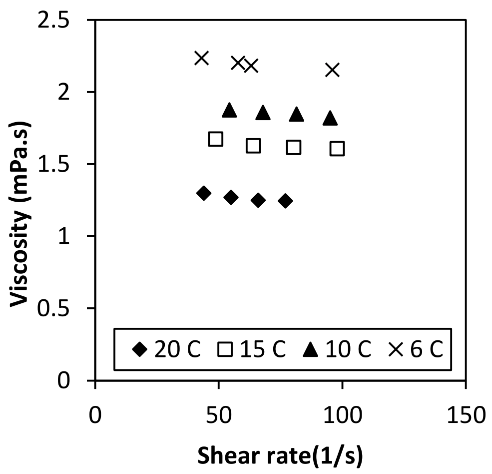



Fig. 4. Schema of heat transfer characteristic test

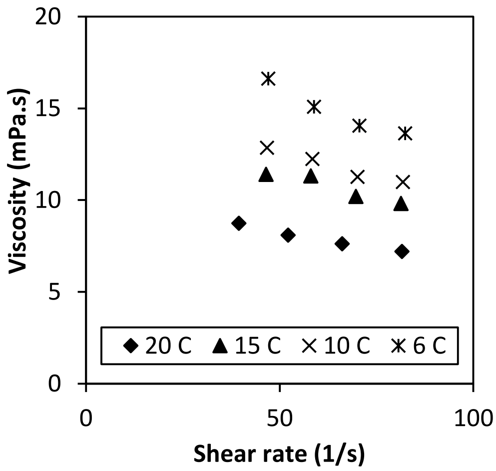
## 3. Results and Discussion

The characteristics of heat transfer for both hydrate salts have been shown in relation to the Reynolds number. Reynolds number used is apparent Reynolds number ($Re_{app}$). In this test, the Reynolds number other than influenced by the fluid velocity is also affected by the viscosity. The change of fluid velocity affects the shear rate, as shown in Eq. 1.[10] The viscosity value is affected by the shear rate as shown in Fig. 5. The viscosity of these two hydrates salt diminishes with increasing the shear rate, so that can be classified as pseudoplastic fluid.

$$\dot{\gamma} = \frac{8U}{D}\frac{(3n+1)}{4n} \quad (1)$$




a. $Na_2HPO_4 \cdot 149H_2O$




a. $CaCl_2 \cdot 9H_2O$

Fig. 5. The viscosity of the hydrate salt is based on shear rate

From the result of this test, the equations of viscosity with variable temperature and shear rate applied at 6 - 20°C temperature range are shown in Eq. 2 for $Na_2HPO_4 \cdot 149H_2O$ and Eq. 3 for $CaCl_2 \cdot 9H_2O$. Using this equation, the viscosity can be obtained for the fluid flow and temperature velocity. These data are used to calculate $Re_{app}$.

$$\mu_{app} = 0,1(40,622 - 3,5316T + 0,2328T^2 - 0,0057T^3)\dot{\gamma}^{-0,01(3,2476+0,4047T-0,0383T^2+0,0015T^3)} \quad (2)$$

$$\mu_{app} = (186,39 - 31,554T + 2,2279T^2 - 0,0529T^3)\dot{\gamma}^{-0,01(66,976-8,1848T+0,5876T^2-0,014T^3)} \quad (3)$$

In double pipe type heat exchanger, cold fluid from hydrate salt flows in the inner pipe and taking thermal energy from hot fluid which is water flowing in external pipe. The total of heat transfer taking place can be calculated by using Eq. 4.

$$Q = UA\Delta T_{lm} \quad (4)$$

Overall heat transfer coefficient (U) with the assumption of negligible fouling due to the condition of the pipe that was new, formulated as follows

$$\frac{1}{UA} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = \frac{1}{(hA)_i} + \frac{\ln(D_o/D_i)}{2\pi kL} + \frac{1}{(hA)_o} \quad (5)$$

