Springer

Journal of Mechanical Science and Technology

Journal of Mechanical Science and Technology 22 (2008) 575~582

www.springerlink.com/content/1738-494x

Performance characteristics of a MPCM slurry cooled unit designed for telecommunication equipment

Jongmin Choi[1], Jongug Jeon[2] and Yongchan Kim[2,*]

[1]*Department of Mechanical Engineering, Hanbat National University, Duckmyung-Dong, Yusung-Gu, Daejeon, 305-719, Korea*
[2]*Department of Mechanical Engineering, Korea University, Anam-Dong, Sungbuk-Gu, Seoul, 136-701, Korea*

(Manuscript Received July 24, 2007; Revised December 26, 2007; Accepted December 26, 2007)

Abstract

Optimum control of the PCB surface temperature is very important in achieving high performance and operational reliability of telecommunication equipment with high power density and thermal density. In this study, the performance of a liquid cooling unit with MPCM slurries (called as "MPCM cooled unit") was tested and analyzed. In addition, its performance was compared with that of an air cooled unit and a water cooled unit. The maximum surface temperature and the index of uniform temperature distribution (IUTD) were introduced to analyze cooling performance. The surface temperature in the unit rack of telecommunication equipment can be controlled properly by using an MPCM cooled unit instead of an air cooled unit. The maximum surface temperature and IUTD of the MPCM cooled unit at the inlet temperature of 19°C were lower than those at inlet temperatures of 25°C and 27°C due to the increases of heat capacity and heat transfer rate. The heat capacity of the MPCM cooled unit increased significantly with the increase of mass flow rate due to high specific heat of MPCM particles with latent heat transfer rate. The cooling performance of the MPCM cooled unit was superior to that of the water cooled unit.

Keywords: MPCM; Liquid cooling; Heat density; Telecommunication equipment

1. Introduction

Electronic and telecommunication industries are trying to develop increasingly compact components with high power density. The equipment installed in telecommunication equipment rooms consists of rack-mounted units with chips on the PCB (printed circuit board) module. The power density and heat dissipation rate per unit area of the PCB module have increased with technological advancement in the telecommunication hardware [1-3]. A proper heat dissipation method from the PCB module of the unit rack of the telecommunication equipment is very important for reliable operation of electronic components. Therefore, maintaining the optimum surface temperature of the PCB module is crucial for achieving thermal reliability and high performance of electronic components [4-7].

Generally, telecommunication equipment has been air-cooled, which may not be sufficient under high heat flux conditions. Therefore, other methods of thermal management have been considered [8, 9]. Liquid cooling is an alternative method for providing proper cooling for high heat flux equipment [3, 10, 11]. The application of phase change material (PCM) slurries as an active liquid cooling method is attractive for thermal management in high power electronics. The potential benefits of using PCM slurries are the enhanced heat absorption by using the phase change process and the conductivity enhancement induced by the motion of the particles [9]. In this study, a microencapsulated phase change material (MPCM) was used as a working fluid in the liquid cooling unit. The MPCM is microencapsulated and suspended in a conventional single-phase heat trans-

*Corresponding author. Tel.: +82 2 3290 3366, Fax.: +82 2 921 5439
E-mail address: yongckim@korea.ac.kr
DOI 10.1007/s12206-007-1212-5

fer fluid to generate phase change [9, 12, 13]. The MPCM slurries serve not only as thermal storage medium but also as heat transfer fluid.

McGlen et al. [3] analyzed the cooling performance of the PCB by applying various advanced cooling methods. Generally, the miniaturization of electronic devices and increasing processing speed decrease the heat transfer area and increase the power density of these devices. Therefore, the high heat flux generated from the PCB raises the surface temperature greatly. Hayama and Nakao [14] investigated design factors in air flow systems of telecommunication equipment with high heat density. Lock et al. [15] measured the heat transfer and pressure drop characteristics of the PCB module. The performance of liquid cooling heat exchangers has been extensively investigated by several researchers. Dumont et al. [10] investigated the possibility of removing heat from the electronics by using the water cooling method. They concluded that the water cooled unit would allow the increase of power in the electronics. Leung et al. [16] numerically analyzed the heat transfer characteristics of a horizontal PCB assembly in fully developed laminar flow. Inaba [12] presented classification and characteristics of functionally thermal fluids such as MPCM and their applications. Alvarado et al. [17] evaluated thermal properties of MPCM with tetradecane as a phase change material. Yamagishi et al. [18] presented experimental data for MPCM with octadecane.

