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Experimental investigation of natural dehumidification over an annular finned-tube

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ABSTRACT

In this study, heat and mass transfer during natural condensation of humid air over a horizontal annular finned-tube is investigated experimentally. The finned-tube is made by extruded process and fins are circular with rectangular cross-section. Outer diameter of central tube, fin diameter, fin thickness and fin density are 25.4 mm, 0.4 mm, 56.0 mm and 433 FPM (fins per meter), respectively. The test case is placed in a specially constructed insulated test room to control test conditions and simulate pure natural dehumidification. Ambient air temperature and relative humidity are controlled by heating, cooling and humidifying equipment. Ethylene glycol–water solution is used as refrigerant to control and keep fin base temperature constant. Experiments are performed for ambient air temperature of 25 °C, 30 °C and 35 °C, relative humidity of 40%, 50%, 60% and 70% and fin base temperature of 4 °C, 6 °C and 8 °C. Observations indicate that the water drops form mainly on tip of the fins and for the conducted tests, no condensation is observed between the fins which is mainly due to small fin spacing (2.0 mm) and lack of convective heat and mass transfer between the fins. The test results also show that condensation and heat transfer rate depend mainly on the temperature and relative humidity of the surrounding air and fin base temperature. The increase in ambient air temperature and relative humidity and the decrease in fin base temperature lead to increase in heat and mass transfer rate. Furthermore, based on the results, new correlations are developed for heat and mass transfer during natural dehumidification over compact annular finned-tubes.

1. Introduction

One of the most common ways to enhance convection heat transfer is employing extended surfaces (Fins). There are many different kinds of the fins, such as longitudinal, spin and annular. In order to amplify the heat transfer between the environment and a tube, the annular fins with rectangular cross-section are usually used. Tubes with this kind of fins are widely employed in industrial systems such as air conditioning, dehumidifier and cooling systems, heat exchangers and chemical processes. In some applications like dehumidification processes, air conditioning and cooling systems, condensation may occur over the surfaces of the finned-tubes.

Condensation over a surface happens when surface temperature is below the saturated temperature of pure vapor or below the dew point temperature of gas–vapor combination. At this condition, vapor energy is released as latent heat, transfers to the surface and nucleus of liquid drops form on the surface. For dehumidification and air conditioning processes, condensation always occurs over finned-tube surfaces and heat transfer is accompanied with mass transfer due to lower temperature than dew point temperature of its surrounding air.

The first study about condensation of air humidity over fins is carried out by Threlkeld [1] in 1970. He described an analytical solution for the overall fin efficiency of straight longitudinal fins by using the enthalpy difference as the driving force for the combined heat and mass process. In 1975, McQuiston [2] investigated the overall efficiency of a fully wet straight longitudinal fin analytically. He assumed that the temperature and humidity ratio are the driving forces for heat and mass transfer. Elmahdi and Biggs [3] performed the same study on annular finned-tube and obtained the overall fin efficiency. According to the results of this study, with an increase in temperature and relative humidity of air, condensation and heat transfer rate increase, while the fin efficiency decreases. Coney et al. [4] investigated numerically the efficiency

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Nomenclature

A	total surface area, m^2
A_i	inner surface area, m^2
A_o	outer surface area, m^2
d	tube outer diameter, mm
D	fin outer diameter, mm
D_{AB}	mass diffusion coefficient, m^2/s
F	view factor
g	acceleration of gravity, m/s^2
h	overall heat transfer coefficient, $W/m^2\,K$
h_{fg}	enthalpy of vaporization, J/kg K
k	thermal conductivity, $W/m^2\,K$
L	length of the finned tube, m
Nu_s	Nusselt number, $h\,s/k_a$
q	total heat transfer rate, W
q_{conv}	convection heat transfer rate, W
q_{lat}	latent heat transfer rate, W
q_{rad}	radiation heat transfer rate, W
r	radius, mm
R	thermal resistance, K/W
R_c	contact resistance, K/W
Ra_s	Rayleigh number, $g\,\beta\,\Delta T\,s^4/\nu\,\alpha\,D$
RH	relative humidity, %
s	fin spacing, mm
t	time, min
T	temperature, °C
ΔT	temperature difference, $T_a - T_{fb}$

