EFFECT OF POROUS COATING ON CONDENSATION HEAT TRANSFER

Ying Zheng, Chien-hua Chen, Howard Pearlman, Matt Flannery and Richard Bonner*
***Author for correspondence**
Advanced Cooling Technologies, Inc.
1046 New Holland Avenue
Lancaster, PA 17601, US
E-mail: Richard.Bonner@1-act.com

ABSTRACT

The effects of porous coating on both dropwise and filmwise condensation were studied. The hydrophobic surface was achieved by Self-Assembled Monolayer (SAM), a family of coatings that spontaneously form one molecular layer thick coatings on the surface. The porous surface was formed via sintered copper powder. Using a condensation heat transfer test apparatus developed at Advanced Cooling Technologies, Inc. (ACT), experiments were performed to evaluate the condensation heat transfer on samples having different surface treatments at temperatures range from 35 to 60^{o}C, a typical condensation temperature for power plant air-cooled condensers. The coating types evaluated included sintered powder porous surfaces with and without hydrophobic SAM coatings. A bare uncoated surface was served as a baseline. The experimental results showed: (1) porous coating can further improve the condensation heat transfer coefficient for dropwise condensation (surface with SAM coating), (2) porous coated surface exhibited a surprisingly high heat transfer coefficient for filmwise condensation mode (surface without a SAM coating). Droplet motion/ removal (desirable for enhanced condensation) by tailoring the surface properties via porous coating was observed and it can potentially be used to further improve the condensation heat transfer.

INTRODUCTION

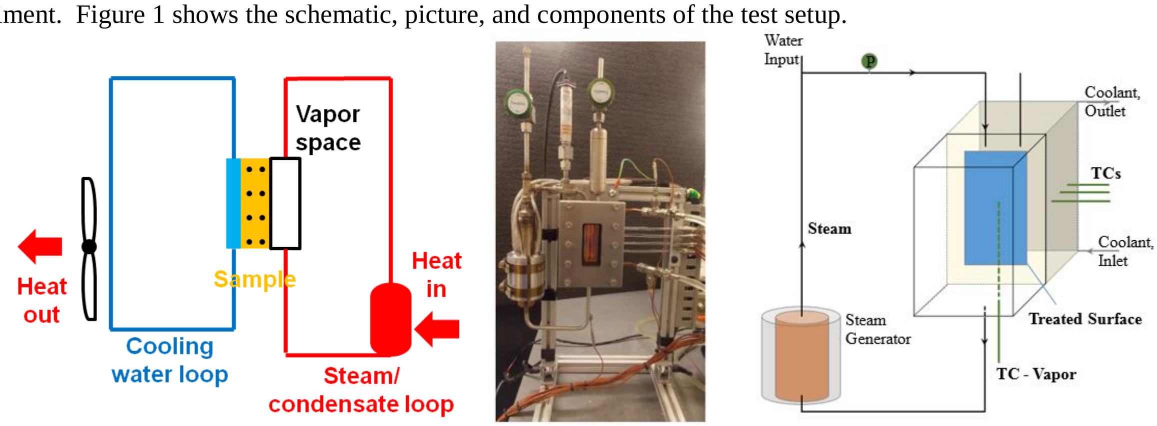
For the past 60 years dropwise condensation has been studied for its ability to produce heat transfer coefficients an order of magnitude higher than filmwise condensation (Collier et al. 1994). Dropwise condensation occurs on a surface when the surface energy of the condensing surface is low enough to inhibit wetting of the surface by the condensing fluid. On these so called "hydrophobic" (when the fluid is water) or "oleophobic" (when the fluid is a low surface tension oil or refrigerant) surfaces, the condensing fluid forms liquid droplets on the condensing surface. In filmwise condensation, the condensing fluid wets the relatively high surface energy condensing surfaces creating a thin continuous film of liquid (Bejan et al, 2003). On these so called "hydrophilic" surfaces, the heat transfer to the condensing surface is many times lower, as the continuous liquid film acts as an insulator. In dropwise condensation modes, the droplets coalescence process keep the droplet sizes small (compared to the film thickness in filmwise condensation) over the majority of the surface, creating regions of high heat transfer. Although portions of the dropwise condensation surface are covered by large droplets (much larger than the film thickness in filmwise condensation), the small droplets transfer the majority of the power at an overall lower thermal resistance since the smaller size droplets transfer heat in parallel with the large droplets. The ability of dropwise condensation to increase heat transfer coefficients over film condensation is well established. The continuing research in this topic is inspired by economic incentives attainable if the heat transfer coefficients of dropwise condensation can be sustained (Rohsenow et al, 1998). However, only recently have researchers been able to create surfaces which can maintain their properties and sustain the dropwise condensation mode over time (Ma et al, 2000). Failure of the low surface energy coatings ultimately causes filmwise condensation to occur since the exposed surfaces are generally high in surface energy. But many of these hydrophobic coating introduce additional thermal resistance due to the relatively thick coating layer, resulting minimum or no improvement on the overall condensation heat transfer.