Since the conventional air cooling technology has some difficulties in its applications to electronic devices with high power density, an effective thermal management device has to be developed by using the liquid cooling method. Most previous works on the cooling of telecommunication equipment focused on micro scale heat transfer characteristics using air or single-phase liquid as a working fluid. In addition, the application of MPCM slurries to a heat exchanger is very limited in the open literature. Most studies on MPCM slurries have been executed to analyze thermal properties and heat transfer characteristics in a single tube. In this study, the performance characteristics of a liquid cooling unit with MPCM slurries (called as MPCM cooled unit) were measured and analyzed according to the heat density and operating conditions of the telecommunication equipment. In addition, the measured performance data of the MPCM cooled unit were compared with those of the conventional air cooled unit.

2. Experimental setup and test procedure

As shown in Fig. 1, a unit rack of telecommunication equipment with the air cooled unit used in the field consists of a PCB board, fans, and fin-plate heat exchangers. The cooling characteristics of the unit rack with the air cooled unit were measured in the field to provide reference data in the design and analysis of the MPCM cooled unit. Table 1 shows the specifications of the air cooled unit used in the unit rack for telecommunication equipment.

After the field tests were finished, the PCB board in the unit rack was replaced by a silicon rubber heater equipped with a power supplier to control the heat input to the air cooled unit. The size of the silicon rubber heater was the same as that of the PCB board. In order to minimize thermal contact resistance between the air cooled unit and the silicon rubber heater, a thin thermal grease film with high thermal conductivity was used at their interface. The performance of the air cooled unit with the silicon rubber heater was measured in a psychrometric chamber. The psychrometric chamber, containing a refrigerator, an

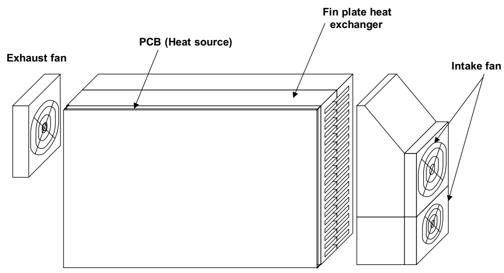

Fig. 1. Schematic diagram of the unit rack for telecommunication equipment.

Table 1. Specifications of air cooled unit for the unit rack.

Item		Specification
Full unit	Structure	Fans/ Fins/ Base
	Size	420 x 330 x 140 mm^3
Fins	Type / pitch	Flat plate type / 4 mm
	Size	34 x 305 x 1 mm^3
Fan 1,3 (inlet & exit)	Manufacturer	Nidec
	Models no.	TA 450DC B33534-33A
	Input (Rated)	(Nidec 24 V/ 0.45A)
Fan 2 (inlet)	Manufacturer	Nidec
	Models no.	TA 350DC M34261-16
	Input (Rated)	(Nidec 24 V/ 0.28A)
Heat source	Heating area	280 x 200 mm^2

electric heater, and a humidifier, allowed easy control of the inlet air temperature and heat rejection from the unit rack.

Fig. 2 shows a schematic diagram of the experimental setup used to measure the performance of the MPCM cooled unit. In the MPCM cooled unit, the air cooled heat exchanger in the unit rack was replaced by an MPCM cooled heat exchanger. The test rig consisted of a constant temperature bath, a magnetic gear pump, a test section, and a chiller. The constant temperature bath including the chiller and an electric heater was used to control the supplied temperature of the MPCM slurries. The test section consisted of a liquid cooling heat exchanger and a silicon rubber heater. The silicon rubber heater was attached to the liquid cooling heat exchanger to control the heat input. The silicon rubber heater had the same geometries as that used in the air cooled unit. As shown in Fig. 3, the liquid cooling heat exchanger was made of plate aluminum with single-path having a cross sectional area of 215×300 mm^2. The rectangular channel size was 5.0×3.0 mm^2. The volume and the weight of the

