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PROPOSAL OF UTILIZING UNI-DIRECTIONAL POROUS METAL FOR EXTREMELY HIGH HEAT FLUX REMOVAL

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Key Words: *Uni-directional porous copper, High heat flux, Heat transfer, Boiling, Evaporation*

ABSTRACT

This paper proposes new heat removal devices utilizing uni-directional porous metal under extremely high heat flux conditions. Before designing the detailed structure of the porous media, we discuss some key parameters of the porous media to enable a high heat flux removal over 10 MW/m^2 at a low flow rate of water, which are effective thermal conductivity, permeability, direct liquid supply toward a heat transfer surface, vapor discharge, and contact thermal resistance between the porous medium and the heat transfer surface. Discussions based on the experimental results indicate that utilizing the uni-directional porous media will lead to breakthrough from the view point of its higher thermal conductivity, direct supply of cooling liquid toward the heat transfer surface, discharge of vapor, reduction in flow resistance and the thermal contact resistance.

The experimental apparatus to verify this proposal is composed of the coolant supplying pump, the heat transfer test section, and the heat exchanger. Distilled water is used as cooling liquid. The heat transfer test section mainly consists of the heat transfer copper block and the uni-directional porous medium attached onto the heat transfer surface. The uni-directional porous copper has small holes of 0.5 mm in diameter for the liquid supply at the pitch of 1.0mm and five big holes of 2.6 mm in diameter for the vapor discharge. The thickness is 10 mm and the diameter of the porous medium is 20 mm. As a result, the heat transfer experiments verify that utilizing the uni-directional porous cooling device strongly enhances the boiling/evaporation heat transfer and leads to the heat flux removal of over 10 MW/m^2 as well as being able to reduce the pumping power.

INTRODUCTION

Porous media are defined as a material that has an extraordinarily large number of fine pores inside it. Taking advantage of the vast surface and the capillary phenomenon induced by fine pores, the porous media have widely and actively been applied to heat transport technology for electronics in the forms of heat pipes and vapor chambers, fuel cell technology, radiation heat transfer technology, packed beds, etc.

We have attempted to apply the porous media to heat transfer equipment especially under the heat flux conditions from several MW/m2 to 10 MW/m^2 and conducted many heat transfer experiments and numerical simulations [1-12]. The heat removal device is called EVAPORON. The primary principle of EVAPORON is to remove heat by evaporating cooling liquid, taking advantage of the vast heat transfer surface of microchannels inside the porous medium. This is referred to as latent heat transfer with strong evaporation heat transfer. Additionally, not relying on the capillary phenomena as observed in the heat pipes, high heat flux is removed by evaporating a small amount of a liquid which is supplied to a two-phase region in the porous medium with quite low pumping power of a mechanical pump.

On the other hand, porous media actually have such a wide variety of structures such as pore diameter and porosity, permeability with regard to the flow conductance, and effective thermal conductivity which indicates the heat conductance in the porous medium, as well as their pore structure. When applying the porous media as a heat removal device, it needs to recognize the heat flux level and introduce adequate porous media. For example, convection heat transfer enhancement and the increase in pressure loss have a trade-off relationship, so that careless application of porous media could increase pumping power more than the heat transfer enhancing rate.

This study summarizes various findings and knowledge regarding the application of the porous media which we have obtained through our high heat flux experiments [1-12]. The purpose of this study is to propose a new cooling method with new porous media which are suitable for heat removal exceeding 10 MW/m^2 for water cooling and almost 1 MW/m^2 for low boiling point coolant, such as Fluorinert. In Addition, boiling/evaporation heat transfer performance are