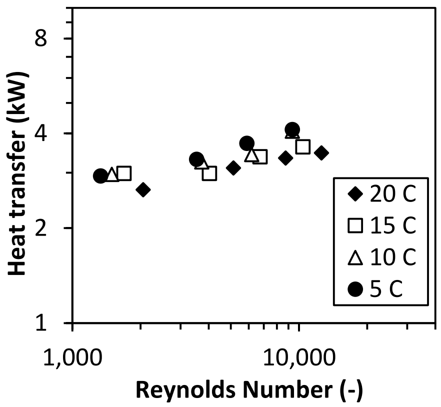
$\Delta T_{lm}$ is the average temperature difference of heat exchangers. To flow in the opposite direction, the value of $\Delta T_{lm}$ is as follows.

$$\Delta T_{lm} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln(T_{h,o} - T_{c,i})/(T_{h,i} - T_{c,o})} \quad (6)$$

In addition, the rate of heat transfer to the cold and hot fluid satisfies Eq. 7.

$$Q = \dot{m}C_p\Delta T \quad (7)$$

Act of heat transfer on hydrate salt of $CaCl_2 \cdot 9H_2O$ increases as temperature decreases, as shown in Fig. 6. In Figure 6a, it is shown that heat transfer rate increases with the increase in Reynolds number. At high Reynolds number, increase in flow turbulence takes place thus interaction between fluid molecules will become greater. In Fig. 6b, starting from temperature of 15°C to temperature of 5°C, a significant rate of heat transfer takes place. In this temperature, the solid particles formed have become abundant at 4% with temperature of 10°C and 9% with temperature of 5°C. Interactions between solid particles, solid and liquid particles, and with pipe wall are extremely helpful in heat transfer. The process of melting requires great energy compared to increase in temperature due to sensible heat. This is quite helpful in the absorption of energy.



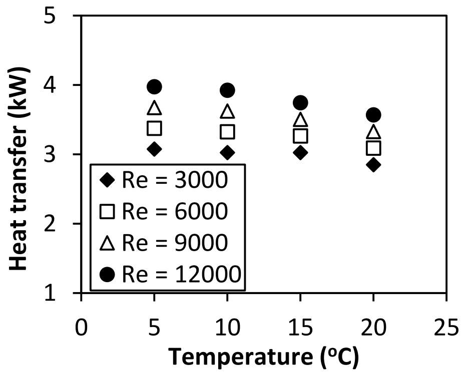
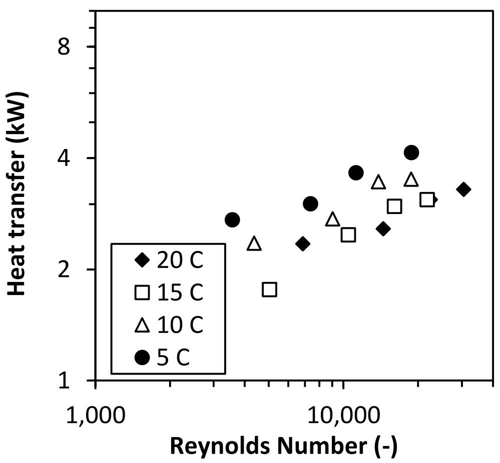




Fig. 6. Effect of temperature on heat transfer rate for $CaCl_2 \cdot 9H_2O$

The same also happens in hydrate salt of $Na_2HPO_4 \cdot 149H_2O$, in which the heat transfer increases with the decrease in temperature, as shown in Figure 7. The significant increase in heat transfer rate takes place starting from temperature of 10°C, in which at this temperature solid particles of 2.9% have formed and will continue to form into 9% at temperature of 5°C.