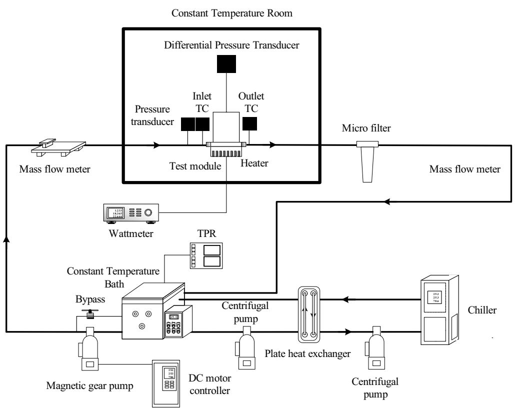

Fig. 2. Schematic diagram of the test setup.

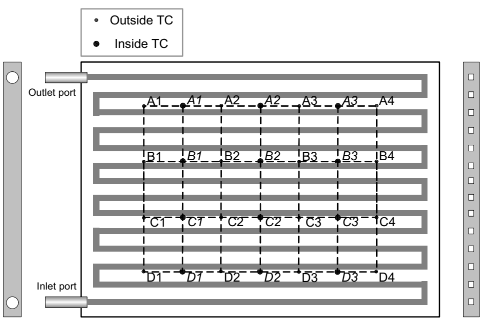

Fig. 3. Schematic diagram of the liquid cooling heat exchanger.

liquid cooling heat exchanger were 17% and 36% of the air cooled heat exchanger, respectively. The flow rate was controlled by adjusting the speed of the magnetic gear pump. The test section was heavily insulated by using an insulator and installed in the psychrometric calorimeter to minimize ambient effects.

Commercialized MPCM slurry, which passed the durability test, was used in this study. MPCM particles contained in the slurries had diameters of 10 μm, and the MPCM concentration was 30 wt % of water. The core material of MPCM particles was n-octadecane, which has a melting temperature of 28.2^{o}C, and its surface medium was melamine. Table 2 summarizes the properties of n-octadecane and water.

The power input to the silicon rubber heater was adjusted by a power supplier. The power input was measured by using a power meter with an uncertainty of ±0.01% of full scale (12 kW). As shown in Fig. 3, T-type thermocouples were attached on the surface of the silicon rubber heater to measure the cooling performance according to heat density. The working fluid temperatures before and after the test section were measured by RTD sensors, which were calibrated with an accuracy of ± 0.1°C. The mass flow rate of MPCM slurries was measured by using a Coriolis type mass flow meter with an uncertainty of ± 0.2% of reading. Table 3 shows the uncertainties of the measured parameters in this study.

Table 2. Properties of MPCM and water.

Specification		
Material	n-octadecane	Water
Melting point (^{o}C)	28.2	0
Density (kg/m^3)	86.7(solid), 9.56(liquid)	997
Specific heat (kJ/kg·K)	1.8(solid), 2.3(liquid)	4.2
Thermal conductivity(W/m·K)	0.15	0.606
Heat of fusion (kJ/kg)	243	333

Table 3. Uncertainties of measured parameters.

Parameter	Uncertainty
Temperature (T-type thermocouple)	± 0.1^{o}C
Temperature (RTD)	± 0.1^{o}C
Mass flow meter (Coriolis meter)	± 0.2% of reading
Power meter	± 0.01% of full scale (12 kW)

Table 4. Test conditions.

Parameter	Test conditions
Flow rate (kg/h)	25 - 72
Heat input (W)	293 - 800
Fluid inlet temperature (°C)	19 - 27

As shown in Table 4, the MPCM cooled unit was tested by varying the mass flow rate, heat input, and inlet temperature. The water cooled unit was also tested to provide reference data in the analysis of the cooling performance of the MPCM cooled unit. The data were recorded every 5 seconds and averaged for a period of 30 minutes at steady state.

