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Phase change materials development from salt hydrate for application as secondary refrigerant in air-conditioning systems

MUHAMMAD IRSYAD[1,2,*], ARYADI SUWONO[1,†], YULI SETYO INDARTONO[1], ARI DARMAWAN PASEK[1], and MUHAMMAD AKBAR PRADIPTA[1]

[1] *Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Jl. Ganesha No. 10 Taman Sari, Bandung 41032 Jawa Barat, Indonesia*
[2] *Mechanical Engineering Department, Universitas Lampung, Lampung, Indonesia*

Salt hydrate for application as secondary refrigerant in the air-conditioning system are selected based on the slurry forming according to the evaporator temperature 5°C–12°C. Research development of salt hydrate for application is done in three stages, namely; the study of the properties, flow, and heat transfer characteristics, also applications in air-conditioning systems. The study of the properties of the phase change materials is in the form of latent heat, freezing and melting temperature, thermal stability properties, viscosity, and rate of corrosion. The study of flow and heat transfer characteristics determine the effect of salt hydrates on the pressure drop and heat transfer in a heat exchanger. Studies on the application of the air-conditioning system is made to use a type of cooling room air-handling units and fan coil unit. The results of the researches for each of two stages are described in the discussion of the current article. The characteristics of salt hydrates from Na_2HPO_4 and $CaCl_2$ are fitted to be applied as secondary refrigerant. This material has high latent heat value and matched phase change temperature, as well as a very low corrosion rate. This material also demonstrates excellent heat transfer performance, in which an increase as much as 18.62% for salt hydrate from calcium chloride and 13.9% for salt hydrate from disodium hydrogen phosphate. For its flow characteristics, there was a less significant increase on pressure drop for Na_2HPO_4.

Introduction

Today, air-conditioning (AC) systems are a primary necessity to experience thermal room comfort. The huge demand on this equipment consequently causes a large increase in energy consumption for buildings. In commercial buildings, AC energy buildings is one of the biggest. Like in the United States and China 38% (Xia et al. 2014), Malaysia 57% (Saidur 2009), and Indonesia 65% (JICA 2007). Thus, reducing AC energy consumption has become a priority to minimize energy consumption in buildings.

The chilled water type AC system is used for medium and large capacity. This type reduced the use of primary refrigerant both the hydrochlorofluorocarbons (HCFC) group and hydrocarbon (HC) group, so it helps to reduce glass house effect. Water is used to obtain heat energy in the cooled air. A way for the energy use efficiency in this type of AC system is the use of phase change materials (PCM). This method utilized phase change as thermal energy storage.

Salt hydrate is a PCM for the AC system application that contains latent heat and high thermal conductivity. Besides, melting and freezing temperatures are highly considered ranging between 5°C–12°C (Maa et al. 2010). To choose salt hydrate initially, it is started with its phase diagram. The salt concentrate is in the compound can be applied for secondary refrigerant application, as shown in Figure 1. Na_2HPO_4 concentrate is around 3%–5%. Disodium hydrogen phosphate has been used as a PCM in the form of salt hydrates on absorption chiller with the name of the chemical compound is disodium hydrogen phosphate dodecahydrate ($Na_2HPO_4.12H_2O$; Suzuki et al. 2010). The salt hydrate has