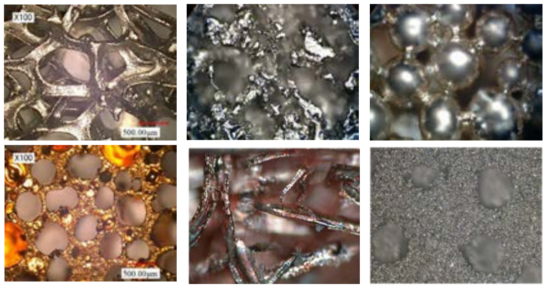

Fig. 1 Various porous media (Foam, Particle-sintered porous compacts, Lotus porous, Fibrous, Biporous)

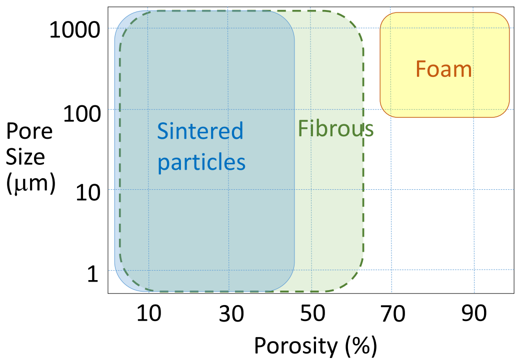

Fig. 2 Porosity and pore size of representative porous media

evaluated to verify the assumption and the feasibility of the proposed porous media.

2. VARIOUS CHARACTERISTICS OF POROUS MEDIA

Figure 1 shows structures of various porous media, while Fig. 2 indicates the porosity and the pore size of representative porous media that are foam, particle-sintered porous compacts, lotus porous, fibrous, and biporous. By referring to Table 1, the following section overviews above-mentioned some parameters that affect the heat removal performance based on phase change of the cooling liquid under high heat flux conditions.

2.1 Thermal Conductivity of Porous Media

Discussion in this section is developed based on a simple equation, $k_{eff} = \varepsilon k_f + (1-\varepsilon)k_s$, which expresses the effective thermal conductivity of porous media, k_{eff}. Here, ε indicates the porosity, k_f is the thermal conductivity of a fluid phase, and k_s is the thermal conductivity of a solid phase that comprises the porous structure. We should notice here that k_f and k_s indicate, not the thermal conductivities of the fluid and solid phases themselves, but those with thermal resistance taking into account the porous structure. From the k_{eff} formula, the effective thermal conductivity of the porous media depends significantly on the porosity. Since foams with high porosities as shown in Fig. 2 have a low thermal conductivity, there is not much hope in the enlargement of the heat transfer area based on the fin effect. These foams are often used as turbulent promoters for gas heat transfer. On the other hand, particle-sintered compacts having fine filling structures can produce a lower porosity below 0.3. In order to reduce thermal contact resistance and control the effective thermal conductivity, contacting structure between the particles needs to be controlled depending on the sintering level. However, our numerical simulation [4] actually predicted that even though bronze particle-sintered compact having the neck structure with a higher sintering level, as shown in the upper right of Fig. 1, have the effective thermal conductivity about 10 to 20 W/m/K. This value is significantly below the mother material's thermal conductivity, 128 W/m/K. The fibrous porous media naturally have a high thermal conductivity toward fibrous direction. Moreover, controlling porosities is relatively easier and can make it possible to enhance the effective thermal conductivity of the fibrous porous media. As for utilizing the fibrous porous media, however, it is important to control the fibrous arrays for direction of heat flow.

2.2 Flow Resistance of Porous Media (Vapor Discharge)

The flow rate of supplied liquid naturally increases in a high heat flux environment. In addition to this point, it is also important how to discharge the vapor generated within the porous medium out of the porous medium. In that sense, while foams having a high permeability excel in discharging vapor, as mentioned earlier, we cannot expect much of phase change within the porous medium. Therefore, the boiling and/or the evaporation is induced only near and on the heat transfer surface. On the other hand, the particle-sintered compacts have low porosities and high effective thermal conductivities, while we cannot ignore the flow resistance of high velocity vapor flow under high heat flux conditions of several MW/m^2. In fact, our experiments clarified that in an environment with a high heat flux exceeding a few MW/m^2, such porous media which have a high permeability can have higher heat transfer rates, compared with that for a low permeability porous media. Moreover, we successfully completed the heat removal, which exceeds 20 MW/m^2, by installing sub-channels for discharging vapor generated forcedly out of the porous medium [7-9]. Here we call this device EVAPORON-2. On the other hand, fibrous porous media are often used as wicks in heat pipes, since the flow resistance in the fibrous direction is significantly reduced.