3. Experimental results and discussion

3.1 Performance comparison of the air cooled unit with the MPCM cooled unit

Generally, the PCB board of telecommunication equipment is cooled by air because of ease maintenance and good electrical insulation [1]. PCB surface temperature, and inlet and outlet air temperatures of the unit rack for the telecommunication equipment operated in the field were measured for a month. Fig. 4 shows the surface temperature of the PCB module when the average inlet and outlet air temperatures in the rack were 25.0°C and 30.4°C, respectively. The surface temperature of the PCB module was not uniform, but ranged from 32.1°C to 62.8°C. When the inlet air temperature increased, the surface temperature increased due to the reduction in the temperature difference between the heated surface and air. The heat trap and improper air distribution in the unit rack raised the temperatures at certain locations. In order to assure thermal reliability of the equipment, it is essential to control the maximum surface temperature below a certain level. After finishing the field tests, we replaced the PCB board in the unit rack by a silicon rubber heater to control the heat input. Based on the comparison of the field data with the measured data of the cooled unit with respect to heat input to the silicon rubber heater, the maximum heat load and inlet temperature of the unit rack in the field were determined at 293 W and 25°C, respectively.

Fig. 5 compares the performance of the MPCM cooled unit with that of the air cooled unit at the inlet temperature and heat load of 25°C and 293 W, respectively. The silicon rubber heaters were installed on both units instead of the PCB board to control the heat input. The maximum surface temperature and the average surface temperature for the air cooled unit were higher than those for the MPCM cooled unit. The temperature differences between the inlet and outlet for air and MPCM slurries were 5.3°C and 9.6°C, respectively, at the same inlet temperature. These differences may be due to flow stagnation at a hot spot inside the unit rack in the air cooled unit. The maximum surface temperature in the air cooled unit was observed at the left lower corner and the right upper corner of the air cooled heat exchanger. However, the maximum surface temperature in the MPCM cooled unit was observed at the exit region of the MPCM slurry due to the increase in the temperature of MPCM slurries. Normally, it is difficult to obtain uniform air flow distribution inside the air cooled unit because of the structures of the fan and heat exchanger.

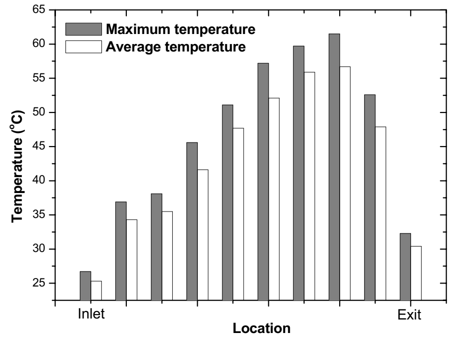

Fig. 4. Temperature distribution measured in telecommunication equipment.

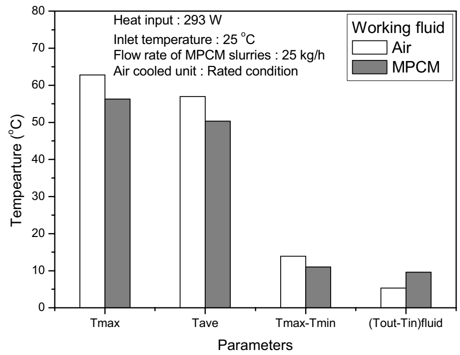

Fig. 5. Comparison of thermal characteristics of the air cooled unit with the MPCM cooled unit.

Fig. 6 shows the maximum surface temperature with respect to heat input to the unit rack. The maximum surface temperature of the air cooled unit was

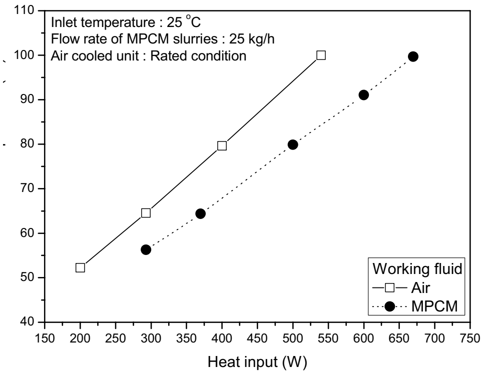

Fig. 6. Comparison of the maximum surface temperature in the air cooled unit with that in the MPCM cooled unit.