Self-Assembled Monolayers (SAM) are a family of coatings that spontaneously form one molecular layer thick coatings. The chemicals used in preparation consist of short polymer chains with one of the terminal end groups having reactive properties capable of forming a chemical bond with a surface. The other end group is engineered to have a desirable surface property, such as low surface energy. The chemicals used in these types of surface preparations are typically polymer chains approximately 8-20 molecules long (Deniel, 2001). On one side of the polymer chain is a reactive functional group, capable of forming a chemical bond with a surface. In all of this research a thiol (-SH) functional group capable of creating a chemical bond with copper was used, although other materials such as gold and silver can be coated with thiols. Other end groups are also available to bond to other materials, with silicon and silane being one of the more popular tandems. It should be pointed out that the “coating” used in this process is more than just paint, as the chemical bond between the molecule and the metal surface is of a permanent nature. Since only one of the functional groups on the polymer chains reacts with the surface while the other functional group is non-reactive, the molecules tend to self-assemble on the surface, creating a layer of molecules that is one layer thick. The result is a surface which is chemically altered possessing only the surface properties of the functional end group of the molecule. In the dropwise condensation research, low surface energy surfaces are desired. Surfaces with low energy are considered hydrophobic or non-wetting, which is required to from droplets. The functional groups used are typically $-CH_3$ or $-CF_3$ groups which tend to have the low surface energy desired (Das et al, 2000 (1), Das et al 2000(2)).

The hydrophobicity can be further increased by changing the surface texture (e.g. lotus effect). One simple method to create different surface texture is via sintered copper power. This method also potentially provides the flexibility on “turning” the surface wettability and therefore create wettability gradient to further help the droplet moving and increase the condensation heat transfer. In previous work Lehigh and ACT have demonstrated the beneficial effects of using gradient in wettability to enhance dropwise condensation on polished surfaces (Bonner, 2013). In this work, the wettability gradient will be created by varying the density of the powder particles on the surface. By moving droplets more efficiently, the maximum droplet size will be reduced. Reducing the size of droplets on the surface reduced the liquid film thickness causing an increase in heat transfer. In addition to the effect on the dropwise condensation, the surface texture change by porous coating and its effect on the filmwise condensation is also investigated and the result shows surprising high heat transfer improvement, which is likely due to increased surface area.

EXPERIMENTAL TEST SETUP

A test apparatus was designed and fabricated to determine the condensation heat transfer coefficient (H) on various prepared surfaces. The test facility consists of a boiling section and a condensation section. In the boiling section, a stainless-steel boiling chamber continuously supplies saturated steam formed by continuous heating by embedded cartridge heaters. The steam flow rate and steam temperature is controlled by varying the power inputs to the heaters, and the prepared surface was tested with vapor temperatures from ~ 35°C to 60°C, covering the temperature range representative of vapor/ steam in industrial air cooled condensers. In the condensation section, a cooling loop was used to recirculate cold water between the base of the prepared surface and a large reservoir used to transfer heat out of the system (sink). The condensation surface tested was 1.5 cm wide and 5 cm high. The condensation surface was visualized with a glass window in the front of the test section. The test section was under vacuum at the beginning of every test to remove non-condensable gas and maintain a gas-tight seal during the experiment. Figure 1 shows the schematic, picture, and components of the test setup.



(A) (B)

Figure 1 (A) Schematic of test loop. (B) Picture and components of the test facility for measurement of heat transfer performance on condensation with various applied coatings.

In a typical experiment, the test facility was initially evacuated and then charged with 30 mL of water from the water supply port. Water steam was then produced with cartridge heaters in the boiling chamber. The steam was then condensed on the prepared surfaces in the condensation test section. The temperature of the vapor was obtained with a thermocouple placed at the midpoint of test section’s vapor space. Twelve thermocouples were placed in various locations inside the condenser block, as shown in Figure 2 to measure the temperature variations from the inside condensation surface to the outside cooling water surface. The average of four thermocouples was used to represent the average temperature at each lateral location. The heat transfer coefficient was experimental determined according to Fourier's law as described by Eqn 5-1 to 5-3, where the heat flux is determined by the measured temperature gradient inside the copper material, and the surface temperature on the condensation surface was extrapolated with these temperature measurements. Meanwhile, the vapor pressure was measured to ensure saturation conditions. All the measurements were collected by a data acquisition system.

