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Review Paper

A review of high heat transfer coatings in steam power plant condensers

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1. ABSTRACT
Condensation occurs in most heat transfer processes, from cooling electronic devices to heat removal in power plants. The overall heat transfer coefficient of dropwise condensation (DWC) is several times higher than that of filmwise condensation (FWC). Therefore, obtaining a stable DWC is very important for better performance. DWC stability depends on surface hydrophobicity, surface free energy, and surface tension of the condensed liquid. The properties required for DWC may be achieved by micro-scale surface modification. In this review, micro/nanoscale coatings such as noble metals, ion implantation, rare earth oxides, lubricant-injected surfaces, polymers, nanostructured surfaces, carbon nanotubes, graphene, and porous coatings have been reviewed and discussed. Surface coating methods, applications, and potential have been compared with respect to heat transfer ability, durability, and efficiency. In addition, common limitations and challenges for densification enhancement applications are summarized to provide future research directions.

Keywords: Filmwise Condensation, Dropwise Condensation, Surface Coatings, Heat Transfer.

2. INTRODUCTION
Phase change heat transfer (PCHT) is involved in every energy conversion application, from small-scale processor cooling to large-scale power plants. The main advantage of PCHT is that large amounts of heat can be transferred with a small temperature difference [2]. It is estimated that 50% of desalination plants and 85% of power generation plants worldwide are based on steam condensers. However, due to the poor thermal efficiency of PCHT processes, the associated losses are high. Therefore, any improvement in heat transfer will lead to an improvement in overall efficiency, leading to a reduction in capital/operating costs (CAPEX/OPEX) and environmental burden. Improving heat transfer requires physical improvements to the system, and with a wide range of PCHT applications, minor improvements may result in significant energy, economic, and environmental impacts. The phenomenon of condensation occurs when the vapor in the saturated or supersaturated phase contacts the surface/wall or fluid at a lower saturation temperature. Due to the lower energy barrier in almost all industrial applications, vapors condense on the surface instead of directly condensing. The convection mode in the condensation process, where surface tension is dominant, and the density difference are the key factors that make the flow buoyant. Natural convection and latent heat enable a higher heat transfer rate compared to single-phase convection. There are two main types of condensation: dropwise condensation (DWC) and filmwise condensation (FWC) as shown in Figure 1. In DWC, droplets form as condensation and move discontinuously, while in FWC, a continuous thin liquid film forms and completely covers the cold surface, resulting in increased thermal resistance and consequently the heat transfer coefficient decreases.

3. Increasing condensation by surface coatings
Common metals used in condensers, such as copper (Cu), aluminum (Al), stainless steel (SS) and titanium (Ti), have high surface energy, which leads to high wettability and thus the formation of FWC. Surface coatings have been used in many studies to reduce surface energy and achieve DWC [2]. Figure 2 shows a copper surface that is partially coated with a film and the rest is not coated. The coated areas represent DWC, while the bare parts of the surface are coated with a liquid layer, representing FWC. Various types of surface coatings have been tested to enhance condensation, such as inorganic compounds, noble metals, polymers, surface alloys, and organic compounds (for vapor/liquid systems with high surface tension) [3]. For each type and technique of surface modification, there are advantages and disadvantages

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associated with them. The main parameters for evaluating different coatings are: water repellency, thermal resistance/conductivity, durability/stability and cost.

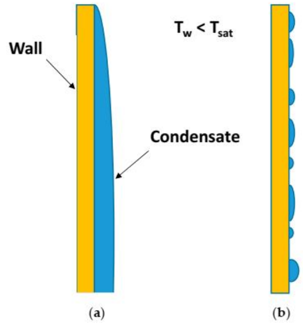

Figure 1. Schematic of (a) Filmwise condensation and (b) Droplet condensation, where T_w is the wall temperature and T_{sat} is the fluid saturation temperature.

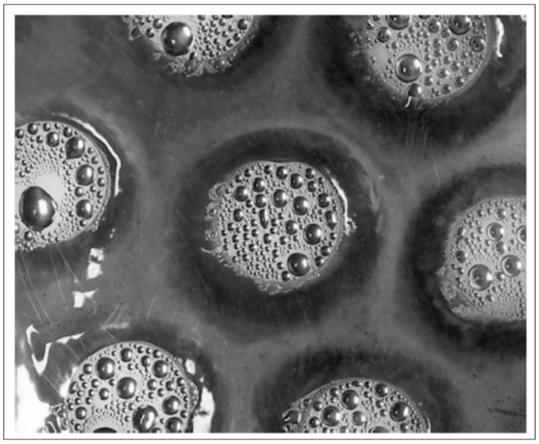

Figure 2. Droplet condensation on the coated part of the substrate and filmwise condensation on the uncoated parts of the same substrate [4].