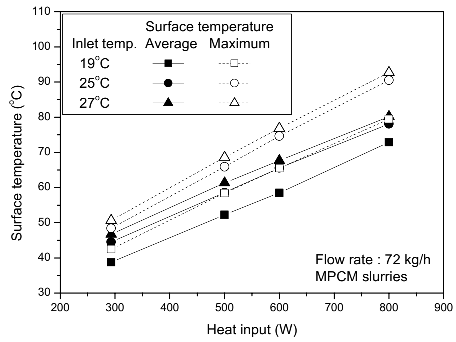

Fig. 7. Variations of the maximum and average surface temperatures with heat input.

higher by 9.1°C and 14.3°C than that of the MPCM cooled unit at heat inputs of 293 W and 500 W, respectively. In addition, the increasing slope of the maximum surface temperature with respect to heat input in the air cooled unit was higher than that in the MPCM cooled unit. The maximum surface temperature of electronic equipment such as telecommunication equipment cannot be properly controlled by increasing the air flow rate because of a heat trap and limitation in the convection heat transfer coefficient [19]. Therefore, the air cooled unit has difficulty meeting the performance requirements of high heat density, compact electronic equipment.

3.2 Performance characteristics of the MPCM cooled unit

Fig. 7 shows the variations of the maximum surface temperature and the average surface temperature for different inlet temperatures of MPCM slurries according to the heat input. As the heat input increased, the surface temperature of the unit rack increased due to the fixed heat capacity of the working fluid. Therefore, the maximum and the average surface temperatures increased with the increase of the heat input. The increasing slope of the maximum surface temperature with respect to heat input at the inlet temperature of 19°C was slightly lower than at other temperature conditions. When the heat input varied from 293 W to 800 W, the maximum surface temperatures at the inlet temperatures of 19°C and 25°C increased by 35.8°C and 42.1°C, respectively.

The application of the MPCM cooled unit to telecommunication equipment can increase the uniformity of the surface temperature across the entire heat source while controlling the maximum surface temperature within an acceptable level. As given in Eq. (1), an index of uniform temperature distribution (IUTD) was introduced to represent the uniformity of the surface temperature based on the reference of the maximum surface temperature. As the IUTD decreases, the surface temperature approaches the maximum value, and the uniformity of the surface temperature is enhanced as well.

$$IUTD = \int_A (T_{max} - T)\, dA \Big/ \int_A dA \tag{1}$$

Fig. 8 shows IUTD with respect to heat input. Generally, the IUTD increased with the increase of the heat input at all inlet temperatures. However, the increasing slope of the IUTD according to heat input at the inlet temperature of 19°C was much lower than those at the inlet temperatures of 25°C and 27°C. The dominant parameters affecting the heat transfer enhancement in the MPCM slurries were the subcooling and superheat. A large temperature difference between the transfer fluid and the phase change material was required during the heat storage (melting) and heat release (solidification) processes because of the thermal resistance in the capsule shell. The melting temperature of n-octadecane, which was used as the phase change material of the micro-capsule, is 28.2°C. At the inlet temperatures of 25°C and 27°C, the latent heat transfer rate in MPCM particles may not be significant due to the small temperature difference between the water and MPCM particles at high heat input. However, it may become dominant at an inlet temperature of 19°C, resulting in more uniform surface temperature distribution. It is very important to select an appropriate phase change material to achieve high latent heat transfer rate at given operating conditions. At the heat input of 800 W, the IUTD

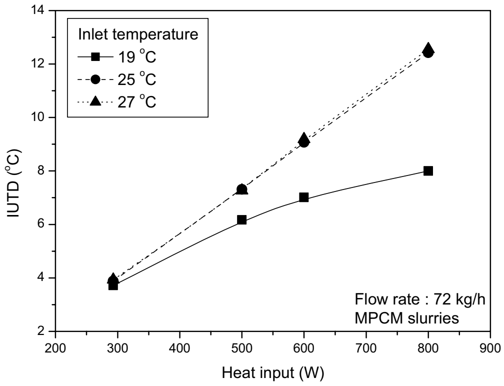

Fig. 8. IUTD variation with heat input at different inlet conditions.