$$q" = k\frac{dT}{dx} \qquad \text{Eqn 5-1}$$

$$q" = H(T_{vapor} - T_{wall}) \qquad \text{Eqn 5-2}$$

$$H = k\frac{dT}{dx}/(T_{vapor} - T_{wall}) \qquad \text{Eqn 5-3}$$

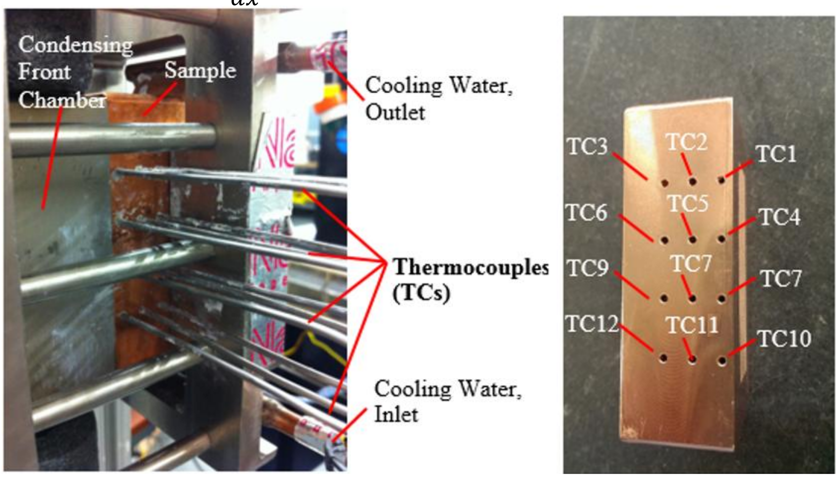


Figure 2 Thermocouples arrangements in the test facility for determination of heat transfer coefficient on condensation. Thermal grease was used to minimize the thermal resistance of the interface.

Several test articles were fabricated in this project and their surface were prepared for condensation in different modes, i.e. filmwise and dropwise. These test articles were tabulated and classified in Table 1.

Table 1 Test articles with different condensation modes

	Test Articles
Control Experiment (Baseline)	Copper Bare Surface
Dropwise	SAM Coating on Copper Bare Surface
	SAM Coating on Copper Powder* Monolayer
	SAM Coating on Graded Copper Powder
	SAM Coating on Striped Copper Powder
	NeverWet Commercial Coating
Filmwise	Copper Powder (250 um) Monolayer
	Copper Powder (63 um) Monolayer
	Copper Powder Monolayer Pretreated by H_2O_2
	Copper Powder Multilayer

*: copper powder size is 250 um in all articles that it is applied unless indicated as other.

The first test article, a bare copper surface, was prepared to exhibit a hydrophilic filmwise condensation which served as the baseline for validation of the test apparatus. Filmwise condensation was selected as a baseline for this characterization and the analytical solution for the filmwise condensation heat transfer coefficient, known as the Nusselt Equation, was used for comparison and validation. For this baseline test sample, the copper surface was carefully polished to remove any impurities/ oxide layer. A new oxidation layer did however develop as the sample was exposed to the environment, which appeared as a brown color in contrast to the reddish-orange freshly polished surface. In addition, oil residue from the polishing tools and/or from handing were removed using acetone to avoid any change in the hydrophilic nature of the polished surface. Before inserting the test piece into the test facility, the surface hydrophilicity was visually verified by placing a droplet of water on the surface to observe the wettability.The second condensing surface was a copper surface with non-wetting SAM coated surface. Here, the non-wetting surface was completely covered with a hydrophobic self-assembled monolayer, providing a surface with maximum hydrophobicity to promote dropwise condensation. The copper surface was first polished smooth then cleaned by acetone. The sample was then blown dry and submersed in a very dilute solution of heptadecafluorodecanethiol ($CF_3(CF_2)_7CH_2CH_2SH$) + isopropanol (0.1mL : 20mL). The sulfhydryl functional group –SH reacts and creates a chemical bond with the copper surface, while the trifluoromethyl group $–CF_3$ has a desired low surface energy to promote hydrophobicity on the copper surface. Since \ only one of the functional groups (that is –SH) on the polymer chain reacts with the copper metal surface, the molecules tend to self-assemble on the surface, creating a layer of molecules that is one layer thick. The copper sample was immersed in this solution for 2 days, which is long enough for the molecules to assemble on the surface and ensure its long-term stability. A photograph of a water droplet on the surface with SAM coating is shown in Figure 3 (2) with the case for bare surface as a comparison on the right-hand side of the figure. It can be seen that the water droplet on the SAM coated surface has a very large contact angle, about 110°, which indicates the hydrophobic non-wetting features of the surface. In contrast, the bare surface is hydrophilic as demonstrated with by a water droplet spreading over the surface Figure 3 (1). The third coating was a SAM coating on a copper power monolayer. This idea originates from the 'lotus effect', in which a rough hydrophobic surface turns out to be "superhydrophobic." To generate such an effect and evaluate its benefit on dropwise condensation, copper powder (250 micron particle size) was sintered to a smooth copper surface to create a roughened surface, then the SAM coating was applied to the copper powder monolayer to create a super-hydrophobic surface. In this case, the water droplets have an even larger contact angle. In the preparation of this sample, the copper surface was first polished then cleaned with acetone. Copper powder was placed on the surface and then sintered at 900°C. Before then being immersed in a SAM chemical solution, the copper sample was cleaned in the hydrogen environment to remove the oxidization layer formed in the sintering process.

