Chapter

Heat Transfer Enhancement Using Unidirectional Porous Media under High Heat Flux Conditions

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Abstract

In this chapter, new heat transfer enhancement technologies with unidirectional porous metal called "EVAPORON" and "Lotus' Breathing" are introduced to remove and manage heat from high heat flux equipment. The unidirectional porous metals introduced here can be easily fabricated by unique techniques such as mold casting technique, explosive welding technique, and 3D printing technique. First of all, many kinds of porous media, which have been introduced by the author so far as a heat transfer promoter, are compared each other to clarify what kind of porous metal is more suitable for high heat flux removal and cooling by focusing on the permeability and the effective thermal conductivity. For the practical use of the unidirectional porous copper with high permeability and high thermal conductivity, at first, heat transfer performance of two-phase flow cooling using a heat removal device called "EVAPORON" is reviewed aiming at extremely high heat flux removal beyond 10 MW/m^2. We have been proposing this device with the unidirectional porous copper fabricated by 3D printing technique as the heat sink of a nuclear fusion divertor and a continuous casting mold. Second, two-phase immersion cooling technique called "Lotus' Breathing" utilizing "Breathing Phenomenon" is introduced targeting at thermal management of various electronics such as power electronics and high performance computers. The level of the heat flux is 0.1 MW/m^2 to 5 MW/m^2. In addition, as the other heat transfer enhancing technology with unidirectional porous metals, unidirectional porous copper pipes fabricated by explosive welding technique are also introduced for heat transfer enhancement of single-phase flow.

Keywords: unidirectional porous metal, cooling, high heat flux, permeability, effective thermal conductivity, heat transfer, phase change, EVAPORON, lotus' breathing

1. Introduction

Porous media are defined as "materials containing very large numbers of pores with various sizes." Owing to their characteristic large surface area, the porous media are used in various fields such as chemical plants, architecture, agriculture, environment, medical care, biology etc. In heat transfer engineering, which is one of this book's topics, heat pipes [1] and vapor chambers [2] that utilize independent liquid supply based on the capillarity in a porous wick play an active part in the thermal management of electronic devices. For instance, thin heat pipes of <1 mm in thickness are even used in smartphones whose usage has witnessed an exponential increase [3]. In addition, in recent years, to cool electronic devices, two-phase immersion cooling with saturated pool boiling heat transfer has attracted attention for increasing the heat generation density and reducing the costs of thermal management. In particular, great numbers of studies have focused on improving the critical heat flux by loading a porous medium with a functional shape and structure onto the cooling surface, in addition to enhance the boiling heat transfer. It is recommended to refer to the review studies of Yuki [4], Mori [5, 6], and Kandlikar et al. [7]; however, there have been multiple studies that attempted to separate liquid supply and vapor discharge, such as the honeycomb porous plate of Mori et al. [8], the porous layers having a non-uniform spatial structure [9–11], and porous meshes provided with hydrophilic and hydrophobic functions [12, 13]. Note that the results of Bai et al. [14] and Yuki et al. [15] in which the critical heat flux of the saturated pool boiling of water in an atmospheric pressure environment exceeded 5 MW/m^2, thus demonstrating the high potential of the porous media as a latent heat transport promoter. On the other hand, also for a single-phase flow, there have been a large number of attempts to utilize the porous media as a heat transfer promoter. The examples include heat transfer enhancement by metal foams [16, 17], utilization as a radiation converter [18, 19], and promotion of heat transfer using sphere-packed tubes [20, 21].

Focusing on high potential of the porous media as the heat transfer promoter as mentioned above, multiple studies have introduced porous metals for heat removal from high-heat flux equipment of a level of 10 MW/m^2. For example, the divertor of a nuclear fusion reactor currently under research and development is exposed to a steady heat load of approximately 10 MW/m^2 due to the inflow of α particles generated by nuclear fusion reaction. Sharafat et al. [22, 23] introduced metal foams as a heat transfer promoter of He gas flow pressurized to 40 MPa and demonstrated high cooling performance of >10 MW/m^2. Furthermore, Joshi et al. proposed a cooling technology that makes use of the phase change of coolant in a pin-fins microchannel for high heat generation density electronic devices exceeding 10 MW/m^2 [24–26]. Moreover, he attempted a technology that assists heat transfer in the promotion of evaporation in a nanoporous film via a gas impinging jet [27]. Regarding additional applications of the porous media under high heat flux conditions, refer to the review article by Smakulski et al. [28]. Obviously, in the thermal management of these high heat flux devices, in addition to securing the cooling performance, it is necessary to consider both economical efficiency and maintainability; therefore, thermal management with low flow rate and low pumping power is indispensable.

As an efficient heat removal technology at a level of 10 MW/m^2, Toda and Yuki proposed a cooling device known as EVAPORON (Evaporated Fluid Porous-Thermodevice) to take maximum advantage of the latent heat of vaporization of the coolant [29, 30]. EVAPORON can remove extremely high heat flux by evaporating the cooling liquid that is fed inside the porous medium jointed to the heat transfer surface against a heat flow, using the vast surface area with microchannels of the porous media. Because rather than relying on capillarity such as in the heat pipes, a minimum amount of liquid corresponding to the heat flux level is gently pumped into the porous medium for cooling, a significant reduction in pumping power can then be expected. Furthermore, we verified that the important factor of this technological breakthrough is the quick discharge of considerable amounts of vapor generated in the porous medium [31]. Subsequently, the authors proposed EVAPORON-2 [32, 33] loaded with subchannels for vapor discharge within sintered copper particles and succeeded in the heat removal of over 20 MW/m^2. Targeting at a cooling performance exceeding 10 MW/m^2 under much lower pumping power conditions, furthermore, the EVAPORON-3 equipped with a vapor–liquid separator on the upper part of the porous medium was also proposed [34].

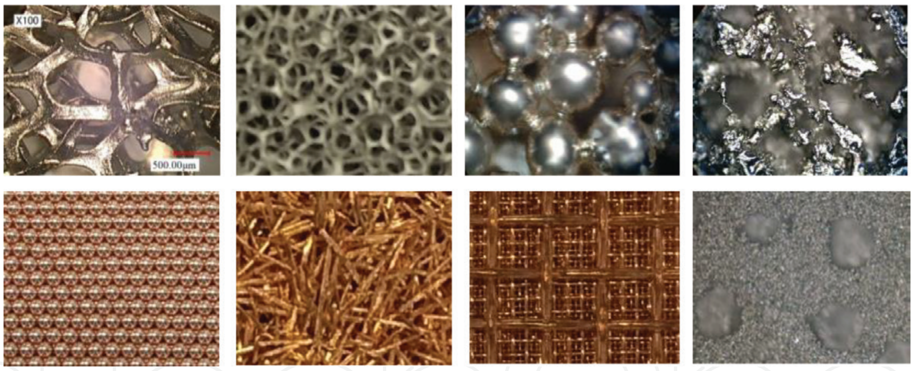


Figure 1.
Various kinds of porous media.