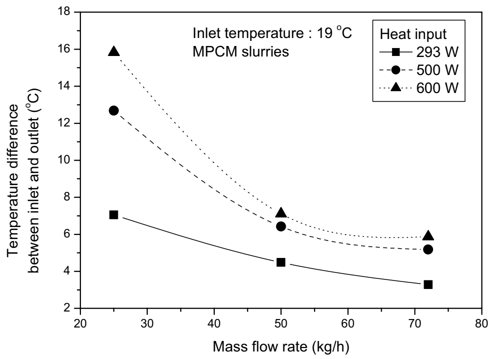

Fig. 9. Temperature difference between the inlet and outlet of the heat exchanger according to mass flow rate of MPCM slurries.

at the inlet temperature of 19°C was lower by 4.4°C and 4.6°C than at inlet temperatures of 25°C and 27°C, respectively.

Fig. 9 shows the temperature difference of MPCM slurries between the inlet and outlet of the heat exchanger as a function of the mass flow rate of MPCM slurries. In the present experiments, the mass flow rate of MPCM slurries was varied from 25 kg/h to 72 kg/h, while the heat input was changed from 293 W to 800 W at the inlet temperature of 19°C. Generally, the heat transfer rate through the tube wall of the MPCM cooled unit increased with the increase of the mass flow rate of MPCM slurries. The convective heat transfer coefficient increased with the increase of the fluid velocity corresponding to mass flow rate. The heat transfer enhancement with the increase of mass flow rate was much higher at high heat input than that at low heat input because the heat flux from the tube wall to the fluid and the temperature difference between the inside and outside of the MPCM shell increased with the increase of heat input. Therefore, the decreasing slope of the temperature difference between the inlet and outlet of the heat exchanger increased with the increase of the heat input.

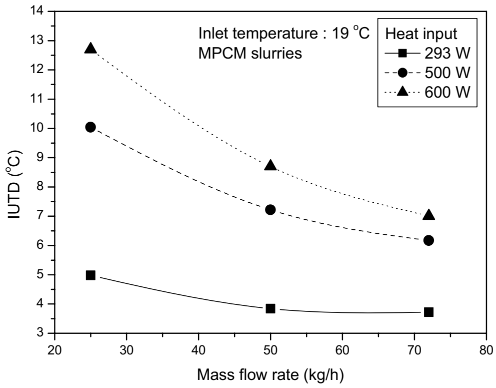

Fig. 10. IUTD variation according to mass flow rate of MPCM slurries.

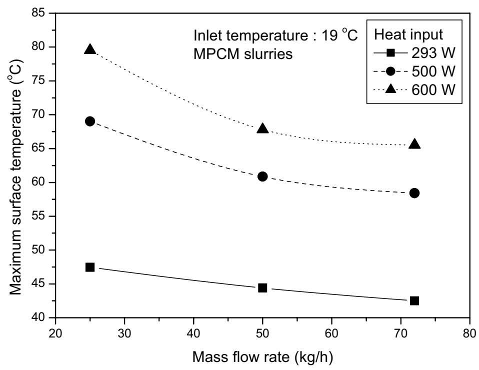

Fig. 11. Variation of the maximum surface temperature according to mass flow rate of MPCM slurries.

Figs. 10 and 11 show IUTD and maximum surface temperature with the variation of the mass flow rate of MPCM slurries. Generally, the IUTD decreased with the increase of mass flow rate due to the increase in heat capacity of the fluid and the heat transfer enhancement. In addition, the trend of the maximum surface temperature with respect to mass flow rate was very similar to that of the IUTD. As the mass flow rate increased from 25 kg/h to 72 kg/h, the IUTD decreased by 1.3°C and 5.7°C and the maximum surface temperature decreased by 5.0°C and 14.0°C at heat inputs of 293 W and 600 W, respectively. The reductions of both IUTD and maximum surface temperature became more obvious with the increase of heat input.

