5th International Conference on Porous Media and Their Applications in Science, Engineering and Industry

Refereed Proceedings

Summer 6-24-2014

Application of nanoparticles-assembled bi-porous structures to power electronics cooling

Kazuhisa Yuki
Tokyo University of Science

Tessai Sugiura
Tokyo University of Science

Koichi Suzuki
Tokyo University of Science

Proceedings of the 5th International Conference on Porous Media and its Applications in Science and Engineering
ICPM5
June 22-27, 2014, Kona, Hawaii

APPLICATION OF NANOPARTICLES-ASSEMBLED BI-POROUS STRUCTURES TO POWER ELECTRONICS COOLING

Kazuhisa Yuki, Tessai Sugiura and Koichi Suzuki

Tokyo University of Science, Yamaguchi, Sanyo-Onoda, Yamaguchi, 756-0884, Japan

ABSTRACT
Nanoparticles-assembled bi-porous structure is newly proposed and its potential to enhance the boiling heat transfer is evaluated in order to develop a new cooling device toward 300W/cm^2 of on-vehicle inverter cooling. In order to assemble nanoparticles on to a heat transfer surface as a thin layer, a boiling adhesion method (BAM) is originally introduced in which, water or water/ethanol solution with mono-dispersed nanoparticles is dropped or sprayed onto a high temperature surface, and then the nanoparticles deposit onto the heat transfer surface during the boiling. In addition to that, it is expected that boiling bubbles can produce micro or milli scale of pores at the same time. In order to evaluate the applicability of the nanoparticles-assembled bi-porous structures, droplet behavior on a high temperature surface is visualized with a high speed camera The experimental results show that the boiling adhesion method can produce multi-scale pore structures composed of nano-scale pores and micro-scale pores and that the water droplet intensely boils and evaporates on a high temperature of a wall with nanoparticles-assembled bi-porous layer even under Leidenfrost conditions, which proves that the nanoparticles-assembled bi-porous structure enables the increase in both the critical heat flux and the boiling heat transfer in a nucleate boiling regime.

INTRODUCTION
Currently, it is expected that advance in SiC-based semiconductor element drastically contributes to control the global warming. However, this big progress could increase heat power density of various electronics especially such as power electronics. For instance, in the present Si-based power electronics such as inverter of recent hybrid cars, the heat flux has already exceeded 100 W/cm^2. Under this condition, the temperature of Si should be kept at less than 120 ^{o}C. On the other hand, in the Si-based power electronics such as the future electric vehicles and fuel cell vehicles, the heat flux reach 300 W/cm^2. Against this high heat flux, the future inverter should be maintained at an optimal temperature of approximately 220 ^{o}C. Of course, the best way for cooling the on-vehicle inverter is not to use a circulation pump for the coolant in order to reduce power consumption except for a motor. In that sense, a heat removal technology with pool boiling heat transfer could be one of the candidates.

On the other hand, it is well-known that there is a cooling limit of the pool boiling. For example, the critical heat flux of the pool boiling is almost 100 W/cm^2 at an atmospheric pressure. Sub-cooled pool boiling is also useful [1], however, this system needs additional pump in order to keep the liquid temperature constant. This fact indicates that we have to make an effort of enhancing the boiling heat transfer.

Here, focusing on the boiling heat transfer enhancement utilizing porous layers, many researchers have used it to heat pipes [2] and vapor chambers [3], and also studied the heat transfer characteristics of the pool boiling with the porous film. Furthermore, they clarified that the increase in both the boiling heat transfer and the critical heat flux. The key issue of the porous cooling technology is getting a breakthrough for a tradeoff relationship between capillarity and liquid/vapor permeability. For instance, Mori et al. achieved the heat removal almost 250 W/cm^2 using honeycomb type of porous media to control both the liquid path and vapor path separately.

Summarizing the past porous cooling researches, the important things to increase both the boiling heat transfer and the critical heat flux could be (1) increase of cavity, (2) enhancement of wettability and capillarity, and (3) enhancement of liquid-vapor exchange. In that sense, this study focus on foam-like bi-porous structure composed of nanoparticles-assembled layer with high wettability and capillarity, micro/milli scale of pores that works as the cavity and the vapor path. This paper reports the feasibility of this unique porous layer to enhance the boiling heat transfer by evaluating a life time of a boiling droplet on a high temperature surface.