The use of the SAM coating to create a hydrophobic surface raises some additional questions. The first question is how to remove the condensed droplets more quickly, and how the droplet removal rate affects the condensation heat transfer coefficient. In dropwise condensation, the faster the condensed droplets can be removed, more of the surface would be exposed to vapor for condensation and the heat transfer coefficient can be increased. For completeness, ACT and Lehigh have shown that a gradient in wettability can enhance dropwise condensation by providing a driving force for the droplet motion. The second question is what is the effect of the thickness of the copper powder layer? The copper powder layer between the SAM coating and bare condensation surface creates a thermal resistance for the heat transfer to the inside surface. The thickness of the copper powder layer can be controlled in two ways – controlling the powder size or the numbers of layers. For the monolayer, the thermal resistance would be smaller for smaller size particles. However, with smaller size particles, condensation on the surface is accompanied by a smaller contact angle and less wettability. Therefore, there is an optimum particle size for the enhancement of condensation. The following two paragraphs describe the experimental methods and sample preparation for evaluating the effects of droplet removal and thickness of the copper powder layer, respectively. In order to evaluate the effects of droplet removal rate on the condensation heat transfer coefficient, a sample was prepared having a graded copper powder layer, as shown in Figure 3 (3). The copper powder layer is thinner (less dense) in the upstream, and thicker (more dense) in the downstream, to create a surface with locally varying wettability. In the thinner layer, the contact angle of the water droplets is larger, while in the location with thicker layer, the contact angle is smaller. Another method to create a large wettability gradient is to have a striped copper powder surface with SAM coating as shown in Figure 3 (4). Since the copper powder surface has higher contact angle than bare surface, droplets will move from the porous surface to bare surface and accelerate the droplet washed out rate. In the experiment, it has been shown that the droplets were easily and quickly swept away at almost the same elevation where they formed, instead of traveling all to lower region before removal in traditional dropwise condensation. In preparation of this sample, tape was placed at discrete distances along the sample at which time the copper powder was placed and sintered in the unmasked areas and further SAM coated to create the stripes.

To evaluate the effects of the thickness of copper powder layer, samples were prepared with different number of layers and various sizes of the powder on the bare surface. These samples were prepared with the copper powder sintered on the surface without further SAM coating. Two copper powder sizes, 250 um and 63 um were chosen since they were available in our laboratory. The surface with larger powder size showed a higher heat transfer coefficient in our current test, encouraging us to evaluate the effect of the number of layers. As such, samples with multiple layers were prepared with 250 micron size particles evenly spaced over the surface.

Copper is very easily oxidized and always covered by a thin oxidization layer. For select samples with copper powder monolayer, they were further chemically treated by placing them in a hydrogen peroxide (H_2O_2) solution for one hour in order to ensure the copper was fully oxidized (i.e., create a controlled oxidization layer). These samples were also subject to long-term testing. As shown in Figure 3 (5), the color of the powder layer changed to amber after being treated with H_2O_2.

For comparison, a commercially available coating called "NeverWet" was also tested and applied directly on a copper surface, as shown in Figure 3. It was seen that the surface is quite hydrophobic, as seen in the large contact angle of the water drops. This sample was prepared in order to compare the performances of a commercially available hydrophobic coating and SAM coated samples. The test results are discussed in detail later.