Greek Symbols

α	thermal diffusivity, m^2/s
β	volumetric thermal expansion coefficient, 1/K
Γ	condensate mass transfer rate, kg/s
δ	fin thickness, mm
ε	emissivity
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, $5.67 \times 10^{-8}\,W/m^2\,K^4$
Ψ	dimensionless mass transfer rate, $\Gamma/s\,\rho\,D_{AB}$

Subscripts

1	aluminum tube
2	steel tube
3	insulator layer
a	ambient air
dp	dew point
fb	fin base
i	inner
o	outer
s	surroundings

of single straight longitudinal fin by forced convection heat transfer and filmwise condensation. Their results show that with increased velocity, temperature and relative humidity of air, heat and mass transfer rate increase whereas fin efficiency decreases. In the other study, Coney et al. [5] analyzed experimentally forced convection heat transfer for a single vertical longitudinal fin which is connected to a cooled base and subjected to a dry and humid air flow. Results of this study are in agreement with their previous numerical results [4]. Wu and Bong [6] in an analytical study, investigated the efficiency of a single longitudinal fin when the surface of the fin is fully or partially wet. The purpose of their work was to study the effect of relative humidity and geometrical parameters on fin efficiency. Kazeminejad [7] numerically analyzed natural convection heat transfer for fully wet longitudinal fins for filmwise condensation. The results of this work revealed that when condensation occurs, the amount of heat transfer rate is more than the condition in which the surface remains dry. This enhancement is due to transfer of latent heat during condensation process. Furthermore, the amount of heat transfer rate is increased by increasing the temperature and relative humidity of ambient air and decreasing the fin base temperature. Salah El-Din [8] analytically analyzed heat transfer and performance of longitudinal fins in partially and fully wet condition. He revealed that the rise in thermal conductivity of fin, enhance the wet region and performance of the fins. Rosario and Rahman [9] carried out the same research of Coney et al. [4] in which the annular fin was used instead of longitudinal one. In this study, the overall efficiency of annular fins in a fully wet condition is studied numerically. Rosario and Rahman [10] continued their prior work by numerically investigating heat transfer of annular fins in partially wet condition. In this study, the effect of changing cold fluid temperature, relative humidity and temperature of humid air on heat transfer is investigated. Results of this study indicate that increase in relative humidity results in extension of wet region. In addition, reduction of cold fluid temperature and rise of ambient air temperature and humidity, increase in heat transfer. Naphon [11] in a numerical study analyzed effective parameters on forced convection heat transfer with filmwise condensation over finned-tube in dry, partially and fully wet conditions. His results revealed that when Biot number increases, fin temperature increases and becomes close to the ambient air temperature. Sharqawy and Zubair [12] analytically studied forced convection heat transfer with film condensation over a circular finned-tube in a fully wet condition. In this study the effect of ambient pressure on fin efficiency is considered and results show that increase in ambient pressure, enhances fin efficiency. Kundu and Barman [13] numerically and analytically investigated circular fins with two kinds of profiles (rectangular and triangular) in a condition that forced convection heat transfer is accompanied with filmwise condensation. According to the results of this study, increase in Biot number causes an enhancement in heat transfer and efficiency and a decrement in performance of the fin. Sharqawy et al. [14] in another effort, numerically studied heat and mass transfer over circular fins with diversity of profiles (rectangular, triangular, concave and convex parabolic). Moinuddin et al. [15] continued the study of Sharqawy et al. [14] numerically, and investigated heat transfer with film condensation over an annular finned-tube with variable cross sectional area. The purpose of this study was optimizing the geometrical parameters of the finned-tube in fully wet condition. Recently, Nabovati et al. [16] experimentally studied dehumidification over an inclined smooth tube by natural convection. They demonstrated that dehumidification decreases with increasing tube angle. Yaghoubi and Mahdavi [17] investigated numerically natural convection heat transfer over a compact finned-tube and proposed a relation to predict the amount of convective heat transfer coefficient.

Based on the above literature review, few analytical and numerical studies about natural convection heat transfer accompanied with condensation over annular finned-tubes are available and the majority of experimental studies are about condensation of saturated water vapor and refrigerants. Further, the experimental works about dehumidification are belonging to inclined smooth tubes and longitudinal fins. No experimental studies about natural condensation of humid air over compact annular finned-tubes are