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Muhammad Irsyad, MT, is a Lecturer. **Aryadi Suwono†, PhD,** is a Professor. **Yuli Setyo Indartono, DrEng,** is a Member of the Indonesia Chapter and an Associate Professor. **Ari Darmawan Pasek, PhD,** Member ASHRAE, is a Member of the Indonesia Chapter and a Professor. **Muhammad Akbar Pradipta, ST.**
†Aryadi Suwono is deceased.
*Corresponding author e-mail: irsyad71@students.itb.ac.id
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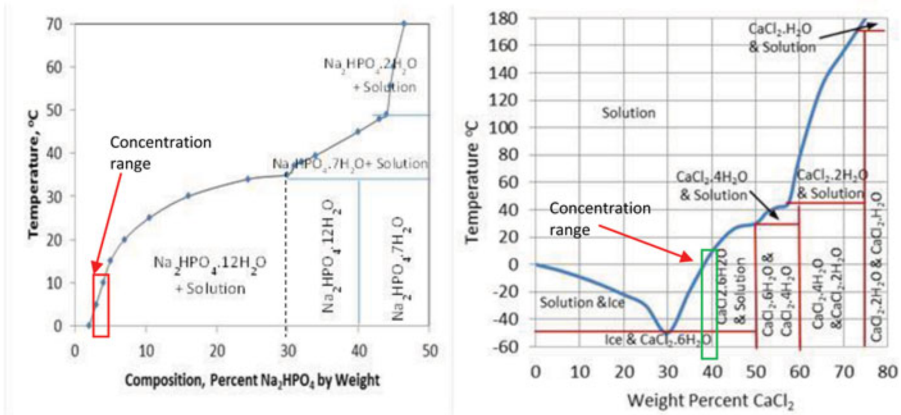


a. Na_2HPO_4 b. $CaCl_2$

Fig. 1. Phase diagram of salt hydrate (Kenisarin and Mahkamov 2016).

been a latent heat of 281 kJ/kg and the phase change temperature of 35°C. As for the salt hydrate of $CaCl_2$, suitable concentration is in the range 38%–42%. The chemical compound commonly used as the thermal energy storage for salt hydrates is calcium chloride hexahydrate $CaCl_2.6H_2O$. This has had the latent heat of 187kJ/kg, and a melting temperature of 29.9°C (Agyenim et al. 2010).

From the few researched, development of PCM to be applied in the secondary refrigerant can be grouped into three sections namely; research material properties, slurry PCM research, and research applications in the AC chiller systems. The third development has been described in Table 1. Description of PCM development of salt hydrates as a secondary refrigerant in this article covers material properties, characteristics of flow and heat transfer and application in AC system, chiller type.

Experimental methods

The development of PCM for the application of secondary refrigerant in chiller type-AC system in the current study was initiated with theoretical study of material characteristics, and flow features as well as the heat characteristics.

Materials

In the current study, disodium hydrogen phosphate and calcium chloride are applied as salt hydrate producers. Referring to the phase diagram in Figure 1 as initial reference, the concentrate to be employed was obtained, which is 15% of Na_2HPO_4 in market scale and 85% water. When this compound is heated for 1 hour at 200°C until they dry, 5.03% salt concentrate is achieved. While, to make the hydrate salt of $CaCl_2$, 55% $CaCl_2.2H_2O$ (calcium chloride dehydration) of the composition is required. $CaCl_2$ actual percentage after dried at a temperature of 200°C was 40%. As a reference to properties the salt hydrate is a compound $Na_2HPO_4.12H_2O$ and $CaCl_2.6H_2O$, as shown in Table 2.

Material properties test

This experiment tested the thermal and corrosive natures. The thermal features test was administered using differential scanning calorimetry (DSC) operated in Perkin Elmer type 8500 equipment. A sample weighing 5–7 mg is used, with the cooling and heating processes at temperatures ranging from 30°C to −30°C and the same cooling temperature, that is; 2°C/min.

The corrosion flow was examined by running two different methods: immersion test and electrochemical test. Carbon steel, copper, and brass materials were utilized as the specimens.

Flow and heat transfer characteristic

PCM as a secondary refrigerant in AC systems performs two phase conditions; the first is liquid phase and the second

Table 1. Development research of PCM as secondary refrigerant.

Research of material properties	Research of PCM slurry	Research of PCM application in Chiller system
- Thermal properties (Indartono et al. 2010; Lu and Tassou 2012) - Stability (Shulka et al. 2008; Tyagi and Buddhi 2008) - Corrosion (Farrell et al. 2006)	- Flow and heat transfer characteristic Lu and Tassou 2012; Suzuki et al. 2013)	- Direct system (Indartono et al. 2008) - Indirect system (Zhai et al. 2013)

Table 2. Thermal properties of salt hydrate to cooling application.

