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ENHANCED FILMWISE CONDENSATION WITH THIN POROUS COATING

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ABSTRACT

Condensation heat transfer has been extensively investigated since Nusselt first established the theory of filmwise condensation on planar and horizontal cylindrical surfaces. Recent research into the enhancement of the phase-change heat transfer has been greatly stimulated by economic incentives attainable if the heat transfer coefficient can be increased. Research conducted at Advanced Cooling Technologies, Inc. (ACT) has successfully demonstrated condensation heat transfer improvement techniques for filmwise condensation. It has been found that surfaces coated with monolayers of sintered metallic powder can significantly enhance the heat transfer in filmwise condensation by more than two times. The extent of the heat transfer improvement is strongly related with the size of the metal powder. Presented here are experimental data on condensing surfaces with different diameters of sintered powder. The heat transfer enhancement with a specific size of sintered powder is compared to a baseline plain surface under different steam temperatures. The current work provides a preliminary experimental investigation of the effect of sintered powder size on the condensation heat transfer enhancement. Exploration of heat transfer mechanism for the surface with sintered powder, will be suggested upon current work for prediction and optimization of condensation heat transfer improvement when applied in different areas.

KEYWORDS: Filmwise condensation, porous coating, sintered metallic power coating, steam condensation, condensation heat transfer

1. INTRODUCTION

Condensation in a porous medium has been receiving increased attentions in the phase-change heat transfer areas. Research into the in-depth understanding of the condensing phenomenon has been stimulated by continuing interests from industries and governments. For condensation in the porous layers, it has been widely used and investigated in heat pipes, in which porous wicks are mainly used to transport the condensate from the condensing section back to the evaporator, for a continuous heat extraction from the heat source [1]. While the majority of studies using thin porous coating to augment heat transfer have been devoted to evaporation [2,3,4], a few researches and development effects have pioneered the use of porous coating on improvement of condensation heat transfer [5,6,7]. Several reports have been focused on foametal metallic coating, such as foametal copper porous coating on copper surface to enhance the steam condensation [5]. It has been reported that a conductive porous coating may yield a considerable heat transfer enhancement during film condensation, in which the porous coating was screwed and welded onto the substrate [5]. The challenges in applying such foametal coating will lie in the engineering control of coating properties, including thickness, porosity and permeability.

Following those investigations, ACT leverages its sintering experience and creates a monolayer metallic porous coating on plain surface. Since the coating is monolayer, the thickness of the coating can be easily tuned by choosing different diameters of metallic powder. To investigate the heat transfer enhancement in condensation with the sintered porous coating, a test apparatus is designed, build and calibrated to measure

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the heat transfer coefficient on the coated condensing surface. Surface with various sizes of sintered powder size is tested in the facility. The heat transfer improvement for a specific size of sintered powder is compared to a baseline plain surface under different steam temperatures.

2. EXPERIMENT AND RESULTS

3.1 Test Apparatus and Measurement of Heat Transfer Coefficient

A test apparatus is designed and fabricated to determine the condensation heat transfer coefficient on surface with sintered metallic powder, as shown in Fig. 1. The two key components of the test apparatus are the boiling section and condensation section. In the boiling section, a stainless-steel boiling chamber continuously supplies saturated steam with surrounded cartridge heaters. The steam flow rate and steam temperature are controlled by varying the power inputs to the heaters. In current experiments, the vapor temperature is in the range of ~ 35 °C to ~ 70 °C, for applications of low-grade steam condensation, such as the vapor/steam in industrial air cooled condenser after turbine. In the condensation section, a cooling loop circulates cold water in and out of a cold plate, which is attached to the back of prepared sample, to continuously extract the heat out of the steam in the front-side of the prepared sample (that is, surface with sintered powder). The tested condensing surface is planar, with 1.5 cm width and 5 cm height, exposed to the steam in the test loop. A glass window is assembled in the front of the test section for visualization of the condensation process. The test section is vacuumed before each test and maintained a gas-tight seal during the experiment.

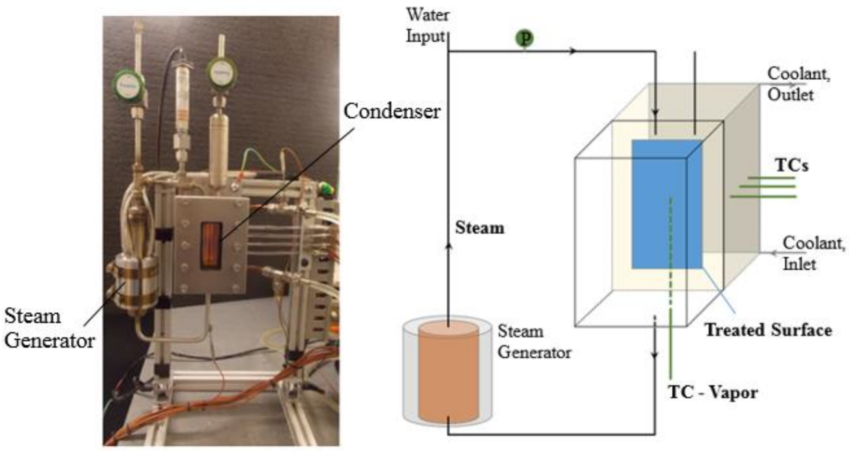

Fig. 1 Test appratus for measurement of heat transfer performance on condensing surface.