To summarize, when applying the porous media in the two-phase cooling technology for high heat flux environment, the most important factor is to actively promote the vapor discharge that was generated in the porous medium. Moreover, it is necessary to optimize the porous structure to maximize the advantage of the latent heat of vaporization of the coolant. On the other hand, there are various porous media such as foams, open cells, sintered particle/fiber, meshes etc. (see **Figure 1**), even if all of these are simply called porous metals. Generally, it is impossible to generalize the thermophysical properties and mechanical properties of the porous media with these different structures, thus referring only on their porosity and pore size. However, to promote phase change heat transfer in the porous medium, it is an undisputed fact that a porous medium with high permeability, which enables rapid discharge of the vapor generated, should be introduced in which its thermal conductivity is also increased to expand the effective heat transfer area. In general, there is a trade-off relationship between increasing the effective thermal conductivity and reducing the flow resistance of the vapor flow (increasing the permeability). Thus, the porous media to be introduced should be selected based on the heat flux level and coolant used. In this chapter, the effective thermal conductivity and absolute permeability for various porous media are first discussed. Subsequently, the effectiveness of unidirectional porous coppers [35] proposed by the author is quantitatively evaluated as a cooling technique on a level of 10 MW/m^2. Finally, two our innovative cooling technologies are introduced; "EVAPORON-4", which is the newest EVAPORON that combines the unidirectional porous copper and a grooved heat transfer surface and "Lotus' Breathing", which makes use of two-phase immersion cooling in a saturated pool boiling environment, based on spontaneous liquid supply effect called "Breathing phenomenon" proposed by the author for the first time all over the world.

2. Thermal conductivity and permeability of various porous media

Figure 2 shows the porosity and pore size distributions of sintered-metal-particles/fibers and foamed metals the author used to date. For example, regarding the thermal conductivity and the permeability of isotropic porous media with a simple structure, their modeling is frequently performed based on the porosity and the pore size for each porous medium. As shown in **Figure 2**, each porous medium has its characteristic porosity and pore diameter. For instance, most foamed metals and open cells have a high porosity of >90%. As far as the author knows, although those with a microscale pore diameter are not commercially available, Unno et al. developed the porous media with high porosity and micropores and demonstrated that it is effective for promoting evaporative heat transfer as per the capillary limit theory [36]. Multiple sintered-metal-particles have a porosity of 30%–50% because

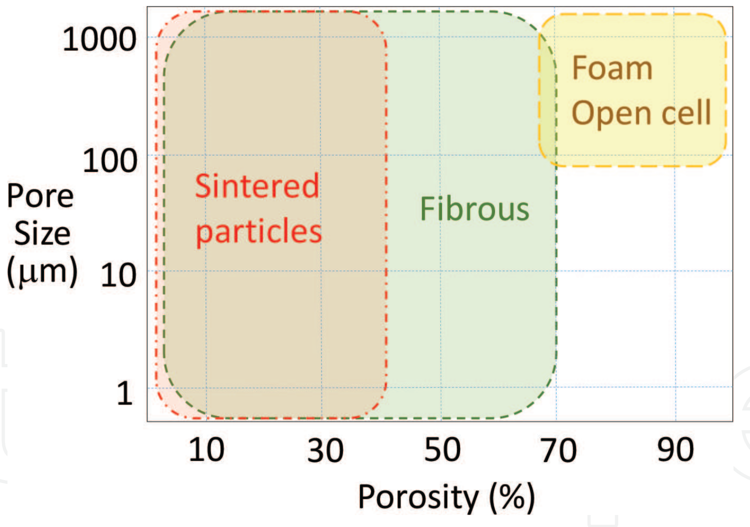


Figure 2.
Porosity and pore size of porous media.

of the producing process and the packing structure; moreover, the pore diameter varies from the order of micron to millimeter. For sintered-metal-fibers (a kind of fibrous porous media), the porosity can be regulated over a wide range by the extent of pressing; however, it is difficult to control the orientation of the fiber. We will now discuss the effective thermal conductivity and permeability of these typical porous media from the view point of phase-change enhancement of coolant.

2.1 Effective thermal conductivity of porous media

To discuss the effective heat transfer area, it is important to examine the effective thermal conductivity of the porous media. The prediction formulae for various porous structures have been developed to date; however, in general, the effective thermal conductivity k_{eff} of the porous media can be discussed based on the following parallel model weighted by the porosity.

$$k_{eff} = \varepsilon k_f + (1-\varepsilon)k_s \tag{1}$$

where k_f and k_s are the thermal conductivity of the fluid phase in the pore and that of the porous solid phase, respectively. Note that both k_f and k_s do not express the thermal conductivity of the material itself but must be taken into account the tortuosity, which expresses the porous structure, and the thermal resistance affected by the degree of sintering, if speaking of a sintered metal. However, Eq. (1) clearly shows that the effective thermal conductivity of the porous media mostly depends on the porosity. For example, for copper-foamed metal with high porosity, if the fluid in the pore is air and the porosity is 0.9, the effective thermal conductivity is estimated to be somewhat <40 W/m/K; however, when estimated from the formula of Boomsma et al. [37], it is ~1 W/m/K. In fact, because the effective thermal conductivity decreases further, depending on the manufacturing method of foamed metals, the expansion of the heat transfer area by the fin effect cannot be expected, particularly for liquid cooling or two-phase immersion cooling. Therefore, the foamed metals and the open cells are often used for gas flows as mechanical dispersion promoters and turbulent promoters. On the other hand, in terms of sintered-metal-particles with a comparatively low porosity, the porous media with the porosity of <0.3 can be produced depending on the degree of sintering and pressing, so that high effective thermal conductivity can be expected. Furthermore, depending on the extent of sintering, the neck structure formed between the particles considerably affects the effective thermal conductivity. As for the fibrous porous media, although the sintered-metal-fibers have high thermal conductivity in the fiber direction, the effective thermal conductivity is assumed to be almost the same as that of the sintered-metal-particles in the direction perpendicularly to the fiber direction.

Herein, as shown in **Figure 3**, we performed heat conduction simulation to estimate the effective thermal conductivity of the sintered-copper-particle, in which a cubic sintered-copper-particle with a side length of 5 mm is sandwiched between copper square rods of 5 × 5 × 50 mm^3. At the lower end surface, the heat flux of 0.5 MW/m^2 is exposed and a constant temperature of 100 °C is given to the upper end surface. Adiabatic conditions are attributed to the side surfaces of the rods and sintered-particles. The effective thermal conductivity of the sintered-copper-particle is evaluated using the Fourier law from the difference in the average temperature at the two interfaces between the copper square rod and the sintered particle. The particle size is 1.0 mm and packed structure of particles is a simple cubic structure. To reproduce the neck structure formed between the particles during sintering, a cylinder with a diameter of d is virtually installed around the contact point between the particles, i.e., the diameter of the cylinder is the neck structure at the time of sintering in a pseudo presentation, and d is determined with the contact angle θ as a parameter. In this calculation, contact angles are 5°, 10°, and 20°. The same is valid for contact between the particles and the end surface of the rods. The porosity at a contact angle of 0° is 0.48. Assuming pure copper, the solid phase has a thermal conductivity of 398 W/m/K; moreover, the air in the pore has a thermal conductivity of 0.026 W/m/K. The heat conduction simulation is performed using Stream v13 developed by Cradle, which adopts the finite volume method (FVM); for comparison, the calculation using the finite element method (FEM) is performed at the same time. Because these simulations do not apply any special model for the discretization of the equation of heat conduction, the effective thermal conductivity of the sintered-particle can be evaluated with a higher accuracy than with experiments. **Figure 4** shows the results of the simulation. The effective thermal conductivity at contact angles of 5°, 10°, and 20°is 7.8, 19.2, and 45.9 W/m/K, respectively. Obviously, a higher degree of sintering involves higher effective thermal conductivity. However, compared with the bulk thermal conductivity of pure copper, it is reduced to 2% – 4% of the thermal conductivity of the Cu