Salt hydrate	T_m (°C)	ΔH (J g^{-1})	C_{ps} (J g^{-1} K^{-1})	C_{pl} (J g^{-1} K^{-1})	k_s (W m^{-1} K^{-1})
$Na_2HPO_4.12H_2O$ (Mehling and Cabeza 2000)	39	104	3.7	4.1	0.4
$CaCl_2.6H_2O$ (Al-Abidi et al. 2012)	28	190	—	—	0.53

is solid–liquid phase which occurs especially when it runs through a chiller evaporator. Both phases are in the form of slurry. To identify the characteristics of the flow and the heat transfer, a test was conducted. The testing equipment scheme is shown in Figure 2.

The testing parameters are flow rate, cold and hot fluid, and fluid temperature. Hot fluid temperature is constant at 40°C with the flow 200 gal/h. On the other hand, cold fluid temperature was started at 5°C with various flow rates. Cold and hot fluid temperature has been measured using type K thermocouple and temperature data logger using Omega OM-DAQ-USB-2401.

Result and discussion

Material properties

Results of the T-history testing of salt hydrate showed freezing temperature and in accordance with the chiller evaporator temperature range as shown in Figure 3. Salt hydrate from disodium hydrogen phosphate showed that solid particles have been formed when the temperature reaches 7°C in the cooling process. While salt hydrate from calcium chloride was added at a temperature of 5°C. The size of the solid particles is very small. The salt hydrates solution before and after the slurry formation is shown in Figure 4.

In the heating process, the DSC test results have shown the phase change temperature according to test T-history. The melting process occurs at a temperature of −4°C and ends at temperatures of 7.5°C. Peak melting temperature has occurred at 4.34°C, and it still meet the application as a secondary refrigerant. The latent heat in the salt hydrate phase change process is high at 290.6 J/g, as shown as in Figure 5. The same is shown by the test results DSC salt hydrate of calcium chloride. In heating process, the material start melted in temperature 8.84°C and latent heat is 315.37 kJ/kg, as shown in Figure 6.

This salt hydrate will go over its phase change temperature when it is chilled. Solid mass percentage within the solution based on the temperature and types of salt hydrate are

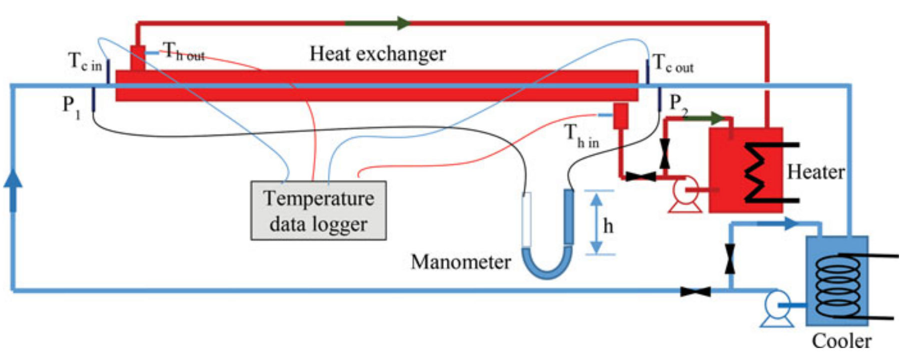


Fig. 2. The testing equipment scheme.

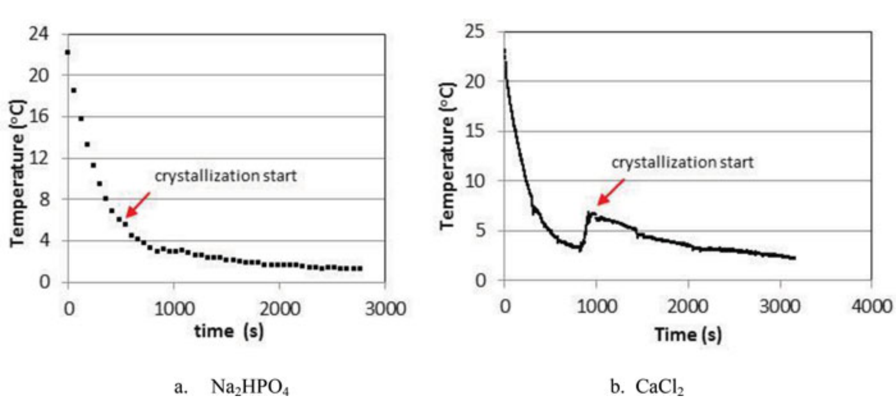


Fig. 3. T-history test in cooling process for salt hydrate.