In a typical experiment, the test facility is evacuated first and then charged with 30 mL of water from the water supply port. With heat inputs to the boiling chamber, the steam is generated in the boiling section, flows to the condensation section, then condenses on the tested surface. During the experiment, the temperature of the vapor is measured with a thermocouple placed at the midpoint of test section's vapor space. Twelve thermocouples are placed in various locations inside the condenser block, as shown in Fig. 2 to measure the temperature variations from the inside condensation surface to the outside cooling water surface. The average temperature at each lateral location is calculated by averaging the corresponding four temperature measurements in axial direction. The heat transfer coefficient is experimentally determined according to Fourier's law as described by Eqn. (1) and Eqn. (2), in which the heat flux is determined by the temperature gradient across the sample block, and the average temperature on the condensing surface is calculated by extrapolating the temperatures along the lateral direction. All of the experimental measurements are recorded by a data acquisition system.

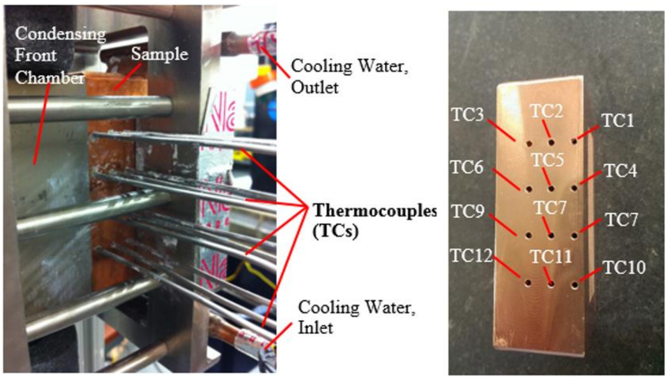

Fig. 2 Thermocouples arrangements in the test appratus for determination of heat transfe coefficient on condensation.

$$q^{"} = k\frac{dT}{dx} \tag{1}$$

and

$$HTC = \frac{q^{"}}{(T_{vapor} - T_{surf})} \tag{2}$$

3.2 Experiment Results and Discussions

To validate the measurement methodology in current test apparatus, a plain copper surface is assembled in the test facility to measure the heat transfer coefficient. The plain sample is polished first by fine sand paper to have a mirror-like surface, then cleaned with acetone to get rid of oil and dirt. The experimental results are shown in Fig. 3 for the plain surface testing with different vapor temperatures (by varying the power inputs in the boiling section). It is seen that when the power input varies from 50 W to 250 W, the vapor temperature changed from ~ 34°C to 61°C. The measured heat transfer coefficient is then calculated as descried previously in Eqn. (1) and Eqn. (2). It is seen that the heat transfer coefficient is in the range of 6500 - 8400 W/m^2·°C for the copper bare surface. Meanwhile, with the measured temperatures, the theoretical heat transfer coefficient can be calculated based on Nusselt Equation [8], and shown in dash line with blue squares in Fig. 3. It is seen that the measured heat transfer coefficient agrees nearly perfectly with predicted values, which validates the test facility in measuring heat transfer performance on the condensing surface.

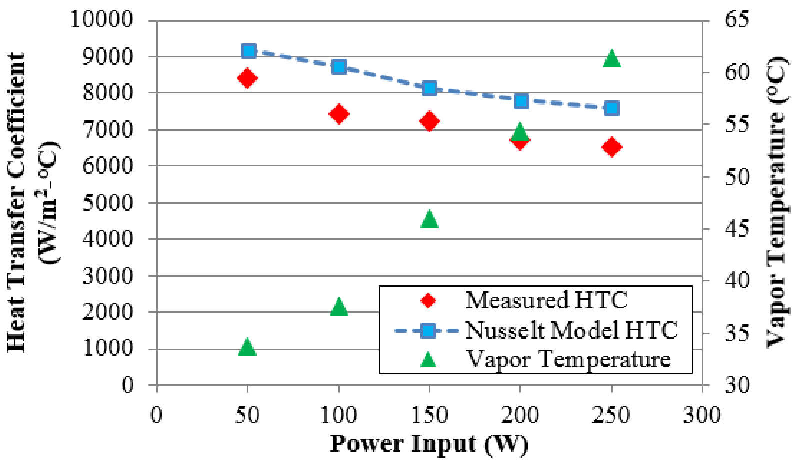

Fig. 3 Heat transfer coefficients on the plain copper bare surface.