3.3 Performance comparison of the MPCM cooled unit with the water cooled unit

The performance of the MPCM cooled unit was compared with that of the water cooled unit to estimate the feasibility of the MPCM cooled unit. The heat input varied from 293 to 800 W at a mass flow rate of 72 kg/h. Fig. 12 compares the maximum surface temperature of the MPCM cooled unit with that of the water cooled unit. Generally, the maximum surface temperature increased with heat input for both units. However, the increasing slope for the water cooled unit was slightly higher than that for the MPCM cooled unit. At a heat input of 293 W and inlet temperature of 19°C, the maximum surface temperature of the MPCM cooled unit was lower by 2.02°C than that of the water cooled unit. However, the maximum surface temperature difference between the MPCM cooled unit and the water cooled unit was 9.7°C at the heat input of 800 W. As the heat input increased, the rotational effects of the MPCM particle remained constant, but the latent heat capacity of the MPCM increased due to the increase of the temperature difference between the inside and outside of the MPCM particles. As shown in Fig. 13, the MPCM cooled unit showed more uniform surface temperature distribution than the water cooled unit. Generally, the IUTD increased with the increase of heat input. However, the increasing slope of the IUTD of the water cooled unit was higher than that of the MPCM cooled unit. Therefore, the IUTD was reduced more significantly by applying the MPCM cooled unit with the increase of heat input.

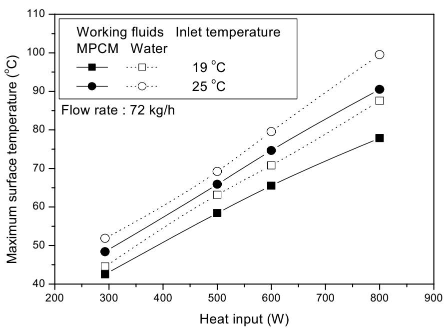

Fig. 12. Comparison of the maximum surface temperature between MPCM slurries and water according to heat input.

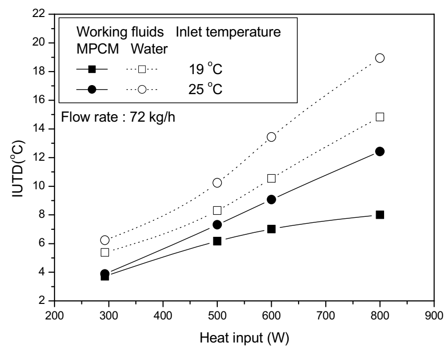

Fig. 13. IUTD comparison between the MPCM cooled unit and the water cooled unit.

4. Conclusions

The performance of both the air cooled unit and the MPCM cooled unit was measured and analyzed by varying operating conditions. In addition, the performance of the MPCM cooled unit was compared with that of the water cooled unit. The surface temperature of the PCB in the field ranged from 32.1°C to 62.8°C. This temperature range was relatively larger than the inlet and the outlet air temperature range due to the heat trap and improper air distribution. The surface temperature of the unit rack of telecommunication equipment can be controlled properly by using the MPCM cooled unit instead of the air cooled unit. The maximum surface temperature of the MPCM cooled unit was lower by 9.1°C and 14.3°C than that of the air cooled unit at heat inputs of 293 W and 500 W, respectively. In this study, the uniformity of the surface temperature was explained by introducing a parameter of IUTD. The maximum surface temperature and IUTD of the MPCM cooled unit at the inlet temperature of 19°C was lower than at inlet temperatures of 25°C and 27°C due to the increase of heat capacity and heat transfer rate. At the heat input of 800 W, the IUTD at the inlet temperature of 19°C was lower by 4.4°C and 4.6°C than at inlet temperatures of 25°C and 27°C, respectively. The heat transfer rate through the tube wall of the MPCM cooled unit increased with the increase of the mass flow rate of MPCM slurries. The heat capacity of the MPCM cooled unit increased significantly with the increase of mass flow rate due to high specific heat with high latent heat transfer rate of MPCM particles. The MPCM cooled unit produced more uniform surface temperature distribution than the water cooled unit. The IUTD was reduced more significantly by applying the MPCM cooled unit than the water cooled unit with the increase of heat input. Generally, the MPCM cooled system was very effective in controlling the maximum surface temperature and the uniform surface temperature distribution.

Acknowledgments

This work was sponsored by the Basic Research Program of the Korea Science & Engineering Foundation (Grant no. R01-2006-000-11014-0).

Nomenclature

A : Area (m^2)
$IUTD$: Index of Uniform Temperature Distribution at the baseline of the maximum surface temperature (^oC), $\int_A (T_{\max} - T)\ dA / \int_A dA$
T : Temperature (^oC)
T_{ave} : Average surface temperature (^oC)
T_{in} : Inlet temperature of the fluid (^oC)
$T_{\max}$: Maximum surface temperature (^oC)
$T_{\min}$: Minimum surface temperature (^oC)
T_{out} : Outlet temperature of the fluid (^oC)

References

[1] R. R. Schmidt and H. Shaukatullah, Computer and telecommunications equipment room cooling: A review of literature, *IEEE Transactions on Components and Packaging Technologies* 26 (1) (2003) 89-98.