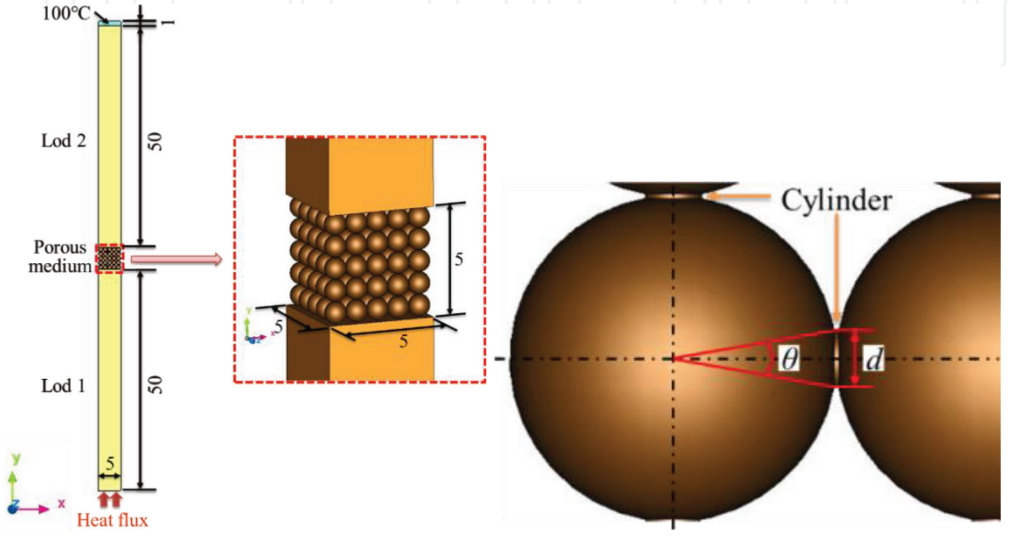


Figure 3.
Calculation of effective thermal conductivity for particle-sintered porous medium.

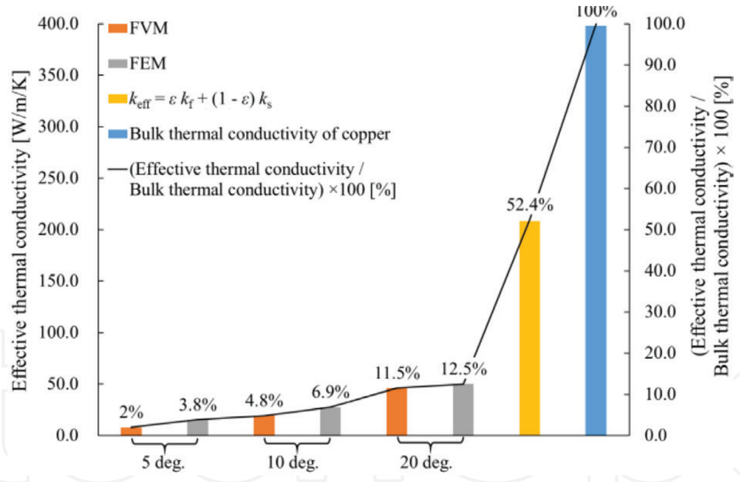


Figure 4.
Effective thermal conductivity of particle-sintered porous medium.

material at a contact angle of 5°; even if the contact angle is 20°, which is the highest degree of sintering, the effective thermal conductivity is reduced to ~12% of the Cu material. The difference from the effective thermal conductivity represented by the parallel model of Eq. (1) is apparent. The abovementioned results verify the necessity to carefully consider the fin effect even when utilizing the sintered-copper-particles due to its low thermal conductivity.

On the other hand, to maximize the effective thermal conductivity of the porous media, a porous medium to which the parallel model of Eq. (1) can be applied is desirable. This indicates that the introduction of a porous medium with unidirectional pore structure is ideal. Its thermal conductivity differs between the direction of the pores ($k_{eff\parallel}$) and the direction perpendicular thereto ($k_{eff\perp}$); they can be predicted from the following equations by Ogushi et al. [38].

$$k_{eff\parallel} = (1-\varepsilon)k_s \tag{2}$$

$$k_{eff\perp} = \frac{(\beta+1)+\varepsilon(\beta-1)}{(\beta+1)-\varepsilon(\beta-1)}k_s \tag{3}$$

The abovementioned equation is driven by adapting the Behrens' thermal conductivity model for composite material to the unidirectional porous media. Because the fluid in the pore is assumed to be a gas and its thermal conductivity can be ignored, Eq. (2) corresponds to the parallel model. β is the thermal conductivity ratio. At the same porosity of 0.48 as in the sintered-particle, the effective thermal conductivity in the pore direction is 220 W/m/K, which is more than five times higher than that of the sintered-particle. When developing cooling devices for a high heat flux equipment, if the pore direction of the unidirectional porous media agrees with the heat flow direction, the effective heat transfer area potential of the porous media can be maximized. With regard to the effective thermal conductivity in the direction perpendicular to the pores, the thermal conductivity simulation as shown in **Figure 3** is also performed on the unidirectional porous media as shown in **Figure 5** whereby the effective thermal conductivity is predicted more accurately. In this simulation, the pores are arranged in two patterns, i.e., a square array and a staggered array, and the porosity is adjusted while changing the pore diameter from 0.1 to 1.9 mm without changing the pore position. As understood from **Figure 6**, the unidirectional porous media exhibits a similarly high thermal conductivity even in the direction perpendicular to the pores because the effective thermal conductivity with the porosity of 0.5 exceeds

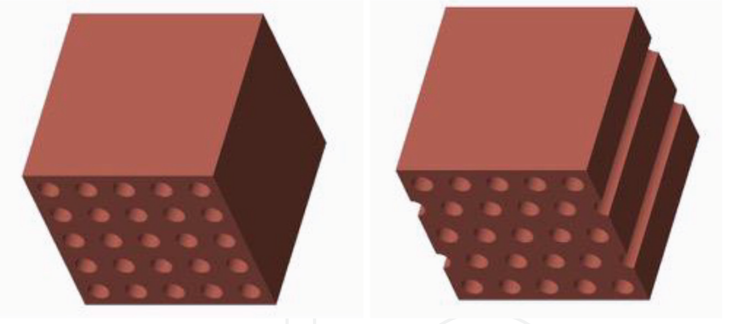


Figure 5.
Square array model and staggered array model for uni-directional porous media.