After the validation tests, copper samples are prepared with various sizes of the powder sintered on the bare copper surface, to evaluate its heat transfer enhancement in filmwise condensation. In current research, two power sizes, 250 µm and 63 µm are chosen to be sintered on plain copper surface. The measured heat transfer coefficients are shown in Fig. 4, for the condensing surface with sintered copper powder. It is seen that compared with plain surface, surface with sintered copper powder layer has a higher heat transfer coefficient in condensing steam. For the surface with sintered 250 µm copper powder, the condensation heat transfer is enhanced by more than twice, with an approximately 20,000 $W/m^2{\cdot}°C$ for the heat transfer coefficient. For surface coated with finer copper powder, 63 µm , the heat transfer is also improved compared to the plain surface, however, the heat transfer coefficient is about 10,000 $W/m^2{\cdot}°C$, lower than the surface with 250 µm coarse powder. This suggests that surface with sintered porous coating would enhance the heat transfer of filmwise condensation significantly. With a certain thickness, the sintered metallic coating would reduce the overall thermal resistance from the vapor to condensing surface. However, further exploration of the mechanism for heat transfer enhancement with the sintered monolayer metallic coating, which relates the heat transfer enhancement to the coating properties, such as diameter of the powder size, will be beneficial in prediction and optimization of heat transfer improvement.

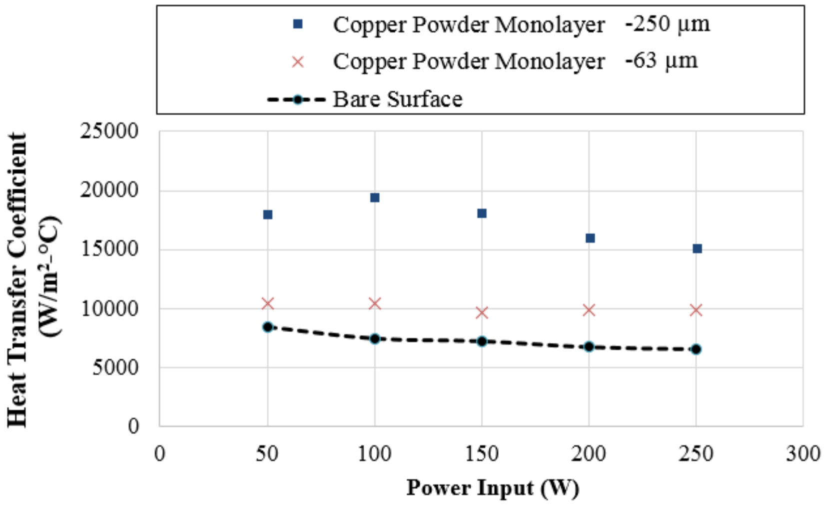

Fig. 4 Measurements of heat transfer coefficient on hydrophilic surfaces with copper powder.

3. CONCLUSIONS

Porous coating can be used to adjust surface physical properties and therefore improves 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, a unique and cost-effective way is presented to create a monolayer of porous coating by sintering the metallic powder on the substrate. A test apparatus is designed and build to measure the enhanced heat transfer for the steam condensation on the surface with sintered powder. The test facility is first tested with plain bare surface, and the instrumentation and measurement methodology is successfully validated with the excellent agreement between the measured heat transfer coefficient and its predicted value based on Nusselt model for bare surface. Then two powder sizes, 250 µm and 63 µm are chosen to be sintered on the copper surface to investigate the heat transfer enhancement, as well as the effect of powder size on the extent of condension heat transfer improvement. Through experimental investigation, the surface with 63 µm shows an approximately 20% increase in heat transfer enhancement on filmwise condensation compared to plain surface. And the surface with 250 µm shows a significant more than twice heat transfer performance. Further work will be suggested to explore the mechanism for such condensing surface with sintered metallic powder, for prediction and optimization of condensation heat transfer improvement in various applications.

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NOMENCLATURE

HTC	heat transfer coefficient	(W/m^2-°C)	T_{surf}	surface temperature	(°C)
k	thermal conductivity	(W/m-°C)	T_{vapor}	vapor temperature	(°C)
q''	heat flux on condensing surface	(W/m^2)	*x*	lateral direction	(m)
T	temperature of sample	(°C)			

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