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# Effect of a micro-grooved fin surface design on the air-side thermal-hydraulic performance of a plain fin-and-tube heat exchanger

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ABSTRACT

In this study, the effectiveness of plain fin-and-tube heat exchangers constructed using anisotropic, micro-patterned aluminum fins has been explored. These fins which can more completely drain the condensate that forms on the heat transfer surface during normal operation were selected with the aim of improving the thermal-hydraulic performance of the heat exchanger. This study presents and critically evaluates the efficacy of four full-scale heat exchangers by measuring and comparing dry/wet air-side pressure drop and dry/wet air-side heat transfer data. The prototype fin surfaces were shown to reduce the wet air-side pressure drop from 9.3% to 53%, while at the same time having a negligible effect on the sensible heat transfer coefficient under both dry and wet conditions. That is to say, this novel fin surface design has shown the ability, through improved condensate management, to enhance the performance of the heat exchanger. Data pertaining to the durability of the alkyl silane coating used in this work are also presented.


# Effet de la conception d'une surface à micro-rainures sur la performance thermique et hydraulique côté air d'un échangeur de chaleur à tubes ailetés

*Mots clés* : conditionnement d'air ; micro-rainure ; condensat ; coefficient de transfert de chaleur ; chute de pression ; enrobage

## 1. Introduction

Liquid-to-air heat exchangers which are present in almost all buildings are used in a wide range of air-cooling applications including residential and commercial air conditioning and refrigeration systems. These heat exchangers usually employ aluminum fins and copper tubes. When the surface temperature of a heat exchanger is below the dew point temperature

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of the incoming air, moisture condenses on the heat exchanger surface, dehumidifying the air. In many cases, water retention on the heat transfer surface is problematic because it increases the air-side core pressure drop and has the potential to reduce the air-side heat transfer coefficient, lead to corrosion, and provide a moist environment for biological activity.

Although a few papers have studied full-scale heat exchangers with modified surfaces, the effect of hydrophobicity on condensation on various types of heat exchangers has not been studied comprehensively. Walpot et al. (2007) studied the effects of various surface coatings (i.e. epoxy, polymer, etc.) on the air-side performance of heat exchangers during condensation conditions. They explained that both the geometry of the heat exchanger and the thickness of the coating affected the overall drainage performance. They also reported that heat exchangers with larger contact angles showed worse drainage behavior than ones with smaller contact angles since increased droplet detachment leads to higher condensation on the surface. It is important to note that this stands in contradiction to the findings of the present study. Contact angle hysteresis which is the difference between the measured advancing and receding contact angles was also not considered in this work. (Note: Contact angle hysteresis has long been used as a gauge of the hydrophobicity of a surface.) Kim et al. (2002) observed that the static contact angle, dynamic contact angle, and pressure drop ratio (i.e. $P_{wet}/P_{dry}$) for an uncoated surface decreased with increasing cycles, but those of a hydrocarbon plasma-treated surface had a weaker dependence on the number of cycles. In addition, the hydrocarbon plasma-treated surface showed better hydrophilicity, lower pressure drop, and a smaller overall fan power requirement than the uncoated surface for the same cooling duty. However, they did not compare the drainage behavior of the hydrophilic heat exchangers with that of hydrophobic ones.

Shin and Ha (2002) studied the drainage performance for three different types of plain fin-and-tube heat exchangers using dynamic contact angle measurement and condensate mass measurement. The results showed that the plasma polymerization method enhanced the hydrophilicity of the surface, decreased the advancing dynamic contact angle from 90° to 65°, and decreased the saturated water hold-up. However, the effect of the air flow rate on the condensate and the effect of this new surface design on the heat transfer coefficient were not discussed. Wang et al. (2002) and Wang and Chang (1998) studied slit-fin-and-tube, louver-fin-and-tube, and plain-fin-and-tube heat exchangers with various geometries and found that hydrophilic surfaces either have a negligible effect on the sensible heat transfer coefficient (as seen in this study) or result in a slight decrease in heat transfer performance. In both studies, however, the hydrophilic surface led to a decrease in the air-side pressure drop. Information about the degree of hydrophilicity of these surfaces, however, was absent.

During the past few years, several studies have been published on the air-side performance of different fin surface patterns. For example, extensive data and correlations for plain fin-and-round-tube heat exchangers were established by Wang et al. (2000a, 2000b), Kim and Kim (2005), Tang et al. (2009a, 2009b), Xie et al. (2009), Paeng et al. (2009), and Choi et al. (2010). Table 1 summarizes the geometries of the plain fin heat exchangers used in these investigations. It should be noted, however, that these studies do not present air-side correlations for heat exchangers with an anisotropic surface wettability. Therefore, predictive correlations are still needed for heat exchangers constructed with anisotropic fins.

Although surface modification techniques are described in the open literature, the application of these techniques to metallic surfaces and the testing of full-scale heat exchangers with a modified surface wettability are only sparsely reported. Thus, the overarching goal of this study was to examine both the potential benefits and feasibility of using these surfaces in HVAC&R systems. The specific goal of this work was to assess the effectiveness of heat exchangers constructed using anisotropic aluminum fins to more completely drain the condensate that forms on the heat transfer surface during normal operation with the aim of improving the thermal-hydraulic performance of the heat exchanger. Air-side pressure drop measurements and heat transfer experiments were used to assess the thermal-hydraulic performance, and dip testing and dynamic contact angle measurements were also conducted to evaluate the durability of an applied hydrophobic coating.

## 2. Experimental method

### 2.1. Fabrication of anisotropic fin surfaces

A standard photolithographic method and chemical etching process were used to fabricate the anisotropic fin surfaces. Photolithography is a method by which a pattern is

**Table 1 – Summary of experimental results from previous studies.**

| Investigator | Number of samples | $D_o$ (mm) | $F_p$ (mm) | $P_t$ (mm) | $P_l$ (mm) | $N$ | $Re$ |
|---|---|---|---|---|---|---|---|
| Wang et al. (2000a) | 74 | 6.35–12.7 | 1.19–8.7 | 17.7–31.75 | 12.4–27.5 | 1–6 | |
| Wang et al. (2000b) | 31 | 7.3–10.08 | 1.21–3.2 | 21/25.4 | 12.4/19.05/22 | | $300 < Re_{Dc} < 5000$ |
| Kim and Kim, (2005) | 22 | 8 | 7.5–15 | 62 | 27 | 1–4 | $600 < Re_{Do} < 2000$ |
| Tang et al. (2009a) | 9 | 18 | 3.1 | 42 | 34 | 6/9/12 | $4000 < Re_{Dc} < 10{,}000$ |
| Tang et al. (2009b) | 5 | 18 | 3.1 | 42 | 34 | 12 | $4000 < Re_{Dc} < 10{,}000$ |
| Xie et al. (2009) | | 16–20 | 2–4 | 38–46 | 32–36 | 2–4 | $1000 < Re_{Dc} < 6000$ |
| Paeng et al. (2009) | 1 | 10.2 | 3.53 | 25 | 22 | 3 | $1082 < Re_{Do} < 1649$ |
| Choi et al. (2010) | 34 | 8 | 7.5–15 | 62 | 27 | 2–4 | $500 < Re_{Do} < 800$ |