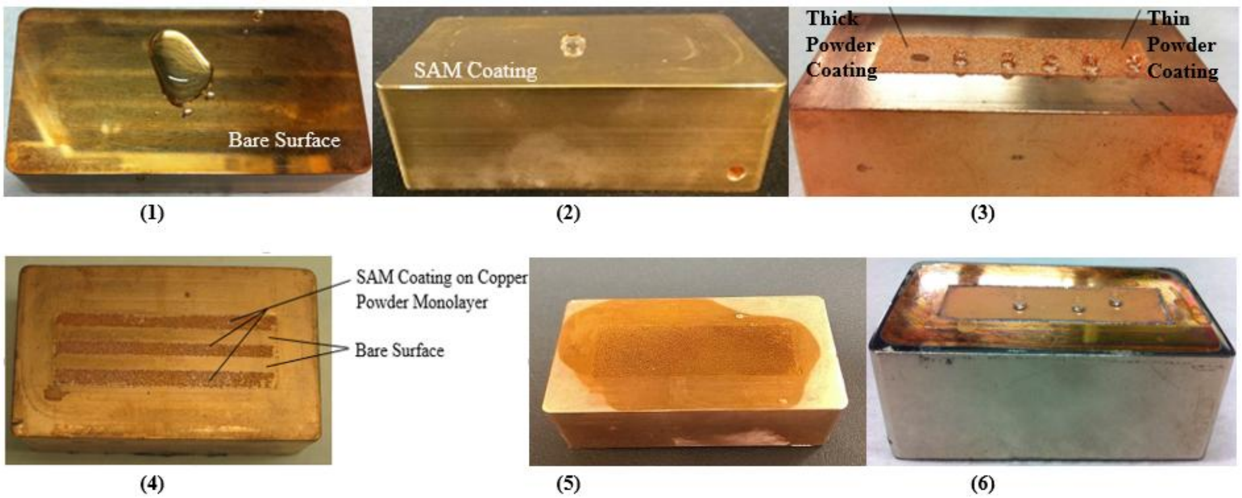


Figure 3 Picutres of test articles. (1): water droplet on the bare surface (baseline); (2): water droplet on treated surface with SAM; (3): copper surface with SAM coating on graduated copper powder layer; (4): surface with stripe copper powder coating; (5): surface with copper powder monolayer was pretreated by H_2O_2; (6) water droplets on surface coated with NeverWet coating.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The copper bare surface was prepared as descried previously and assembled in the test facility to measure the heat transfer coefficient of the condensation of baseline. The experiment was run at different vapor temperatures with various power inputs for the boiling chamber, and the results are shown in Figure 4. It is seen that when the power input varied from 50 W to 250 W, the vapor temperature changed from ~ 34°C to 61.3°C. The measured heat transfer coefficient is in the range of 6500 - 8400 $W/m^2{\cdot}°C$ for the copper bare surface. With the measured vapor temperatures and extrapolated surface temperature at the condensation surface, heat transfer coefficient can be estimated based on Nusselt Equation, and shown in dash line with blue squares in the figure. It is seen that the experimental results of the heat transfer coefficient (H) were well predicted, which demonstrated the validation of the measurements facility in the current test facility.

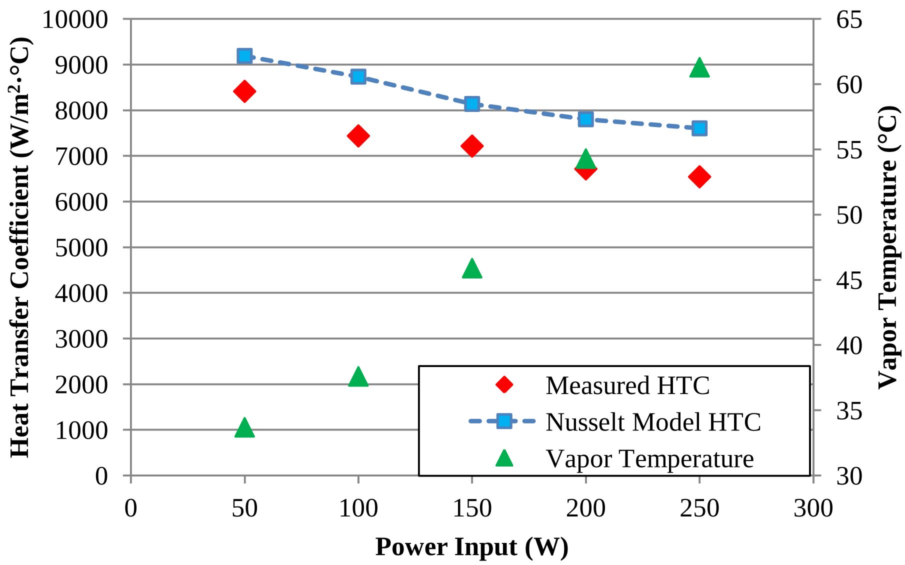


Figure 4 Heat transfer coefficients and vapor temperatures in testing copper bare surface.