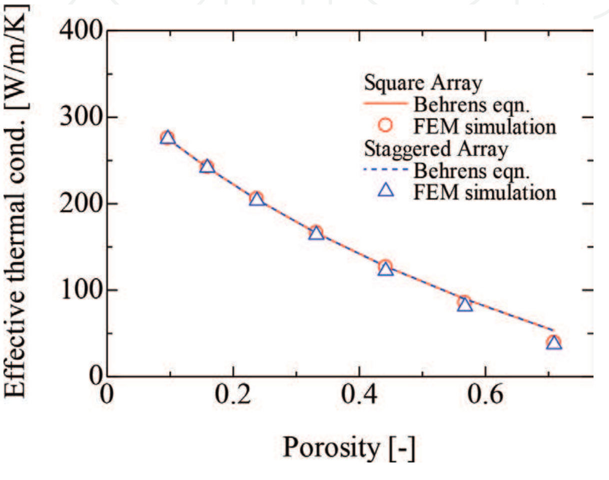


Figure 6.
Effective thermal conductivity $k_{eff\perp}$ of uni-directional porous media.

100 W/m/K. Moreover, the higher the porosity, the larger the deviation of the effective thermal conductivity from the model of Chiba et al. For example, if the porosity is 0.7, the error is ~35% for the square array and ~ 42% for the staggered array. By grasping the effective thermal conductivity, it becomes possible to discuss the fin efficiency of the porous media. Chiba et al. developed a highly accurate model formula [39], which enables the easy evaluation of the criteria for introducing the unidirectional porous media.

2.2 Permeability of porous media

As mentioned above, to effectively use the latent heat of vaporization in a high heat flux environment, a large amount of vapor generated in the porous medium must be quickly discharged to the outside. In other words, it is indispensable to take a mean, including introducing the porous media with high permeability or modifying the spatial structure while considering the improvement in effective thermal conductivity discussed in the previous section. Here, for reference, a simple comparison of the absolute permeability K of the sintered-particle and the foamed metal from the Kozeny–Carman Eq. $K = d^2\varepsilon^3/180/(1\text{-}\varepsilon)^2$ demonstrates that the permeability of the foamed metals is by two orders of magnitude higher than that of the sintered-particles, which clearly shows outstanding fluid fluidity and vapor discharge performance. However, as we have already understood from the discussion on the effective thermal conductivity, if the foamed metal is used as the phase change promoter, the phase change within the porous medium cannot be expected because of the low effective thermal conductivity, i.e., boiling/evaporation is expected to occur only on the heat transfer surface or in its immediate neighborhood. As for the sintered-particles, complicated microchannels with repeated expanded and contracted portions can be considered particularly suitable for the phase change because a thin liquid film can be formed at the contracted portion. Because of an extremely large pressure loss for the sintered-particles compared to that for the foamed metals, however, it is difficult to smoothly discharge large amounts of vapor from the porous medium, particularly under high heat flux conditions of 10 MW/m^2 level. If the upstream pressure of high-speed vapor flow exceeds a pumping pressure/an inlet pressure shortly before the porous medium, the vapor phase near the heat transfer surface particularly starts to excessively grow and form a thermal resistance layer that quickly deteriorates the heat transfer performance. In fact, in the heat transfer tests by the author in which the sintered-metal-particles and the sintered-metal-fibers were used, such phenomena have been confirmed that the heat transfer performance of the porous media with higher permeability is reversed under high heat flux conditions exceeding several MW/m^2 [31, 40]. It is effective to yield a multiple structure to the porous medium (e.g., biporous structure at the lower right of **Figure 1**) to provide a path for vapor discharge, however, it is extremely important to reduce the flow resistance in the porous medium because the vapor is first generated within the porous medium. In fact, the use of microchannels is also important in this technology as we want to promote evaporative heat transfer [41]. Therefore, effecting compromise with curved flow paths such as in the sintered-particles and introducing unidirectional porous media provide powerful means to improve the permeability. Here, to evaluate the permeability of the unidirectional porous media, the absolute permeability is modeled based on the Darcy–Weithbach equation, which gives the pressure loss of a circular pipe flow (the inflow resistance to the porous medium and the outflow resistance are ignored).

$$K = \varepsilon d_p^2 / 32 \tag{4}$$

Figure 7 shows the permeability of the sintered-particles and the unidirectional porous media. The horizontal axis is the porosity with a characteristic length d_p of 100 μm (corresponding to the particle diameter for the sintered-particles and the pore diameter for the unidirectional porous media). Indeed, with increase in porosity, the permeability increases; however, for example, if the porosity is 0.3, 0.4, and 0.5, the permeability ratios of the unidirectional porous media and the sintered-particles are 30.6, 12.7, and 5.6 times, respectively. This ratio does not depend on the characteristic

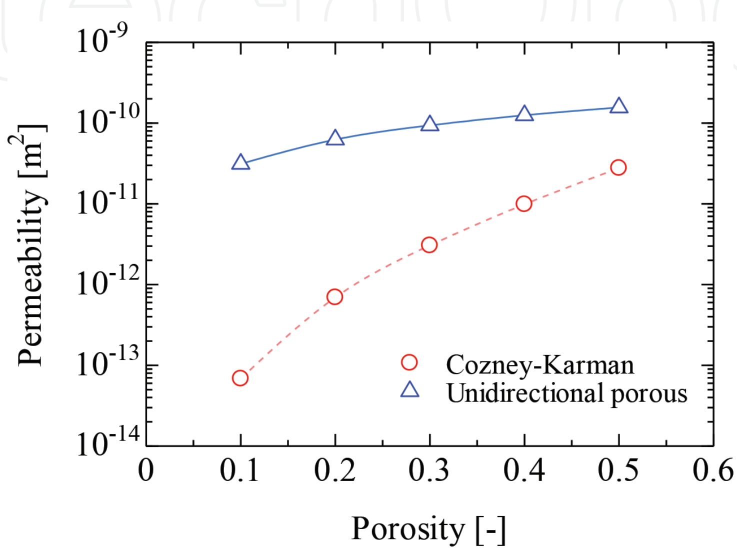


Figure 7.
Permeability of unidirectional porous.

length. In other words, when focusing on the porous structure, the unidirectional porous media can be considered as the one that offers the best compromise between the improvement of the thermal conductivity and the improvement of the permeability. An example of application is a fibrous wick manufactured by sintering fibers, which considerably reduces the flow resistance in the fiber direction to contribute to the improvement in the maximum heat transport capacity of small heat pipes [3].