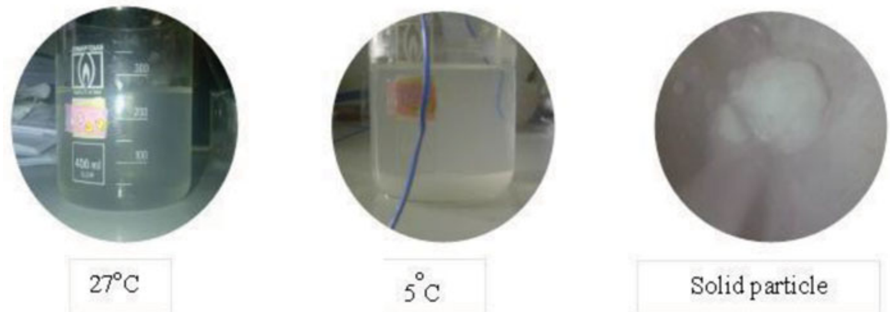


Fig. 4. Visualization of salt hydrate from Na_2HPO_4 3.6% mass fraction.

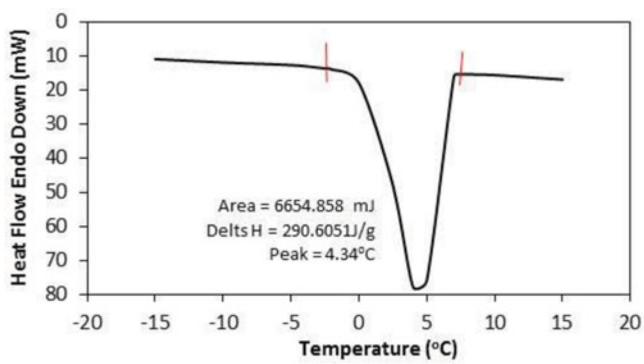


Fig. 5. Melting temperature of salt hydrate from Na_2HPO_4 3.6% and water 96.4% with DSC test.

displayed in Figure 7. The solid particle formation process begins at 15°C for mass concentration of Na_2HPO_4 5.03%, it was 1%. While in 40% concentration of $CaCl_2$ for the same temperature, there will be 4.3% solid particle mass formed. The solid particles formed are $Na_2HPO_4.12H_2O$ to salt hydrate of disodium hydrogen phosphate, and $CaCl_2.6H_2O$ to hydrate salt of calcium chloride. $Na_2HPO_4.12H_2O$ has composition Na_2HPO_4 39.64% and 40.36% water. With this composition to hydrate salt solution of 5.08% Na_2HPO_4 achieves maximum concentration of solid mass is 12.7%. Therefore, the value of the solid mass concentration of the test results is still allowed to happen. The same also applies to the salt hydrate of calcium chloride. Solid mass formed by

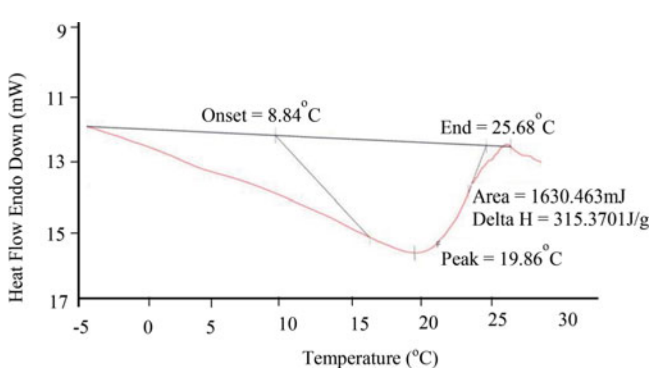


Fig. 6. Melting temperature of salt hydrate from $CaCl_2$ 40% and water 60% with DSC test.