[2] H. Lee, Y. Jeong, J. Shin, J. Baek, M. Kang and K. Chun, Package embedded heat exchanger for stacked multi-chip module, *Sensors and Actuators A.* 114 (2004) 204-211.

[3] R. J. McGlen, R. Jachuck and S. Lin, Integrated thermal management techniques for high power electronic devices, *Applied Thermal Engineering* 24 (2004) 1143-1156.

[4] P. Cinato, C Bianco, L. Licciardi, F. Pizzuti, M. Antonetti and M. Grossoni, An innovative approach to the environmental system design for TLC rooms in Telecom Italia, *INTELEC,* (1998) 770-776.

[5] M. Nakao, H. Hayama and T. Uekusa, An efficient cooling system for telecommunication equipment rooms, *INTELEC,* (1988) 344-349.

[6] K. E. Gill, Telecom HVAC cool connections (HVAC in telecommunication facilities), *HVAC Engineering*. 73 (1) (2001) 29-38.

[7] C. C. Sullivan, Cooling data and dot-coms, *Consulting-Specifying Engineering* 29 (1) (2001) 28-36.

[8] G. Hetsroni, A. Mosyak, Z. Segal and G. Ziskind, A uniform temperature heat sink for cooling of electronic devices, *International Journal of Heat and Mass Transfer* 45 (16) (2002) 3275-3286.

[9] M. Choi and K. Cho, Liquid cooling for a multichip module using fluorinert liquid and paraffin slurry, *International Journal of Heat and Mass Transfer* 43 (2) (2000) 209-218.

[10] G. Dumont, F. V. Roux and B. Righini, Water-cooled electronics, *Nuclear Instruments & Methods in Physics Research A* 440 (2000) 213-223.

[11] H. Y. Zhang, D. Pinjala, T. N. Wong, K. C. Toh and Y. K. Joshi, Single-phase liquid cooled micro-channel heat sink for electronic packages, *Applied Thermal Engineering* 25 (10) (2005) 1427-1487.

[12] H. Inaba, New challenge in advanced thermal energy transportation using functionally thermal fluids, *International Journal of Thermal Science* 19 (2000) 991-1003.

[13] J. G. Lee, J. H. Kim, Y. C. Choi, S. H. Lee, Y. G. Kim, J. G. Choi, H. S. Han, W. M. Lee, H. S. Kim, Y. S. Shin, K. H. Kim, H. J. Lee and J. M. Choi, Development of high density thermal fluid and heat transportation technology, MOST Report M102KP-010001-03K1601-02410 KOSEF, Seoul, Korea (2005).

[14] H. Hayama and M. Nakao, Air flow systems for telecommunications equipment rooms, *INTELEC,* (1989) 1-7.

[15] J. S. Lock, E. Bertson and J. Boissevain, Air cooling of front-end electronics for silicon detectors in collider experiments, *Nuclear Instruments and Methods in Physics Research A* 345 (1994) 284-288.

[16] C. W. Leung, J. J. Kang and S. D. Robert, Horizontal simulated printed-circuit board assembly in fully-developed laminar-flow convection, *Applied Energy* 56 (1) (1997) 71-91.

[17] J. L. Alvarado, C. Marsh, C. Sohn, G. Phetteplace and T. Newell, Thermal performance of microencapsulated phase material slurry in turbulent flow under constant heat flux, *International Journal of Heat and Mass Transfer* 50 (2007) 1938-1952.

[18] Y. Yamagishi, H. Takeuchi, A. T. Pyatenko and N. Kayukawa, Characteristics of MPCM slurry as a heat transfer fluid, *AIChE* 45 (1999) 696-707.

[19] J. Jeon, Y. Kim, J. M. Choi, H. Kang and D. Cheon, Performance comparison of liquid-cooling with air-cooling heat exchangers for telecommunication equipment, The 3rd Asian Conference on Refrigeration and Air-conditioning, Gyeongju, Korea. (2006) Paper No. 227.