2.3 Other heat transfer-related issues for introducing porous media

An important issue when introducing the porous media as a heat transfer promoter is the contact thermal resistance generated at the contact interface between the porous medium and the heat transfer surface. In general, with increasing heat flux, the temperature gap increases due to the increase in contact thermal resistance generated at the interface, so that the heat transfer coefficient is directly affected. For instance, when a sintered-particle is mechanically pressed to the heat transfer surface, a large contact thermal resistance is generated because of the point contact state between the heat transfer surface and the particles. In the point contact state, the heat conduction to the first particle is considerably deteriorated, so that boiling and evaporation occur mainly on the heat transfer surface or the first several layers of the particle, and thus, effective utilization of latent heat of vaporization inside the porous medium cannot be expected. The best measure is sintering the sintered-particle to the heat transfer surface. Remarkable research results are reported by Kibushi et al. [42] regarding the contact thermal resistance in a high heat flux environment exceeding 1 MW/m^2 (for the experimental details refer to the reference). **Figure 8** shows the temperature gap that occurs at the contact interface of two flat surfaces. The loads on a jointing surface of ϕ10 mm are 0.33, 1.71, and 3.03 MPa, and there are the two patterns of mechanical and solder joints. Focusing on the heat flux of 2 MW/m^2, in the mechanical joint case, a temperature difference of ~40 K occurs under a load of 3.03 MPa, and a temperature gap exceeding 100 K takes place at the load of 0.33 MPa. However, it can also be confirmed that the contact thermal resistance is significantly improved by solder bonding. At the heat flux of 5 MW/m^2, the temperature gap is ~10 K, and it is ~20 K upon linear extrapolation to 10 MW/m^2. Accordingly, it is evident that when the porous medium is loaded on the heat transfer surface, the contact thermal resistance should be reduced by solder bonding or the like. Our heat transfer tests regarding a gas impinging jet flow into a sintered-particle verified that the heat transfer coefficient is spectacularly increased by soldering the

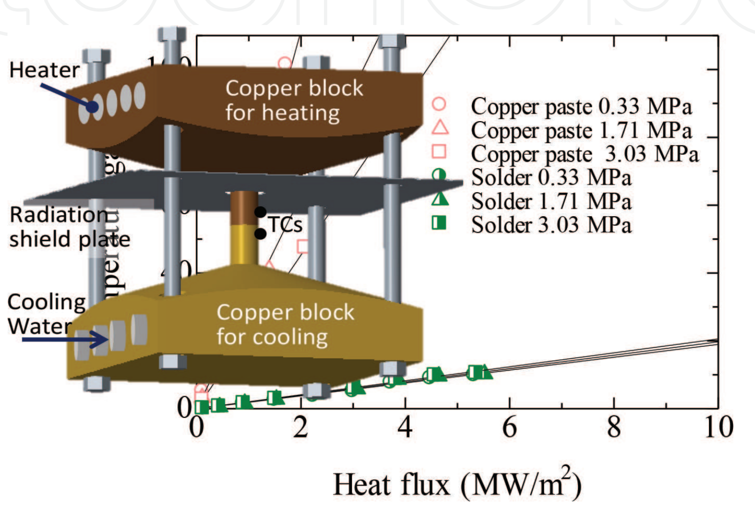


Figure 8.
Temperature gap due to contact thermal resistance.

porous medium to the heat transfer surface [43]. Further, the pool boiling results by Peterson et al. [44] have also demonstrated that boiling heat transfer is dramatically enhanced by HIP bonding of the porous medium to the heat transfer surface.

For introducing the unidirectional porous media proposed this time, if the pores that serve as the flow path are parallel to the heat transfer surface, a perfect surface contact state can be achieved over the entire heat transfer surface. Furthermore, even if the pores are perpendicular to the heat transfer surface, the surface contact state can be maintained in the solid phase portion, which can maximally reduce the contact thermal resistance between the porous medium and the heat transfer surface.

2.4 Introduction of unidirectional porous copper

A majority of unidirectional porous media proposed in this study is generally fabricated by electric discharge machining or MEMS. As the production with these techniques is very expensive, it is desirable to introduce the unidirectional porous media with excellent mass productivity. Here, three unidirectional porous media are presented, which are currently introduced to the author's laboratory. The first is the lotus copper shown in **Figure 9(a)**, in which pores are formed utilizing different saturation degree of dissolved hydrogen existing in molten copper with temperature gradient [45]. Chiba et al. already demonstrated its superiority in single-phase flow heat transfer [46]. The boiling heat transfer enhancement technology that the author is currently developing in cooperation with Lotus Thermal Solutions Co., Ltd. will be introduced in the next section. Hokamoto et al. also proposed a technique for forming a group of thin metal tubes into a unidirectional porous tube by exploded welding technique (**Figure 9(b)** [47]). To date, the author has introduced unidirectional porous copper tubes as a heat transfer promoter of a gas flow in a joint research with Hokamoto et al. of Kumamoto University. Based on single-phase flow heat transfer tests, the unidirectional porous tubes of 21 mm in outer diameter

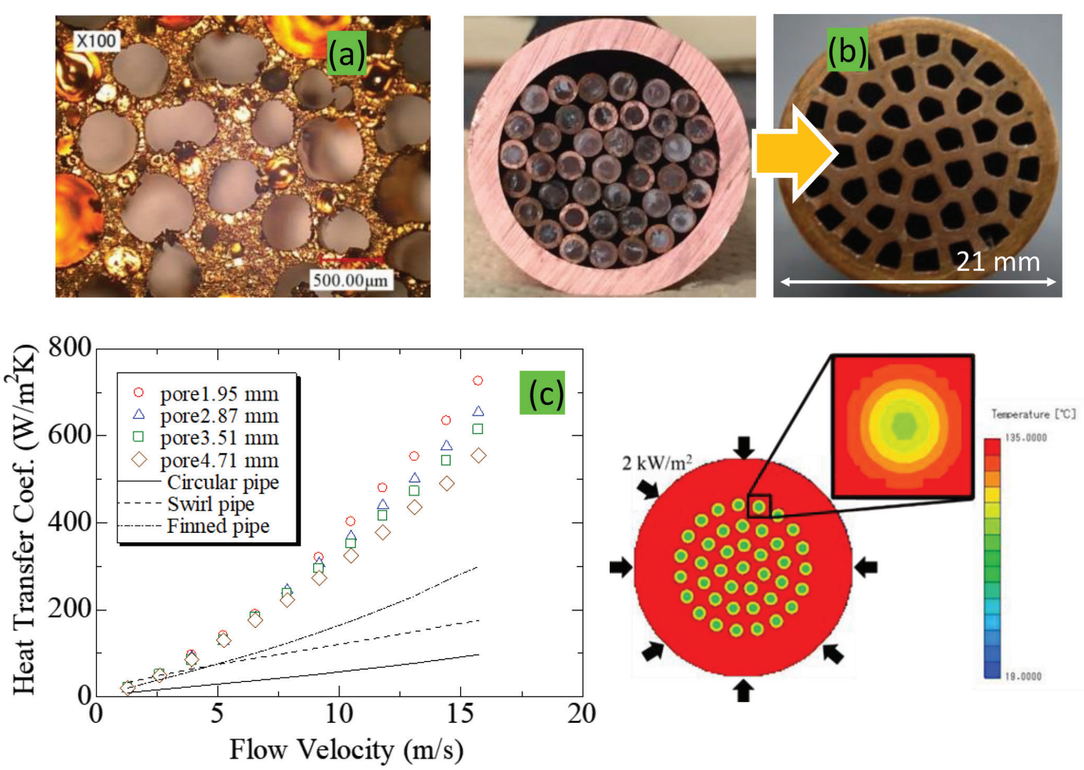


Figure 9.
Unidirectional porous media ((a) lotus copper, (b) exploded welded porous pipe) and (c) heat transfer performance of a gas flow in exploded welded porous pipes & its CFD simulation.