Table 3. Corrosion rate for material.

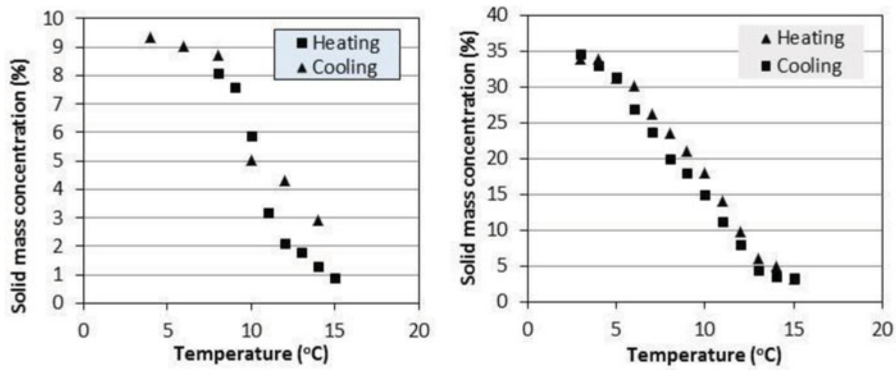
Fluid	Materials	Corrosion rate	Information
Na_2HPO_4	Brass	1.83 (mg/cm^2.yr)	Recommended
	Carbon steel	0.98 (mg/cm^2.yr)	Recommended
	Cooper	3.31 (mg/cm^2.yr)	Recommended
$CaCl_2$	Carbon steel	0.772 (mpy)	Recommended

$CaCl_2.6H_2O$ hydrate salt compound has a composition of 50% $CaCl_2$ and 50% water. With this composition, the maximum concentration of a solid mass is formed for a 40% $CaCl_2$ in solution is 80%, so that the concentration of solid mass that formed 32.5% at a temperature of 5°C was allowed to happen. Solid mass percentage in chilling and heating temperature is similar. Solid mass particle being formed in each decreasing degree of temperature can be used as parameter in calculating the heat transfer value in chiller evaporator. On the other hand, melting mass particle for each increasing degree can be employed as standard in calculating heat transfer value in fan coil unit (FCU) and air-handling units (AHU).

Effect of salt hydrate contact with some kind of metal is shown by the corrosion rate, as shown in Table 3. The corrosion rate for all three materials is very small. Based on the industry standard for corrosion, corrosion rate is recommended (Matousek 2002). The corrosion test results are also compared with the results of corrosion testing with electrochemical method. For instance, the corrosion rate of carbon steel material obtained is also very small is 0.003 mm/yr. This corrosion rate is excellent level when referring to the classification of corrosion rates for closed recirculating cooling water systems (Smothers et al. 2007).

Flow characteristic

This salt hydrate has higher density and viscosity than water, that are 1066.3 kg/m^3 and 1.85 mPa.s for Na_2HPO_4 compound and 1400.7 kg/m^3 and 3.44 mPa.s for $CaCl_2$ compound, cold fluid flow temperature starts from 5°C caused slurry formation. This influenced the pressure drop and friction factor occurred in the pipes as shown in Figure 8. Salt hydrate from $CaCl_2$ has been significantly improved of pressure drop and friction factor. The density and viscosity has been very influential to this improvement. But for the



(a) Na_2HPO_4 : 5.04% (b) $CaCl_2$: 40%

Fig. 7. Solid mass concentration salt hydrate of cooling and heating process.