There are four samples with SAM coating (dropwise condensation mode) as descried previously – SAM coating on copper bare surface, SAM coating on copper powder monolayer, SAM coating on graded copper powder layer and SAM coating on striped copper powder monolayer. Each of the sample was immersed in the SAM chemical solution for two days before experiment, then assembled in the test section for testing the condensation performance on its surface at various vapor temperatures. Figure 5 shows the experimental results for the four samples with SAM coatings, as well as the testing results of NeverWet commercial coating and results of baseline as a comparison. It is seen that the hydrophobic surfaces with SAM coating have a more than 5 times higher heat transfer coefficient compared with the case of the bare copper surface. At 200 W power input and vapor temperature ~ 55°C as shown in Figure 5, the heat transfer coefficient can be increased to ~ 45,000 – 50,000 W/m^2·°C from the baseline 7000 W/m^2·°C, which is promising to reduce the overall cost of the ACC by more than 10% based on cost analysis (Bonner et al 2014).

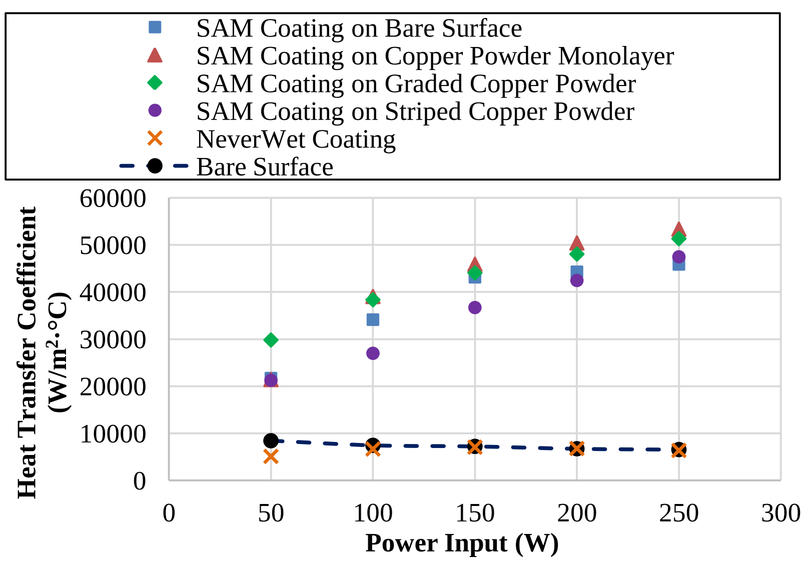


Figure 5 Measurements of heat transfer coefficient on hydrophobic surfaces.

Among the cases with SAM coating, SAM coating on copper powder monolayer seems to have the best heat transfer performance in condensation, with about another 20% enhancement in H compared with the case of SAM coating on bare surface. It seems that the 'lotus effect' has contributed to the condensation significantly after offsetting the thermal resistant across the copper powder monolayer. With various wettability along the condensation surface, graded copper powder provided an extra driving force for the condensation droplet, and it is seen that it enhanced the H significantly as well, with almost similar performance as the case of SAM coating on copper powder monolayer. For the surface with SAM coating on the striped copper powder monolayer, it has an improved, approximately five times, H compared with bare surface. But compared with SAM coating on bare surface, its H did not improve further, which indicate there might not be too much advantages to make this specific pattern. However, for other case with expensive coating materials, such as gold, this method can be a solution to reduce the expense in coating while maintaining similar heat transfer coefficient in condensation.

For the surface with NeverWet coating, although the surface is very hydrophobic as shown previously in Figure 3 (6), due to the thicker layer of the coating, the heat transfer coefficient seems to quite low, with only 5000 – 6500 $W/m^2{\cdot}°C$ in our current testing range. It is even worse than the baseline, which might due to large thermal resistance across the coating materials, which canceled out the benefits with dropwise condensation on the surface.

The droplet moving due to wettability gradient created by the sintered porous coating has been observed on the sample with striped copper powder monolayer with SAM. While the wettability gradient accelerates the droplet removed from the striped powder surface as shown in the **Figure 6**, the overall heat transfer coefficient seems not increased compared to uniform powder surface. This is probably because the bare surface part of the striped powder surface has lower H compared to powder surface and therefore the improvement of H due to higher H in the striped powder surface was canceled by the lower H bare surface. Further optimize of the striped geometry will be able to further improve the overall H.