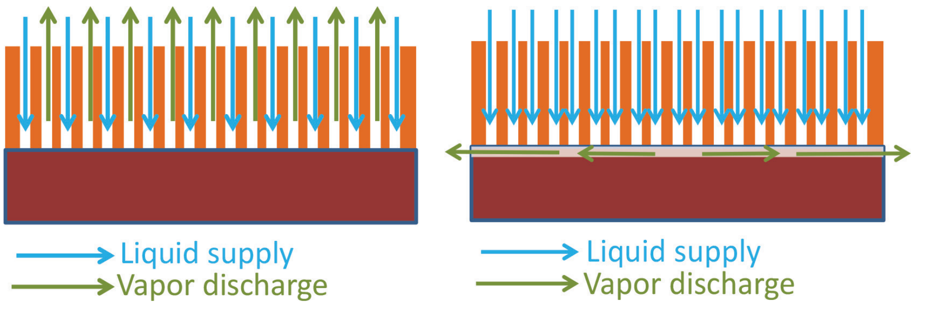


Figure 10.
Two heat removal devices proposed.

shows a heat transfer performance that is up to approximately eight times higher than that of a smooth tube at the maximum as shown in **Figure 9(c)** [48]. The pore size and the porosity of this porous tube can be adjusted by varying the inner diameter and wall thickness of the thin tube. The lastly introduced unidirectional porous copper is the one molded by a metal 3D printing technique [49]. Recent advances in 3D printing technology enabled the molding of even porous media composed of copper and having microchannels. The adjustment of the pore diameter and the pore structure matching the heat transfer mechanism are possible, which is the greatest attraction of this technology.

On the other hand, when this type of unidirectional porous copper is applied as a promoter of boiling/evaporation heat transfer, particularly if the pores are perpendicular to the heat transfer surface, one of the advantages is that the coolant can surely be supplied to the heat transfer surface. The major limitation is how to rapidly discharge a large amount of vapor generated in the porous medium to the outside. As a solution, we propose to joint the unidirectional porous copper to the grooved heat transfer surface; thus, as shown in **Figure 10**, two cooling structures are enabled. The first structure on the left shows the liquid supply direction is opposite to the vapor discharge direction, whereas the second structure on the right shows a method of directly discharging the vapor outside the porous medium via these grooves. In the next section, we will focus on the cooling performance related to flow boiling heat transfer and pool boiling heat transfer using these cooling structures.

3. Enhancement of flow boiling and pool boiling heat transfers using unidirectional porous copper

3.1 Enhancement of flow boiling/evaporative heat transfer with EVAPORON-4

As mentioned in the Introduction, the author proposed EVAPORON, EVAPORON-2, and EVAPORON-3, cooling devices using porous metals [29–34]. The porous metal is connected to the cooling surface as shown in **Figure 11**, the cooling liquid is supplied into the porous medium in a countercurrent to the heat flow, and the heat is removed by the vigorous phase change of the cooling liquid within. To smoothly discharge the large amount of vapor outside the porous medium, EVAPORON-2 has several subchannels inside the porous medium, and EVAPORON-3 has a liquid–vapor-separator on the porous medium. Here, the concept of cooling device EVAPORON-4, using a unidirectional porous media is realized as shown in **Figure 12(a)**. As shown in **Figure 12(b)**, 9 × 5 grooves for the vapor discharge are formed on the heat transfer surface, and the unidirectional porous copper shown in **Figure 12(c)** is joined by soldering. The groove is 1.0 mm in width and 0.5 mm in depth. The unidirectional porous copper with a diameter of 20 mm and a thickness of 10 mm is produced by machining and has 248 small pores of ϕ0.5 mm in diameter. In addition, the porous medium has large five ϕ2.6 mm holes for the vapor discharge. EVAPORON-4 is a once-through type cooling device in which the cooling liquid supplied from the upper part of the unidirectional porous copper through the small pores undergoes phase change in the pores and the grooves to be then discharged through the grooves and the vapor discharging large holes. **Figure 13** shows some of the results in two cases that the unidirectional

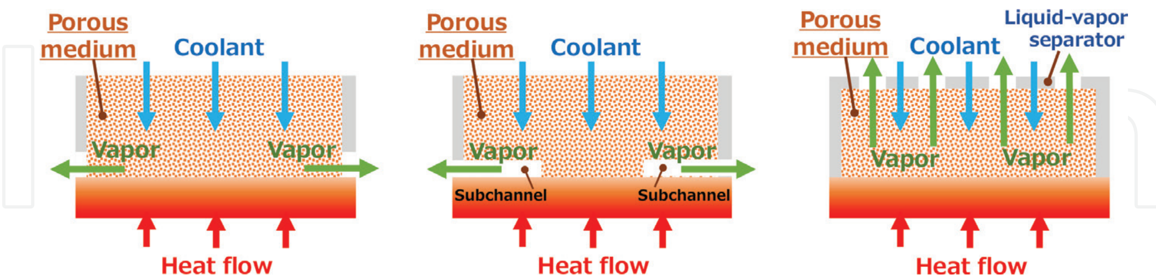


Figure 11.
From the left: EVAPORON, EVAPORON-2, and EVAPORON-3.

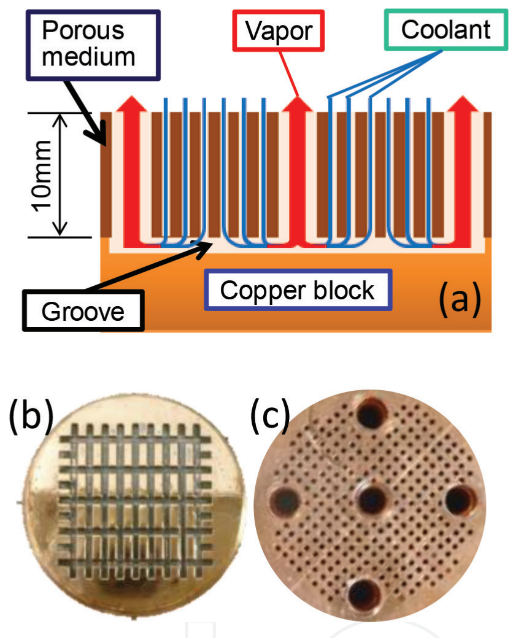


Figure 12.
Outline of EVAPORON-4.