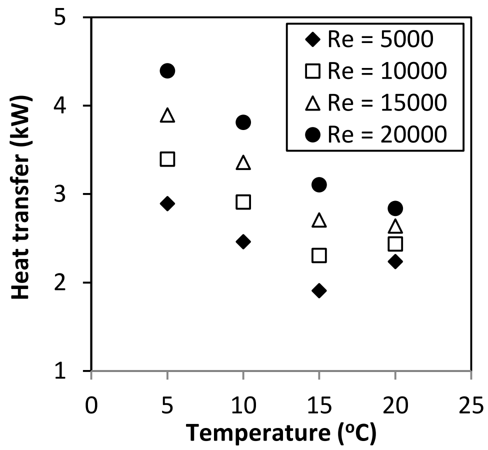




Fig. 7. Effect of temperature on heat transfer rate for $Na_2HPO_4 \cdot 149H_2O$.

The characteristics of heat transfer taking place in this heat exchanger were shown by overall heat transfer coefficient. Temperature decrease also gives impact on overall increase of overall heat transfer coefficient for both of these hydrate salts, as shown in Figure 8. Increase in total heat transfer coefficient rate starts to be significant at temperatures of 10 to 5°C. In this temperature range, the amount of solid mass concentration starts to become abundant, in which at temperature of 5°C, solid mass concentration is 32.5% for hydrate salt from $CaCl_2$ and 9.18% for hydrate salt from $Na_2HPO_4$. This phenomenon is in accordance to the result of ice slurry test by Niezgoda in which heat transfer coefficient increase took place with increase in mass concentration.[11] Grozdek et.al. have gotten the same phenomena too for ice slurry.[12]

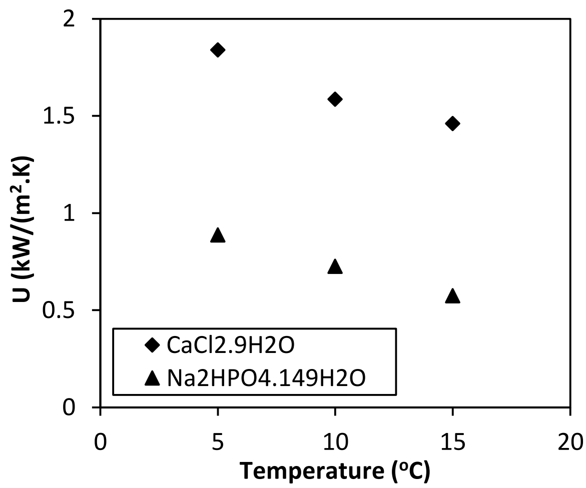



Fig. 8. Overall heat transfer coefficient of salt hydrates at $Rea_{pp}$ = 10.000

Based on the heat transfer of the test results for a one-phase condition, the Nusselt's number equation for $Na_2HPO_4 \cdot 149H_2O$ can use the Dittus-Bolter equation, as shown in Eq. 8. The equation of the Nusselt's number selected for this PCM is the same as that used by Suzuki et al. for the ammonium alum hydrate slurry.[3] While $CaCl_2 \cdot 9H_2O$ use the new Nusselt's number equation as shown by Eq. 9. Some other Nusselt equations for PCM are not suitable for the both PCMs, example: Gnielinski, Vicente, and Song equations. Gnielinski has made the Nusselt's correlation equation for fluid as shown in Eq. 10.[13] Song et al. has made a correlation equation for TBAB CHS fluid type A with a concentration of 18.4%, as shown in Eq. 11 to laminar flow and Eq. 12 to turbulence flow, and TBAB CHS fluid type B with a concentration of 26.2% as shown in Eq. 13 to laminar flow and Eq. 14 to turbulence flow.[14] Vicente et al. have developed a correlation equation for ice slurry fluids, as shown in Eq. 15. [15]