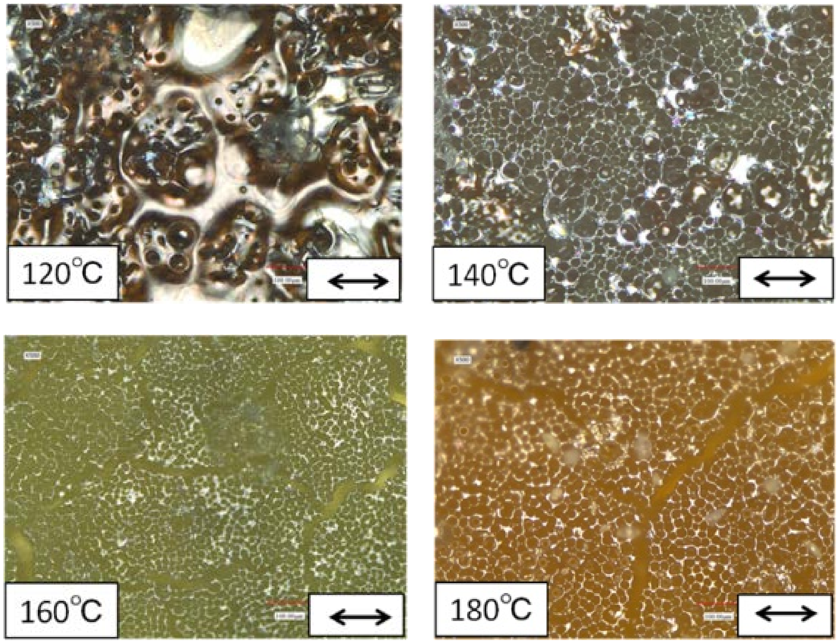

Figure 1: Surface porous structure by boiling adhesion method

NANOPARTICLES ASSEMBLING ON A HEAT TRANSFER SURFACE BY BOILING ADHESION METHOD (BAM)

In order to assemble nanoparticles on to a heat transfer surface as a thin layer, a boiling adhesion method (BAM) is originally introduced in which, water or water/ethanol solution with mono-dispersed nanoparticles is dropped or sprayed onto a high temperature surface, and then the nanoparticles deposit onto the heat transfer surface during the boiling. In addition to that, it is expected that boiling bubbles can produce micro or milli scale of pores at the same time. Although this method is quite simple and reasonable, it needs to be clarified a surface temperature and material of nanoparticles suitable for the optimum coating temperature depending on the wettability of the nanoparticles-included liquid and the metal surface. For example, Fig. 1 shows the surface porous structure for the initial surface temperature of 120, 140, 160, and 180 ^{o}C., which proves that the pore structure and the size strongly depends on the surface temperatures.

In order to evaluate the applicability of the nanoparticles-assembled bi-porous structures, droplet behavior on a high temperature surface is visualized with a high speed camera, as shown Fig. 2. The experimental setup mainly consists of a heat transfer block, an injector, a radiation shielding plate and a hi-speed camera. A single droplet is dropped onto the copper heat transfer cylinder block with a height of 0.08 m and a diameter of 0.05 m. This copper block is heated with cartridge heaters. The copper heat transfer block is composed of three parts, and only the top copper plate with L10 mm x W10 mm x t3.0 mm is coated the nanoparticles Al_2O_3 by BAM at the temperature of 120 ^{o}C. The Al_2O_3 nanoparticles-included water mentioned in the previous section is father diluted with water. The concentrations are 60, 80, and 100 vol%. Atmospheric temperature is approximately 25 ^{o}C. After coating the nanoparticles bi-porous structure on the copper plate, distilled water droplet is dropped onto the heated palate with a temperature over 100 ^{o}C. The size of the droplet is

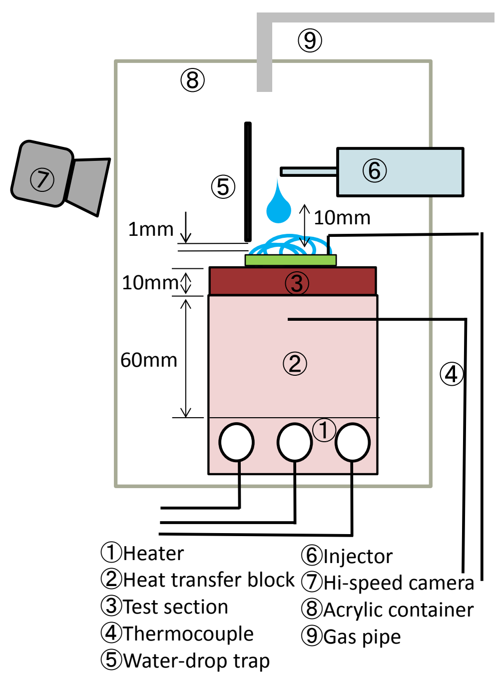

Fig. 2 Experimental setup for visualizing a droplet behavior on high temperature surface

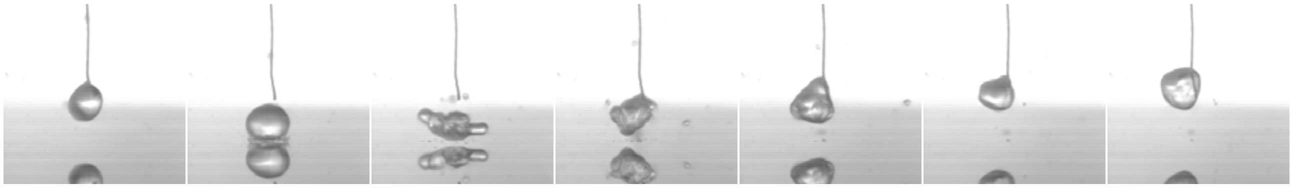

Fig.3 Droplet behavior on heated wall without nanoparticles bi-porous layer

Fig. 4 Droplet behavior on heated wall with nanoparticles bi-porous layer

approximately 2 mm and the We number is less than 1.0 shortly before the droplet falls onto the heating surface, which means that the droplet behaves on the surface in a way similar to Leidenfrost phenomenon.

