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Filmwise condensation of steam on vertical plates with novel pin fin arrays produced by selective laser melting

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ABSTRACT

An experimental investigation of the use of pin fin arrays to enhance filmwise condensation of steam on vertical plates was carried out. New fin geometries of cylindrical, conical and sinusoidal profiles were produced and investigated in a condensation chamber. The effects of fin geometry and fin height were systematically examined and a comparison of the heat transfer performances of the pin fin structures and equivalent longitudinal fins was made. Visualization studies were carried to determine the condensate retention heights of the various fin structures and to elucidate the possible mechanisms affecting the condensation heat transfer coefficient. Our results show that the pin fin structures exhibit higher heat transfer performances as compared to the equivalent longitudinal fins of the same fin base diameter/width, pitch and height even though the longitudinal fins have larger heat transfer area as compared to the pin fins. The conical fin geometry of Specimen *C*1 was shown to promote condensate drainage away from the specimen surface, which reduced the condensate retention height and enhanced the heat transfer. In addition, the three-dimensional geometry of the conical fin also resulted in additional variation of curvature that reduces the film thickness near the fin tip and promotes heat transfer. On the other hand, the sinusoidal fin geometry of Specimen *S*1 promoted the draining of the condensate film from the fin tip to the fin base which significantly improved heat transfer near the fin tip. In comparison with the plain surface, enhancement factors (η) of 2.04 and 1.80 were achieved with Specimens *C*1 and *S*1, respectively.

1. Introduction

Heterogeneous condensation is a common phenomenon which occurs when saturated or superheated vapor comes into contact with a surface that is maintained at a subcooled temperature. Filmwise and dropwise condensation are the two modes of heterogeneous condensation. In filmwise condensation, a liquid film blankets the solid surface whereas in dropwise condensation, discrete liquid droplets are formed on the surface.

Even though dropwise condensation exhibits high heat transfer rates, filmwise condensation remains the dominant mode in many industrial applications such as desalination systems, power generation plants, air-conditioning systems and electronic devices. The application of filmwise condensation heat transfer in these engineering systems can be broadly classified into internal convective condensation and external condensation. In internal convective condensation, the vapor is directed through confined channels where condensation occurs inside the flow channel. Under this condition, the vapor velocity is sufficiently large and assists in the removal of the condensate. Internal convective condensation has been extensively studied by several researchers. For instance, Lambrechts et al. [1], Wu et al. [2] and Guo et al. [3] reported the condensation of refrigerants inside smooth and enhanced tubes of micro-fins and herringbone structures.

On the other hand, external condensation is also widely used. Examples of its applications are in the shell-side of shell-and-tube condensers [4] and in the condensers of two-phase thermosyphons [5]. Due to its ubiquitous applications, it is imperative to enhance external condensation to improve system efficiency and reduce energy consumption. Extended surfaces such as integral fins, longitudinal fins and pin fins have been used to enhance external condensation. These surfaces enhanced the heat transfer by increasing the available heat transfer area and inducing additional surface tension forces on the condensate film. However, the presence of finned structures may also result in excessive condensate retention and limit the heat transfer performance of a surface.

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Nomenclature

A	area (m^2)
A_t	total heat transfer area (mm^2)
d_b	fin base diameter/width (mm)
f_d	fin density (mm^{-2})
k	thermal conductivity (W/m·K)
l	fin height (mm)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient based on base area ($kW/m^2·K$)
h_t	heat transfer coefficient based on total surface area ($kW/m^2·K$)
h_{fg}	latent heat of vaporization (kJ/kg)
H_{ave}	condensate retention height (mm)
H	specimen height (mm)
p	fin pitch (mm)
P	pressure (Pa)
q''	heat flux (kW/m^2)
R	radius of curvature (m)
T	temperature (°C)

Greek symbols

σ	surface tension (N/m)
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m·s)
η	heat transfer enhancement factor
ε	surface area enhancement factor