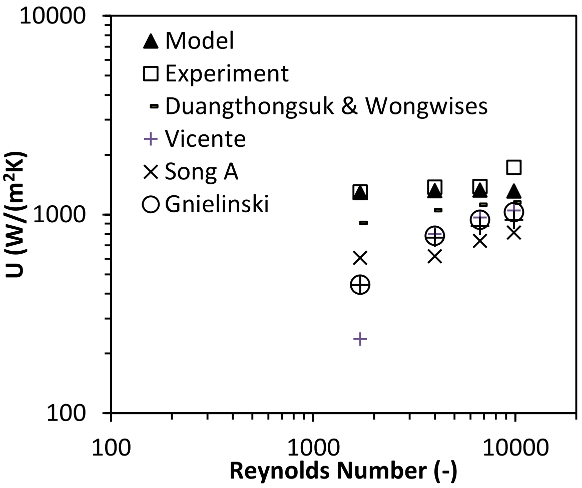



Fig. 8. Overall heat transfer coefficient for $CaCl_2 \cdot 9H_2O$

$$Nu = 0{,}023 Re^{0{,}8} Pr^{0{,}4} \quad (8)$$

$$Nu = 0{,}09 Re^{0{,}8} Pr^{0{,}4} \quad (9)$$

$$Nu = 0{,}012(Re^{0{,}87} - 280) Pr^{0{,}4} \left(1 + (D/L)^{2/3}\right) \quad (10)$$

$$Nu = 1{,}231 \times 10^{-5} Re^{1{,}6606} Pr^{0{,}7073} \quad (11)$$

$$Nu = 5{,}254 \times 10^{-4} Re^{0{,}9097} Pr^{1{,}1202} \quad (12)$$

$$Nu = 1{,}798 \times 10^{-3} Re^{0{,}6648} Pr^{1{,}3309} \quad (13)$$

$$Nu = 6{,}085 \times 10^{-4} Re^{0{,}913} Pr^{1{,}2061} \quad (14)$$

$$Nu = 0{,}034(Re - 1500)^{0{,}78} Pr^{0{,}37} \quad (15)$$

$$Nu = 0{,}074 Re^{0{,}707} Pr^{0{,}385} \phi^{0{,}074} \quad (16)$$

$$Nu = (1 + 4\phi + 2\Delta\phi) 0{,}09 Re^{0{,}8} Pr^{0{,}4} \quad (17)$$

$$Nu = (1 + 4\phi + 2\Delta\phi) 0{,}023 Re^{0{,}8} Pr^{0{,}4} \quad (18)$$

At the time the hydrate salt undergoes phase changes the solid particles begin to form so that the fluid becomes slurry-shaped. The phenomenon of heat transfer in the slurry is similar to that of nano fluid which also has solid nano particles in the fluid. Nusselt number calculation of nano fluid can use the equation of Duangthongsuk and Wongwises as shown Eq.16.[17] This Nusselt number equation involves a solid mass constraint variable. There is little difference in heat transfer that occurs in PCM slurry and nano fluid as cold fluid. In PCM slurry heat transfer involves latent heat, resulting in a change in the amount of mass of solid particles present in the fluid along the heat exchanger. While the nano fluid heat transfer does not involve latent heat and there is no change in the amount of mass of solid particles. The empirical equation of the Nusselt number for the slurry hydrate salt is made by referring to the Nusselt equation of the resulting one-phase condition and the added variable of the solid mass concentration as well as the change in the solid mass concentration.

## 4. Conclusion

The formation of solid particles in hydrate salt can increase heat transfer rate and total heat transfer coefficient. The impact is quite significant with the increase in solid particles compared to hydrate salt in the form of liquid phase only. The decrease in temperature increases the production of solid particles. Hydrate salt has higher heat transfer rate and total heat transfer coefficient compared to water. Hydrate salt from $CaCl_2$ has better heat transfer rate compared to hydrate salt from $Na_2HPO_4$, especially at a temperature of 5°C. The heat transfer process in PCM slurry is similar to nano fluid which solid particles support improve heat transfer process. However, in PCM slurry the concentration of solid particles changes along the heat exchanger, so the Nusselt number equation involves a change in solid mass concentration.

## 5. Acknowledgement

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