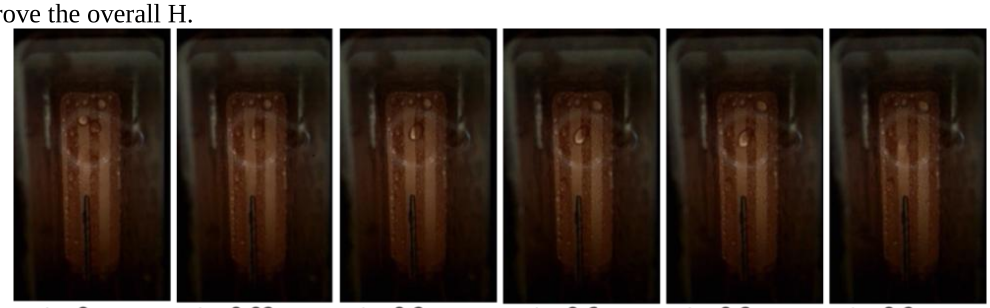


Figure 6 Droplet moving due to wettability gradient created by the sintered powder.

The effect of porous coating on hydrophilic surface is shown in Figure 7. Four samples were prepared, copper powder monolayer with 250 um powder size, copper powder monolayer with 63 um powder size, multi-layer copper powder, and copper power monolayer pretreated by H_2O_2. It is seen that surface with copper powder layer has a higher heat transfer coefficient compared with the case of bare surface. The surface coated by 250 um copper powder monolayer enhanced the condensation with more than twice higher H, about 20,000 $W/m^2{\cdot}°C$ in the current tests. For surface coated with finer copper powder, of which the powder size is about 63 um, the heat transfer coefficient is about 10,000 $W/m^2{\cdot}°C$, still higher than baseline, however, it is not as good as the coarse one.

For the surface sintered with same powder size 250 um, multi-layer copper powder shows about 13,000 $W/m^2{\cdot}°C$ heat transfer coefficient in the condensation, while the monolayer case shows approximately 54% higher value. This might due to the increasing thermal resistance when placing multiple layers of copper powder. When the copper powder monolayer surface was pretreated by H_2O_2 to have a controlled oxidization layer before testing, the measured H was about 21,000 $W/m^2{\cdot}°C$, slightly higher than the case without this treatment. This result might indicates the viability of the copper powder layer in long-term testing considering in continuous running, the coating would be severely oxidized. The reason of porous coated surface improves the filmwise condensation heat transfer has been discussed (Renken eta al 1989, Renken eta al 1993(1), Renken eta al 1993(2), Renken eta al 1994, Renken eta al 1996). The theoretical analysis shows that under certain permeability condition, the porous surface does not increase the overall liquid film thickness but improve the effective conductivity of the film due to the porous structure serves as thermal vias that reduce the thermal resistance.

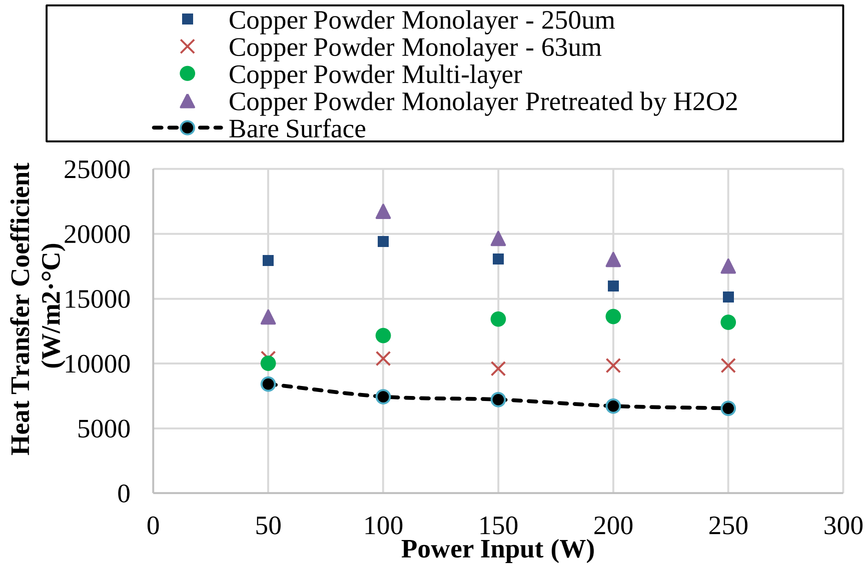


Figure 7 Measurements of heat transfer coefficient on hydrophilic surfaces with copper powder.