2.3 Thermal Resistance on a Heat Transfer Surface

Issue of thermal resistance between the porous medium and the heat transfer surface is an important

Table 1 Flow and thermal characteristics for various kinds of porous media

	Particle	Foam	Fiberous	Lotus
				
Thermal conductivity	△	×	○、△	◎
Thermal Contact Resistance	△	×	×	◎
Flow resistance	×	◎	△	○
Hardness	○	×	△	○
Separation of Liquid & Vapor	×	×	×	×
Liquid supply Vapor discharge	△	○	×	△
Liquid supply toward HT surface	△	○	×	○
Functionally graded structure	○	△	○	△

factor especially under high heat flux conditions. As the heat flux increases, significant temperature difference occurs at the interface, which leads to the increase in the wall temperature and directly affects the decline of the heat transfer coefficient. For instance, where the particle-sintered porous medium is mechanically pressed onto the heat transfer surface, the largest thermal resistance occurs because the heat transfer surface and the porous particles are in a status which is close to a point contact. On the other hand, in the point contact case, we can expect of a wall effect that the generated vapor flows like a high velocity slip flow through a high-porosity area which faces to the wall. However, in this case, boiling and evaporation mainly occur on the heat transfer surface or the first layer of the particles, so that there is not much expectation of drastic increase in high heat transfer coefficient. It is possible to make the contact point of the sphere slightly flat by mechanical processing such as milling. In this case, however, the porosity between the heat transfer surface and the first layer of the particles drastically lowers. This makes it impossible to supply the cooling liquid toward the heat transfer surface. There could be an optimal contacting state that can ease the contact thermal resistance and solve the trade-off relationship between the wall effect and the fin effect. However, controlling the thermal contact resistance is an extremely difficult matter. The same is true with fibrous porous media.

2.4 Direct Supply of Liquid toward Heat Transfer Surface

In order to maintain the liquid supply into the two-phase region even under high heat flux conditions and apply the porous heat removal device to an enlarged heat transfer surface, we proposed EVAPORON-3 [13] that tried to supply the liquid directly to the two-phase region in the porous medium. This device has two layers of copper particles on the heat transfer surface and a liquid-vapor separator on the particle bed enables to separate the liquid supply and the vapor discharge. However, even when introducing this cooling device with the two layer of particles, the results showed that the liquid is pushed back shortly after the liquid inlets by a large amount of generated vapor. This result suggested us to supply the cooling liquid directly toward the heat transfer surface instead of supplying the liquid into the two-phase region.

3. PROPOSAL OF NEW COOLING DEVICE EVAPORON-4 UTILIZING UNI-DIRECTIONAL POROUS MEDIA

To cope with above-mentioned issues, multi-structured porous media have been proposed in order to control the liquid supply by capillary phenomenon and the vapor discharge. Mori et al. [14], have successfully increased the critical heat flux than double for a smooth surface by making use of honeycomb porous media which functionally separate the capillary liquid-supply path and the vapor discharge path. On the other hand, focusing on high wettability and strong capillary phenomenon which occur by assembling nanoparticles, we have proposed boiling heat transfer enhancement technology based on a nanoparticle biporous layer [15] where nano-scale pores and micro~milli-scale pores coexist on the heat transfer surface. We verified that this nanoparticle biporous structure strongly improved the