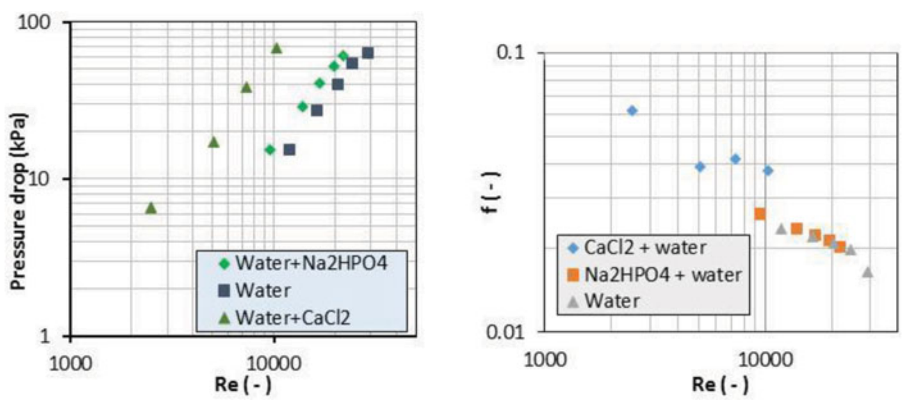
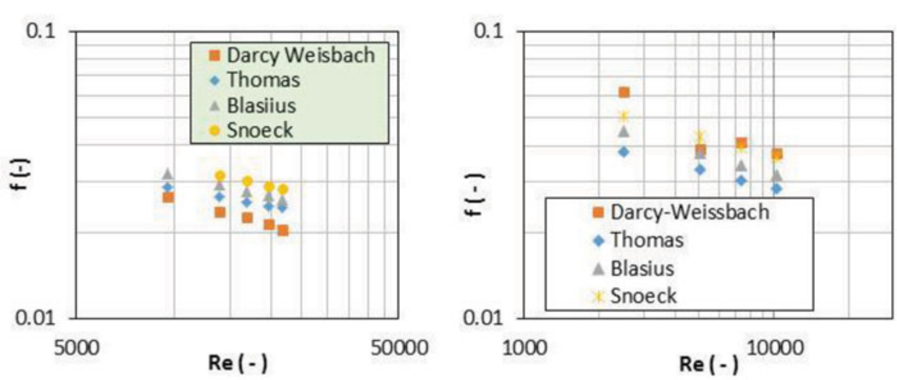


Fig. 8. Pressure drop and friction factor of salt hydrate compared than water.

salt hydrate of Na_2HPO_4, add to pressure drop and friction factor have been slightly significant. The calculation of the friction factor used Darcy Weisbach equation, as shown in Equation 1. The calculation results are the real value occurred to this hydrate salt flow on the copper pipe. The friction flow of slurry has been caused by mechanical friction from the interaction of solid particles and the walls of the pipe and the viscous friction (Indartono et al. 2006).

Since this fluid has a slurry form, a comparing calculation was required. This comparing calculation used Thomas equations applied for turbulent flow and non-Newtonian fluid, as shown by Equation 2, Blasius equation for Newtonian flow and seamless pipe, as shown by Equation 3, and Snoeck equation applied for ice slurry, as shown by Equation 4. The friction factor for the salt hydrate of Na_2HPO_4 was slightly different from the results of calculations using the equations



(a) Na_2HPO_4 : 5.04% (b) $CaCl_2$: 40%

Fig. 9. Friction factor of salt hydrate from many equations.

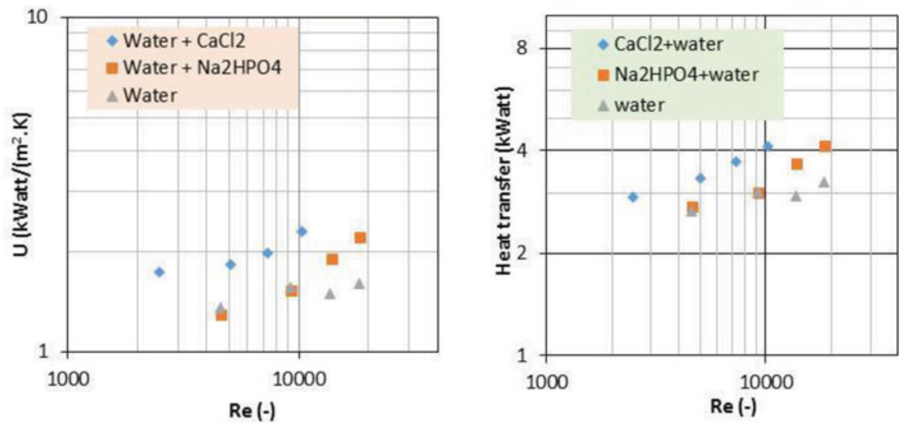


Fig. 10. Overall heat transfer coefficient and heat transfer in hot fluid.