CONCLUSIONS

Porous coating can be used to adjust surface physical properties and therefore improve the transport phenomena. Many researches have focus on its effect on enhancing boiling heat transfer but little discussion can be found on the condensation side. In this work, the effect of porous coating on condensation heat transfer is studied in both hydrophobic and hydrophilic surfaces. The hydrophobic surface is achieved by applying an ultra-thin Self Assembled Monolayer (SAM) coating that is able to minimize the additional thermal resistance introduced by the coating layer. The hydrophobic surface enables the condensation in the dropwise mode to significantly improve heat transfer coefficient over filmwise mode. On the bare surface condition, the experimental result shows about 5 times heat transfer improvement when applying the SAM coating at vapor temperature around 50°C. On the porous coated surface condition, additional 20% improvement of heat transfer coefficient is achieved under the same heat flux or vapor temperature conditions. This is because the porous coated surface amplifies the hydrophobicity and increases the contact angle hysteresis. The use of porous coating to adjust contact angle gradient to further improve the condensation heat transfer is also discussed. While the porous coating is able to enhance the dropwise condensation, our experimental results also show that without SAM coating, it can still improve the condensation heat transfer more than twice (sample surface was pre-treated with H_2O_2 to ensure it is hydrophilic). This is probably because the porous surface reduces the thermal resistance of the liquid film without affecting much on its thickness. In summary, though physical mechanism is different, the porous coating can be used to improve the condensation on both hydrophobic and hydrophilic surfaces. With SAM coating on porous coated surface, significant heat transfer improvement can be achieved in dropwise mode. Without SAM coating, the porous coated surface can still double the heat transfer coefficient in filmwise mode. The robustness of the porous coating provides durable solution for further improvement in condensation heat transfer.

NOMENCLATURE

H heat transfer coefficient, $W/m^2 \cdot °C$
k thermal conductivity, W/m·°C
q'' heat flux, W/m^2
SAM Self-Assembled Monolayer
T temperature, °C
x location, m

REFERENCES

Bejan, A., Kraus, A.D., 2003. Heat Transfer Handbook. NJ : John Wiley & Sons.

Bonner, R., 2013. Advances in heat transfer through coatings and micro-scale features. PhD Dissertation, Lehigh University.

Bonner, R., Chen, C.H. and Zheng, Y., 2014. Enhanced dropwsie condensation for improved dry cooling efficiency. DOE SBIR Phase I Final Report, Award No. DE-SC0011317.

Collier, J.G. Thome, J.R., 1994. Convective Boiling and Condensation,. NY : Oxford University Press.

Das, A. K., Kilty, H .P., et al., 2000. Dropwise condensation of steam on horizontal corrugated tubes using an organic self-assembled monolayer coating. J. Enhanc. Heat Transf. 7(2), 109−123. doi: 10.1615/JEnhHeatTransf.v7.i2.40

Das, A. K., Kilty, H. P., Marto, P. J., et al., 2000. The use of an organic self-assembled monolayer coating to promote dropwise condensation of steam on horizontal tubes. J. Heat Transf. 122(2), 278−286. doi:10.1115/1.521465

Daniel, S., Chaudhury, M.K., Chen, J.C., 2001. Fast drop movements resulting from the phase change on a gradient surface. Science 291(5504), 633-636. doi: 10.1126/science.291.5504.633

Ma, X., Rose, J.R., Xu, D., Lin, J., Wang, B., 2000. Advanced in dropwise condensation heat transfer: Chinese research. Chem. Eng. J. 78, 87-93. doi:10.1016/S1385-8947(00)00155-8

Renken, K. J., Soltykiewicz, D. J. and Poulikakos, D., 1989. A study of laminar film condensation on a vertical surface with a porous coating. Int. Commun. Heat Mass 16 (2), 181-192. doi:10.1016/0735-1933(89)90019-5

Renken, K. J. and Aboye, M., 1993. Analysis of film condensation within inclined thin porous-layer coated surfaces. Int. J. Heat Fluid Fl. 14 (1), 48-53. doi:10.1016/0142-727X(93)90039-P

Renken, K. J. and Mueller, C. D., 1993. Measurement of enhanced film condensation utilizing a porous metallic coating. J. Thermophys. Heat Tr. 7 (1), 148-152. doi: 10.2514/3.11582

Renken, K. J., Carneiro, M. J. and Meechan, K., 1994. Analysis of laminar forced convection condensation within thin porous coatings. J. Thermophys. Heat Transfer 8 (2), 303-308. doi: 10.2514/3.538

Renken, K. J. and Raich, M. R., 1996. Forced convection steam condensation experiments within thin porous coatings. Int. J. Heat Mass 39 (14), 2937-2945. doi:10.1016/0017-9310(95)00367-3

Rohsenow, W.M. , Hartnett, J.P. and Cho, Y.I., 1998. Handbook of Heat Transfer. NY : McGraw-Hill.