The heat transfer coefficient of DWC is several times higher than that of FWC, while the overall heat transfer coefficient can be increased up to three times. Therefore, obtaining a stable DWC state improves the overall performance, but the stability of the DWC state depends on several factors such as wettability, hydrophobicity, condensate surface tension, contact angle hysteresis, and droplet ejection/removal. These required properties can be achieved by applying micronano-scale surface coating. The contact angle can be adjusted by micro-scale roughness, while the contact angle hysteresis can be reduced by nano-scale roughness [5]. However, robustness, cost, durability and application methods are some of the obstacles that need to be overcome for industrial applications. Degradation of coatings under transient conditions usually results in FWC within a few weeks or months. The advantages and disadvantages of different types of coatings are presented in Table 1.

Table1. Advantages and disadvantages associated with different types of surface coatings.

Surface Coating Technique	Advantages	Disadvantages
Noble metals	DWC increases due to the absorption of impurities and hydrocarbons.	High price of the material limits its practical application.
REOs	Possesses hydrophobic nature, which promotes DWC.	Low thermal conductivity. Lack of heat transfer studies.
Ion implantation	Ehances heat transfer capability at low subcooling. Low-temperature process.	Performance decreases with increase of subcooling after a particular level. Expensive, which limits its scalability
Polymer coating	Effective method from both cost and performance aspects. Increases DWC and htc.	Durability of thin coating needs to be addressed.
SAMs	Negligible thermal resistance. High htc.	Robustness and durability for SAM needs to be improved for industrial-based applications
Lubricant-infused surfaces (LIS)	Effective for condensation enhancement. Advantages include self-healing, self-cleaning, antifouling, and omniphobic properties	The removal of lubricants and contaminating condensate makes practical application inadequa

Nanostructured surfaces	HTC enhancement for condensation. Offers chemical unitability, robustness, and low thermal resistivity.	Long-term durability issues. Limits scalability at the industrial level
Porous coating	Increases overall surface area. Quick condensation process.	Liquid trapped has a negative effect on the overall heat transfer from gas phase to the substrate. Unlike boiling, this property makes it less feasible for condensation.

4. Conclusion

Micro/nano manufacturing technologies offer a wide range of possibilities for surface modification and thus performance improvement for condensation processes. The idea of enhancing heat transfer performance through surface modification or coatings is not new, but the development of surface modification technologies, especially micro/nanoscale fabrication and wettability modification of coatings (from hydrophilic to hydrophobic), has opened up a wide range of possibilities for their use in practical applications. In this review, existing micro/nanoscale coatings are discussed and evaluated, and challenges related to their implementation are highlighted. Some of the major highlights are as follows:

• Ion implantation and noble metals provide better hydrophobicity, but the cost of developing coatings is high and their hydrophobicity is not stable compared to polymer coatings.

• The cost of REOs is less than 1% of noble metal coatings and the thermal conductivity is approximately 50 times higher than fluoropolymers. However, heat transfer studies on REOs are limited, so more in-depth analysis is needed before commercialization. If the coating thickness is in the range of microns, polymer coatings can provide a stable and durable DWC condition. However, greater thickness results in increased thermal resistance. On the contrary, the small thickness of the coating can be effective and may be 10 times higher than HTC. The challenges associated with thin coatings are uniformity and durability.

• The thickness of SAM coatings is very low (~10 nm) and uniformity can be maintained. The thermal resistance is negligible, which is beneficial for heat transfer. Despite these desirable properties, its thermal stability in hot flows limits its practical implementation.

• LIS can be an effective alternative to obtain a stable DWC state, but over time, the DWC state changes to a hybrid/FWC state due to lubricant degradation. Lubricant durability still needs improvement. In addition, in applications where condensate quality is important, removing these lubricants and contaminated condensates makes its practical applications insufficient.

• Emerging surface coatings such as CNTs, CF and graphene and nanostructured surfaces can be promising alternatives for stable DWC mode, but the development of these coatings is in the early stages.

• Hybridization of different techniques should be done to study the possibilities of enhanced heat transfer results, such as the combination of nanoparticles and structured porous coatings using durable materials, coating processes, and the combination of porous and hydrophilic structures and hydrophobic coatings.

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