RESULTS AND DISCUSSION

Fig. 3 and Fig. 4 show the droplet behavior without and with the nanoparticles bi-porous layer, respectively. The temperature of the heat transfer surface is almost 160 ^{o}C. In the case without the nanoparticles bi-porous layer, the droplet bounds on the surface slightly accompanying with boiling such as similar to Leidenfrost phenomenon. On the other hand, in case of the nanoparticles bi-porous coating, the droplet intensely boils, evaporates and disappears immediately. This dramatic improvement could enhance the critical heat flux because it enables the utilization of a much higher wall temperature region.

In order to prove this assumption, a life time that is the time interval from the first contact of the droplet onto the hot surface to that the droplet completely disappears. Fig. 5 shows the life time for each nanoparticles-bi-porous coating. For comparison, the life time of the bare surface without the nanoparticles bi-porous layer is also shown in the figure. This result indicates two remarkable features. The first one is that the life time of the water droplet is much shorter than that for the bare surface in a high temperature regime exceeding a wetting limit temperature that is approximately 125 ^{o}C. For instance, the life time using BAM is less than 1/10 times as that of the bare surface. This result could lead to the large enhancement of critical heat flux. On the other hand, in a low temperature region less than the wetting limit temperature, the life time for the nanoparticles bi-porous coating is shorter than that for the bare surface. This means that the boiling heat transfer coefficient is also enhanced in a nucleate boiling regime because BAM has a possibility to increase the number of active cavities. From this experiment, effect of the concentration of the nanoparticles isn't apparent, but it seems that higher concentration, i.e. 100 vol% of BAM, results in shortest life time.

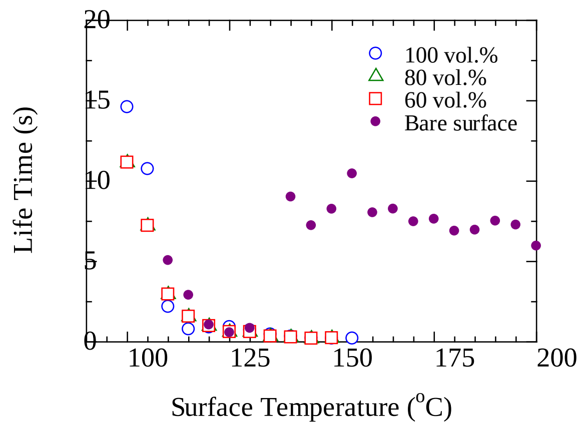

Fig. 5 Life time data for water droplet

CONCLUSIONS

In this study, nanoparticles-assembled bi-porous structure is newly proposed and its potential to enhance the boiling heat transfer is evaluated in order to develop a new cooling device toward 300W/cm^2 of on-vehicle inverter cooling. The findings are summarized as follows.

1. Boiling adhesion method can produce multi-scale pore structures composed of nano-scale pores and micro-scale pores.

2. Water droplet intensely boils and evaporates on a high temperature of a wall with nanoparticles-

assembled bi-porous layer even under Leidenfrost conditions.

3. The nanoparticles-assembled bi-porous structure enables not only the boiling heat transfer under high temperature conditions but also the increase in both the critical heat flux and the boiling heat transfer in a nucleate boiling regime.

REFERENCES

[1] K. Suzuki et al. (2006), "Subcooled Flow Boiling with Microbubble Emission (Development for High Heat Flux Cooling Technology for Power Electronics)", Proceedings of 13th International Heat Transfer Conference, CD-ROM BIO-28, 2006.

[2] D. Reay, R. McGlen, P. Kew, "Heat Pipes", Sixth Edition: Theory, Design and Applications, Butterworth-Heinemann, 2011.

[3] K. M. Kota, "Design and Experimental Study of an Integrated Vapor Chamber-Thermal Energy Storage System", Proquest Umi Dissertation, 2011.

[4] K. Yuki et al. (2010), "Heat transfer augmentation of high-Pr number fluid flow using nano-particles layers on a heating surface", Proceedings of the 14th International Heat Transfer Conference (IHTC-14), IHTC14-23041.

[5] S. Chiba, K. Yuki, et al. (2005), "Effect of nano-scale surface conditions for boiling heat transfer", 2005 ASME summer heat transfer conference, paper no.72758.