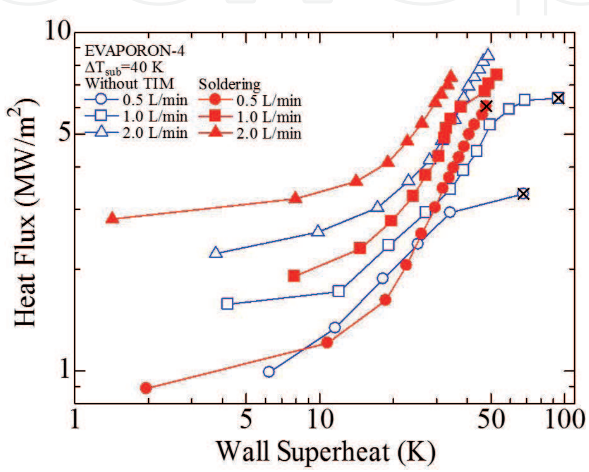


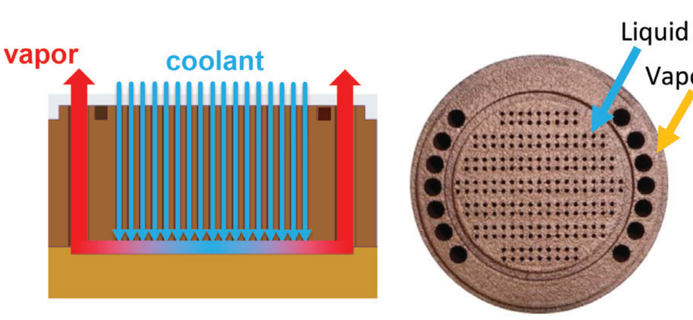
Figure 13.
Boiling curves of EVAPORON-4.

porous copper is jointed onto the heat transfer surface with/without soldering ("Without TIM (Thermal Interface Material)" shows the data of mechanical joint without bonding). For details of the experimental apparatus and various results, please refer to Reference [50]. The inlet liquid subcooling of distilled water is 40 K, whereas the x mark on the plot shows that the obtained data represent the critical heat flux. From this figure, the data with soldering move to the lower wall-superheat side under each flow rate condition, which verifies that the phase change heat transfer is enhanced by solder bonding the porous copper to the grooved heat transfer surface. Focusing on the data obtained at the flow rate of 0.5 L/min, while the critical heat flux without solder bonding is ~3 MW/m^2, the critical heat flux is improved to exceed 6 MW/m^2 by solder bonding (1.8-fold enhancement). For the flow rate of 2.0 L/min, as the maximum heat flux (not the critical heat flux) without solder bonding is approximately 9 MW/m^2, the critical heat flux by solder bonding is expected to exceed 10 MW/m^2, though the experiment was stopped due to the temperature limit of the cartridge heaters we used. For reference, the measured critical heat flux of the impinging jet at the flow rate of 2.0 L/min is approximately 4 MW/m^2 (the same flow rate is ejected from a hole of ϕ2 mm), so that the cooling performance of EVAPORON-4 is much higher compared with other cooling technologies. These results are attributed to the effective functioning of the phase change within and the vapor discharge outside the porous medium, because the heat transfer is remarkably improved under high heat flux conditions.

Currently, we are examining the flow rate distribution and the phase change in porous media by CFD and visualization experiments. From now onward, we intend to push forward discussions and optimization by introducing the porous copper fabricated by a 3D metal printer, as shown in **Figure 14**, thus comprising the un-uniform unidirectional pore and groove structures that can make maximum use of the latent heat of vaporization [49]. Moreover, we are examining a small-sized cold plate having in mind an application to electronic devices, a theme to be referred to in Reference [51].

3.2 Enhancement of critical heat flux of saturated pool boiling using lotus coppers by "breathing phenomenon"

In the past heat transfer experiments using EVAPORONs, the author noticed that the inlet pressure of the fluid rapidly decreases when the phase change in the porous medium is considerable and the vapor is vigorously ejected to the outside, i.e., there must be spontaneous liquid supply phenomenon associated with the discharge of vapor (henceforth referred to as "Breathing Phenomenon"). As shown in **Figure 15**, the author has proposed to attach a porous plate called "lotus copper" with a unidirectional pore structure to the grooved heat transfer surface (**Figure 9(a)**), whereby the critical heat flux of saturated pool boiling is spectacularly increased [15, 52–54].



Pore size	Φ0.47 mm×202
Vapor hole	Φ1.91 mm×14
Thickness	10.0 mm
Porosity	12.1 %

Figure 14.
Unidirectional porous copper fabricated by 3D printing technique.

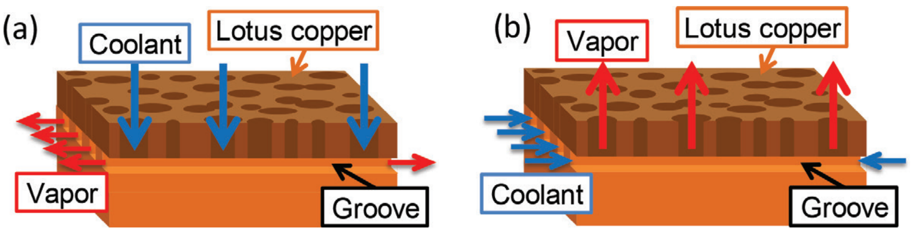


Figure 15.
Breathing phenomenon spontaneously induced by lotus copper on a grooved heat transfer surface ((a) mode-G, (b) mode-L).

This two-phase immersion cooling technique we usually call "Lotus' Breathing" offers the following features.

1. Spontaneous liquid supply phenomenon due to vapor blowout (Breathing Phenomenon)

2. No requirement of capillarity induced in the porous medium

3. Once-through type liquid supply and vapor discharge (**Figure 15**). Liquid supply and vapor discharge are separated and formation of coalesced bubbles is retarded.

4. Use of a unidirectional porous copper with high permeability and high thermal conductivity to enhance the breathing phenomenon and the heat transfer in the porous medium.

There are two possible breathing modes "Mode-G" and "Mode-L", as in **Figure 15(a)** and **(b)**, i.e., the Mode-G on the left in which the vapor is discharged from the groove and accordingly the liquid is supplied from the upper part of the porous medium as well as the inverse mode-L.