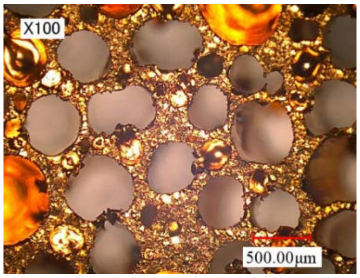

Fig. 3 Lotus copper porous media

wetting limit temperature between the high temperature copper surface and a water droplet, and the evaporation of the single droplet. Currently, we are conducting boiling heat transfer experiments for this new technology. When utilizing multi-structured porous media, isolation of the vapor flow from the liquid supply is essential as indicated in Table 1 to prevent the liquid supply from interfering, i.e. an entrainment limit which becomes a problem in heat pipes. If possible, the liquid supply and the vapor discharge need to be completely isolated by using solid walls etc.

Recently, porous media having uni-directional pore structures have been developed as shown in Fig. 3. The special features of the uni-directional porous media are high effective thermal conductivity and high permeability in the pore direction. The porosity and the pore size can be also controllable in a wider range. Furthermore, surface contacting with the heat transfer surface is possible, which could minimize the contact thermal resistance between the porous medium and the heat transfer surface. In particular, the uni-directional structure can make it possible to forcedly and absolutely lead to direct liquid supply to the heat transfer surface. The most significant issue is how to discharge vapor generated outside the porous medium. This study proposes two different patterns of the device as shown in Fig. 4. The first pattern makes the liquid supply flow and the vapor discharge flow as a counterflow (Upper), while the second pattern discharges vapor along the heat transfer surface (Lower). These concepts can be achieved by installing grid-like or unidirectional grooves on the heat transfer surface on which the uni-directional porous medium should be sintered to the surface. We named this cooling device with the uni-directional porous medium as EVAPORON-4.

4. HEAT TRANSFER PERFORMANCE OF EVAPORON-4

4.1 Experimental setup

The experimental apparatus to verify the heat transfer performance of EVAPORON-4 consists of the coolant supplying pump, the heat transfer test section, and the heat exchanger (see Fig. 5). Distilled water is used as cooling liquid. The heat transfer test section mainly consists of the heat transfer copper block and the

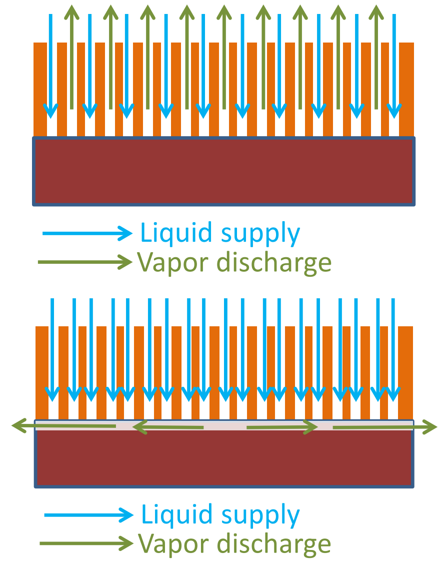

Fig. 4 EVAPORON-4 concept

uni-directional porous medium attached onto the heat transfer surface. High power of eight cartridge heaters are inserted into the bottom of the heat transfer block as the heat source. The heat transfer block is designed in order to achieve the heat flux of over 10 MW/m^2 at the heat transfer surface of 20 mm in diameter. The uni-directional porous copper shown in Fig. 6 has the small holes of 0.5 mm in diameter for the liquid supply at the pitch of 1.0 mm and the big five holes of 2.6 mm in diameter for the vapor discharge. The thickness is 5 mm and the diameter of the porous medium is 20 mm. This porous copper is mechanically attached to the heat transfer surface. On the other hand, the heat transfer has the grid-like groove structure with the width of 1.0 mm and the depth of 0.5 mm.