Subscripts

c	copper
enh	enhanced
l	liquid
Nu	Nusselt
s	specimen
sat	saturated
v	vapor
w	wall

Constants

a	constant in Eq. (6)
b	constant in Eq. (6)

1.1. Effects of fin geometry

Fin parameters such as fin geometry, fin pitch and fin height are the major factors affecting condensation heat transfer. Gregorig [6] first recognized that the existence of a fin profile imposed additional surface tension forces which pulled the condensate from the fin tip to the concave trough of a vertical fluted tube. This resulted in the thinning of the condensate film at the convex fin tip where condensation mainly occurs. Subsequently, Hirasawa et al. [7] studied the effects of longitudinal fin arrays with a parabolic tip. In addition to the thinning of the condensate film at the fin tip, they determined that the suction effects caused by the accumulation of condensate at the trough also resulted in a region of thin film near the fin base. These two effects increased the heat transfer coefficients of the finned surface by up to 3.5 times as compared to a plain surface.

Previous studies were mainly performed on conventional fin geometries such as rectangular, trapezoidal and triangular profiles. Recently, novel fin geometries have also been developed to further enhance external condensation. For example, Zhang et al. [8] introduced the use of three-dimensional finned tubes with petal-shaped fin geometries to improve on-tube condensation using R407c refrigerant as the working fluid and reported enhancement factors of 4.6 to 5.35 as compared to a smooth tube. Qi et al. [9] performed both numerical and experimental investigations on a new type of fluted surface with involuted groove profile. Due to the larger surface tension forces and lower flow resistances, their results showed that the involuted groove had a larger thin film area and resulted in at least 20% higher heat transfer rate than the trapezoidal fin. More recently, a new type of sinuous fins of different shapes was numerically studied by Wang et al. [10]. This type of fins consists of a convex tip and a concave stem. Due to the continuous change in curvature of the sinuous fins, a larger thin-film area near the fin crest region was produced and it was deduced that the sinuous fins have higher heat transfer rate than conventional rectangular and triangular fins.

1.2. Effects of fin arrangement and condensate retention

For external condensation on tubes or on small flat surfaces, the retention of condensate downstream of the drainage path may lead to a reduced effective heat transfer area which significantly affects the condensation heat transfer coefficients. In addition to the fin geometry, condensate retention can also be affected by parameters such as fin height and fin pitch. The effects of these fin parameters have been an area of active research. For instance, Rudy and Webb [11] developed an analytical model to determine the condensate retention angle (α) for integral fin tubes and showed that α depends on the fin pitch, fin height and condensate surface tension-to-density ratio. In addition, for circular tubes and flat plates with the same integral fin geometries and arrangements, it was determined that their liquid retention heights were also the same. This phenomenon was similarly reported by Ali [12] for circular tubes and flat plates with pin fin structures. Subsequently, Honda and Nozu [13] and Adamek and Webb [14] developed predictive models to determine the condensation heat transfer rate from integral fin tubes of fins with a rectangular cross-section and included the effects of flooded and unflooded tube regions. Their models demonstrated an accuracy of within ±20% for different fin arrangements and working fluids.

Experimental investigations on the effects of fin arrangements were also reported. For instance, Kumar et al. [15] conducted experiments to determine the condensation heat transfer performances of circular integral-fin tubes (CIFTs) and spine integral-fin tubes (SIFTs) of different fin pitches and heights in steam and R134a refrigerant. For all fin arrangements, the SIFTs tubes showed higher heat transfer coefficients as compared to CIFTs. Al-Badri et al. [16] studied the influence of fin density and fin height on the condensation heat transfer performances of standard fin tubes (SFTs) and enhanced fin tubes (EFTs) with three-dimensional structures in R134a. For condensation on a single tube, it was shown that the heat transfer coefficients increase with increasing fin pitch for SFTs while a reversed trend was observed for EFTs. Systematic studies on the effects of fin pitch, thickness and height of tubes