To demonstrate the increase in CHF by the breathing phenomenon, saturated pool boiling experiments have been conducted in an atmospheric pressure environment. For details of the experiment, please refer to Reference [15]. The Lotus copper plate (10 mm x 10 mm, thickness = 2 mm, porosity = 65.9%, and average pore diameter = 0.49 mm) is attached to a 10 mm × 10 mm heat transfer surface provided with 0.5 mm-square or 1.0 mm-square unidirectional grooves as a boiling heat transfer surface. The results for water and FC72 are shown in **Figure 16**. In the case of water, the critical heat flux for the smooth surface in this device is 1.4 MW/m^2,

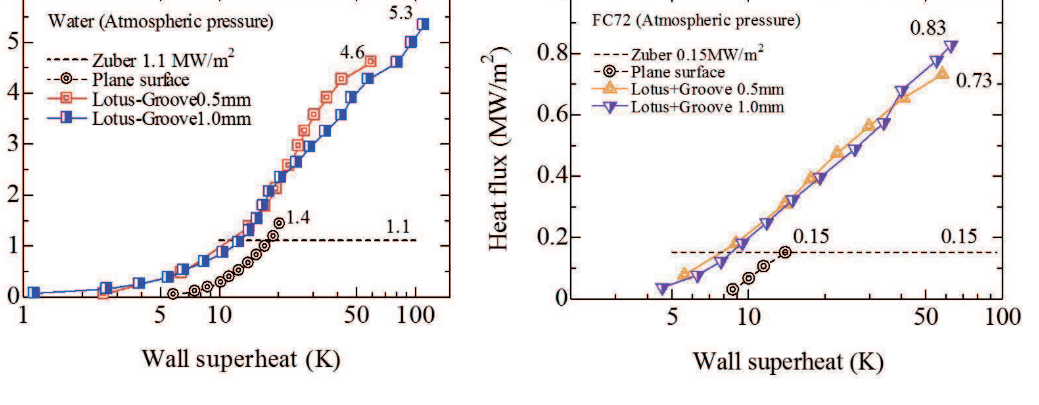


Figure 16.
CHF improvement by breathing phenomenon (left: Water, right: FC72).

which is an adequate value for a boiling heat transfer experiment using the heat transfer block. The results also verify that the critical heat flux when utilizing the lotus copper jointed on the grooved heat transfer surface considerably improves by providing wider grooves. The 0.5 mm-square groove achieves the critical heat flux of 4.6 MW/m^2 at the wall superheat of 58.9 K, and the one of 1.0 mm-square groove achieves the critical heat flux of 5.3 MW/m^2 at the wall superheat of 111 K, which indicates that the groove size is an important factor for improving the critical heat flux by the breathing phenomenon. The boiling heat transfer is also remarkably enhanced even if compared to that for the smooth surface; this technology has proven to achieve both the enhancement of the boiling heat transfer and the critical heat flux. By visualizing the boiling phenomenon shortly before the critical heat

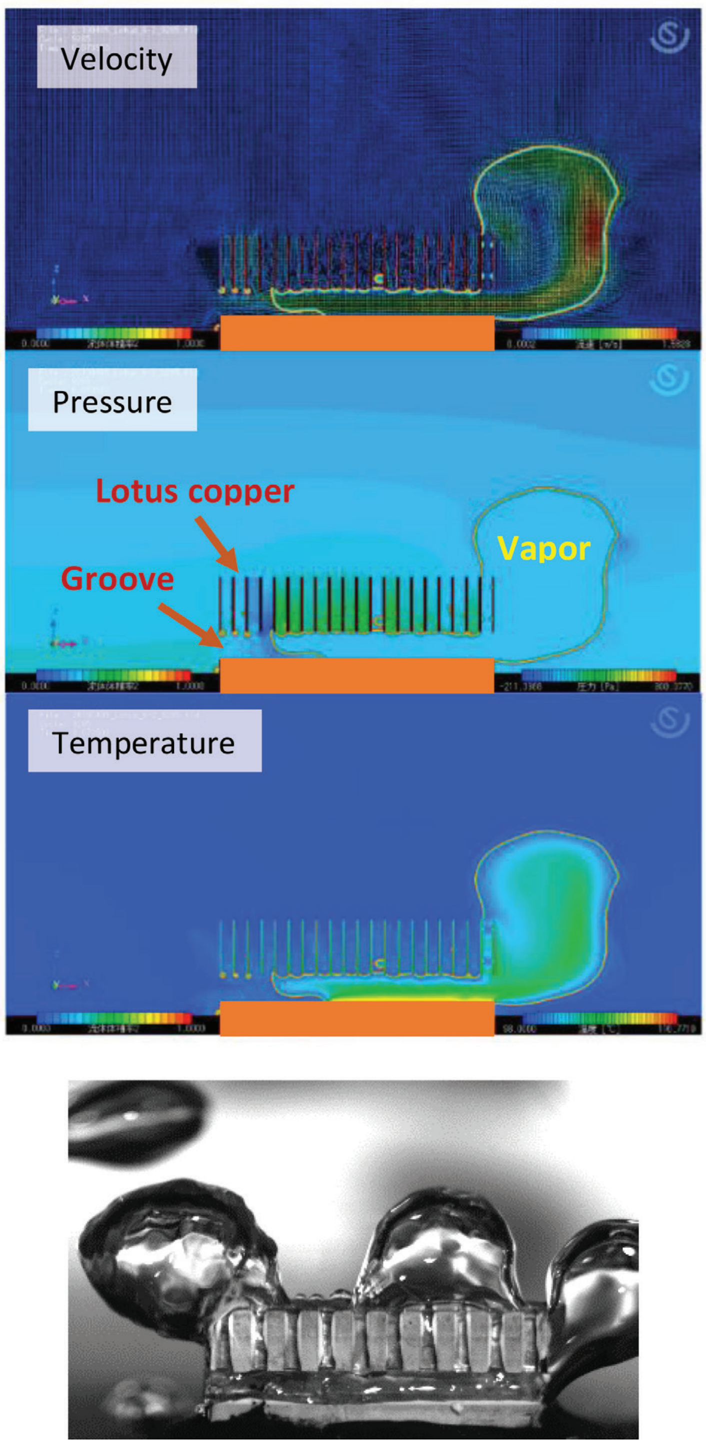


Figure 17.
Example of CFD simulation and visualization experiment of breathing phenomenon.

flux, a large amount of vapor is discharged from the grooves. Thus, the breathing phenomenon in these experiments conceivably corresponds to the Mode-G of **Figure 15(a)**. On the other hand, in the FC72 case, the maximum heat flux, which is not the critical heat flux, is 0.83 (MW/m^2) that is 5.5 times higher than CHF of the smooth surface. This result verifies that the breathing phenomenon can work for dielectric fluid and increases the critical heat flux.

Currently, the mechanism of critical heat flux enhancing and the factors that further entails the breathing phenomenon are being discussed based on the visualization experiment and CFD simulation as shown in **Figure 17**. In addition, the effects of varying the porosity, the pore size of the lotus copper, and the groove structure have been evaluated [55, 56].

4. Conclusion

In this chapter, the thermal conductivity and permeability of various porous media were quantitatively evaluated; as one of the porous media appropriate for high heat flux heat removal, targeted by the author, the introduction of "porous metal with unidirectional pores" was strongly suggested. Furthermore, as an application of using unidirectional porous coppers, we demonstrated the cooling performance of the flow boiling/evaporation cooling device EVAPORON-4, and that of the pool boiling enhancing technology "Lotus Cooler" based on "Breathing Phenomenon". From now onward, we intend to optimize the structure of the unidirectional porous media and the grooved heat transfer surface, thus aiming at improving and controlling the performance of these cooling technologies.

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