4.2 Results and Discussion

Figure 7 shows the heat transfer performance of EVAPORON-4. For comparison, the data obtained was compared with the data for EVAPORON-3 (Type-1 and Tupe-2). The flow rate is 2.0 L/min and the liquid subcooling is 40 K. It is confirmed that the boiling/evaporation heat transfer performance utilizing the uni-directional porous copper is strongly enhanced compared with those of EVAPORON-3. In special, the boiling curve shifts on the low superheat side and EVAPORON-4 succeeded at high heat flux removal of over 10MW/m^2 at a quite low pumping power of below 1W and the mass flow rate of 51 kg/m^2/s. The maximum heat flux is not the critical heat flux, so that the critical/dryout heat flux could be much higher.

5. CONCLUSION

This paper proposed new heat removal devices utilizing uni-directional porous metal under extremely high heat flux conditions. Before designing the detailed

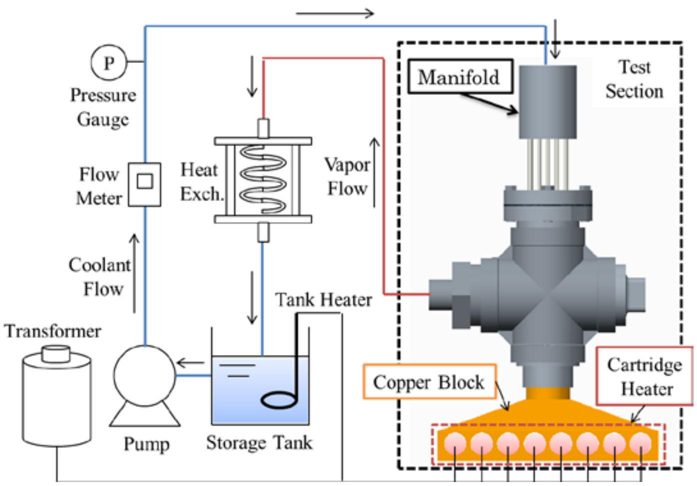

Fig. 5 Experimental setup

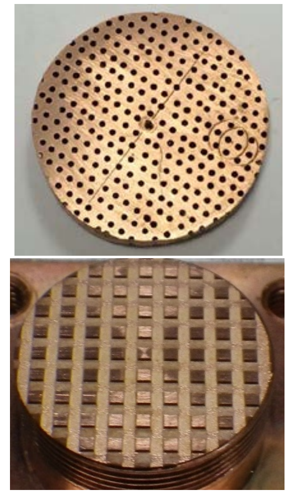

Fig. 6 Uni-directional porous copper and grooves on a heat transfer surface

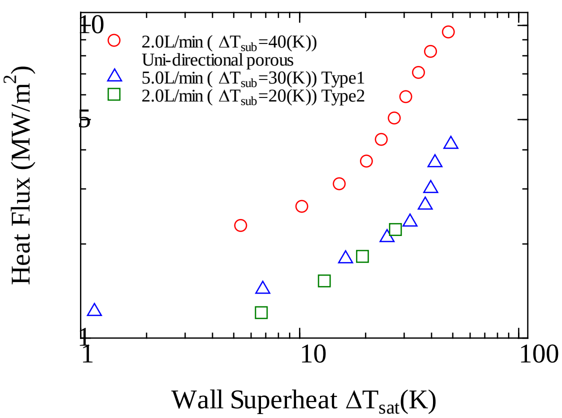

Fig. 7 Heat transfer performance of EVAPORON-4

structure of the porous media, we discussed some key parameters of porous media to enable a high heat flux removal over 10 MW/m^2 at a low flow rate of water, which are effective thermal conductivity, permeability, direct liquid supply toward a heat transfer surface, vapor discharge, and contact thermal resistance between the porous medium and the heat transfer surface. The heat transfer experiments verified that utilizing the uni-directional porous cooling device strongly enhanced the boiling/evaporation heat transfer and lead to the heat flux removal of over 10 MW/m^2 at a low pumping power of below 1 W and the mass flow rate of 51 $kg/m^2/s$.

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