Thomson. While the friction factor for salt hydrate of $CaCl_2$ have been suitably approximated by the Snoeck equation; both are shown in Figure 9.

$$h_{Lmayor} = f\,\frac{l}{D}\,\frac{V^2}{2g}, \tag{1}$$

$$f = 0.1988\ Re^{-0.211}, \tag{2}$$

$$f = 0.3164\ Re^{-0.25}, \tag{3}$$

$$f_d = f\,(1 + 0.119 X_{v,is}^{2.151}\ Re^{0.2422} + 0.02415 X_{v,is}^{0.3996} d^{-0.2845}. \tag{4}$$

Heat transfer characteristic

The calculation of heat transfer in the double-pipe heat exchanger with counter flow is fulfilled by following equations. In short, Equation 5 provides the result of the heat transfer rate formulation.

$$q = UA\Delta T_{lm}. \tag{5}$$

Assuming that the new pipe condition can neglect fouling phenomenon, the coefficient of total heat transfer (U) is formulated as follows:

$$\frac{1}{UA} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = \frac{1}{(hA)_i} + \frac{\ln(D_o/D_i)}{2\pi kL} + \frac{1}{(hA)_o}. \tag{6}$$

Heat exchangers average temperature difference is equated in ΔT_{lm}. The value of ΔT_{lm} for the opposite direction is calculated in the following formulation:

$$\Delta T_{lm} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln(T_{h,o} - T_{c,i})\,/\,(T_{h,i} - T_{c,o})}. \tag{7}$$

Also, cold and hot fluid heat transfer rate is accomplished in Equation 8.

$$q = \dot{m} C_p \Delta T. \tag{8}$$

From the previous calculations, overall heat transfer coefficient for salt hydrate from is higher when the system employs water, as shown in Figure 10. The energy released by hot fluid is used as the heat transfer parameter, in which the fluid is water. As a comparison, heat transfer in cold fluid encounters constraint as the formulated solid mass concentration is difficult to measure. Hot fluid heat transfer increases when the salt hydrate is employed. The average increase of heat transfer is 18.62% of $CaCl_2$ compound and 13.9% of Na_2HPO_4 compound. This trend supports the previous study on ammonium alum hydrate slurry (Suzuki et al. 2013), and trimethylolethane (Indartono et al. 2006).

Conclusion

The salt hydrate from Na_2HPO_4 with 5.04% concentration and $CaCl_2$ with 40% concentration as PCM can be developed as a secondary refrigerant. Factors that support this statement are its phase change temperature, high latent heat value, and its safe effect on the material of chiller systems, such as copper, carbon steel, and brass. Besides, it has a small pressure drop which does not impact on the pumping performance, especially for the Na_2HPO_4 compound. Also, its ability to transfer heat is excellent, in which the transfer increase as much as 18.6% of $CaCl_2$ compound and 13.9% of Na_2HPO_4 compound.

Nomenclature

A	= surface area (m^2)
C_p	= specific heat (kJ kg^{-1} K^{-1})
D	= diameter (m)
D_i	= inner diameter (m)
D_o	= outer diameter (m)
f	= friction factor (–)
h	= convective heat transfer coefficient (W m^{-2} K^{-1})
k	= thermal conductivity (W m^{-1} K^{-1})
l	= length (m)
Re	= Reynolds numbers (–)
T	= temperature (°C)

ΔT = temperature difference (°C)
ΔT_{lm} = log mean temperature difference (°C)
U = overall heat transfer coefficient (W m^{-2} K^{-1})
v = velocity (m s^{-1})
X = solid mass concentration

Subscript

i = inlet
o = outlet

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