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Research Paper

Marangoni condensation of steam-ethanol mixtures on a horizontal low-finned tube

H. Ali [a,e], M.S. Kamran [a,e], Hafiz Muhammad Ali [b,c,*], F. Farukh [d], S. Imran [a,e], H.S. Wang [a]

[a] School of Engineering and Material Science, Queen Mary, University of London, UK
[b] Center of Research Excellence in Renewable Energy (CoRE-RE), King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[c] Mechanical Engineering Department, University of Engineering and Technology, Taxila, Pakistan
[d] School of Engineering and Sustainable Development, De Montfort University, Leicester, UK
[e] Faculty of Mechanical Engineering, University of Engineering and Technology, Lahore, Pakistan

HIGHLIGHTS

- New experimental data for condensation of steam-ethanol mixtures obtained.
- Heat transfer enhancement of around 50% obtained using steam-ethanol mixtures.
- Maximum heat transfer enhancement obtained at initial liquid ethanol concentration of 0.1%.
- Retention angles increased with increasing ethanol concentration and vapor velocity.

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ABSTRACT

Careful heat-transfer measurements have been conducted for condensation of steam-ethanol mixtures in vertical downflow over a horizontal, water-cooled, low-finned copper tube. Care was taken to avoid error due to the presence of air in the vapor. The tube had diameter at the fin root 12.7 mm and rectangular section fins with height 1.6 mm, thickness 0.5 mm and space between fins 1.0 mm. Tests were conducted at pressures of atmospheric, 55 kPa and 14 kPa. Concentrations of ethanol by mass in the boiler when cold prior to start up were 0.025%, 0.05%, 0.1%, 0.5% and 1.0%. The highest vapor velocity at approach to the tube was 7.5 m/s at atmospheric pressure and 15.0 m/s at vapor pressure 14 kPa. Effects of ethanol concentration on both retention angle and heat transfer were measured. The retention angle was strongly dependent on the vapor velocity and ethanol concentration which affected the condensation rate, composition and temperature of the condensate at the interface and consequently the surface tension of condensate. The results are compared with data for pure steam on the same finned tube and Marangoni condensation on a smooth tube under the same conditions. Similarly, results for condensate retention of water on finned tube are compared with earlier data and theoretical model. Vapor-side, heat-transfer coefficients were obtained by subtraction of coolant side and test tube wall thermal resistances from overall measurements.

1. Introduction

Pseudo-dropwise or Marangoni condensation takes place during condensation of binary mixtures when surface tension of low boiling-point component is lower than that of high-boiling point component, discovered by Mirkoverich and Missen in 1961 [1,2]. Significant heat transfer enhancement can be obtained in the dropwise condensation regime of Marangoni Condensation on hydrophilic surfaces. It has been extensively investigated using flat plates and different tube diameters over a range of operating conditions [3]. Maximum heat transfer enhancement up to around 4 and 8 times have been obtained using horizontal tube and flat plates at vapor velocity as low as 0.4 m/s. The heat transfer trends obtained were same in both geometries but the differences were due to geometry, condensate flow as well as variation in geometry and condensate flow around the tube [4]. Heat transfer characteristics, condensing surface geometries and operating conditions investigated by various researchers have been listed in Table 1.

* Corresponding author at: Center of Research Excellence in Renewable Energy (CoRE-RE), King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia.

E-mail address: hafizmali@kfupm.edu.sa (H.M. Ali).

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Nomenclature

C_{iL}	concentration of ethanol by mass in the boiler when cold prior to start up [%]
C_L	concentration of ethanol by mass in water, see Fig. 5 [%]
C_V	equilibrium concentration of ethanol in the vapor [%]
d	outside diameter of test tube (or fin root diameter for finned tubes) [mm]
d_i	inside diameter of test tube [mm]
d_o	diameter at fin tip [mm]
F	dimensionless quantity, $\mu h_{fg} d g / U_V^2 \lambda \Delta T$ [–]
g	specific force of gravity [m/s^2]
h_{fg}	specific enthalpy of evaporation [J/kg]
Nu	Nusselt number, $\alpha d/\lambda$ [–]
Nu_c	Coolant Nusselt number, $\alpha_c\, d_i/\lambda_c$ [–]
P_V	vapor pressure in the test section [kPa]
Pr_c	Prandtl number of coolant [–]
q	heat flux [W/m^2]
q_{max}	maximum heat flux [W/m^2]
Re_c	Reynolds number of coolant flow, $\rho_c u_c d_i/\mu_w$ [–]
Re_{tp}	two-phase Reynolds number, $\rho U_V d/\mu$ [–]
s	fin spacing [mm]
T_v	vapor temperature [K]
T_w	average tube wall temperature [K]
ΔT	vapor-to-surface temperature difference, $T_V - T_w$ [K]
ΔT_{max}	maximum vapor-to-surface temperature difference [K]
u_c	coolant velocity [m/s]
U_V	vapor velocity approach the test section [m/s]

Greek symbols

α	heat-transfer coefficient, $q/\Delta T$ [W/m^2 K]
α_c	heat-transfer coefficient of coolant flow [W/m^2 K]
α_{max}	maximum heat-transfer coefficient [W/m^2 K]
β	fin half tip angle [°]
σ	surface tension [N/m]
φ_f	condensate retention angle or "flooding angle" measured from the top of a horizontal finned tube to the position at which the inter-fin space becomes full of condensate [°]
ρ	density of condensate [kg/m^3]
μ	dynamic viscosity of condensate [kg/ms]
μ_c	dynamic viscosity of coolant [kg/ms]
μ_w	dynamic viscosity of coolant at wall temperature [kg/ms]
λ	thermal conductivity of condensate [W/mK]
λ_c	thermal conductivity of coolant [W/mK]
ε	enhancement ratio, see Eq. (4) $\varepsilon = \left(\frac{\alpha}{\alpha_{Eq.(2)}}\right)_{\text{same }\Delta T\text{ and }U_v}$
ε_{max}	maximum enhancement ratio

Subscripts

c	coolant
m	mixture
max	maximum
V	vapor
o	outside
w	wall

Utaka and Nishikawa [22] determined condensate layer thickness between departing drops and it was found that layer of 1 μm was always present on the condensing surface. Theoretical and experimental study regarding condensation of steam ethanol mixtures was carried out by Hijikata et al. [23]. Instability analysis was performed for steam ethanol mixture condensation on a horizontal flat plate and highlighted theoretical drop growth mechanism during condensation.

Significant condensation heat transfer enhancement can be obtained using enhanced surfaces such as finned and pin fin tubes [24,25]. The enhancement is attributed to the increased area due to addition of fins. Moreover, additional drainage mechanism due to surface tension induced pressure gradients from the flanks and tips of the fins result in thinning of the condensate film [26]. Due to surface tension, condensate thickness increases significantly at a particular angle is known as retention angle. For quiescent vapor the flooding angle can be calculated using mathematical model of Honda et al. [27].

Extensive experimental and theoretical investigations have been conducted using natural and forced convection condensation on finned tubes [26,28,29]. Data have been made available for various fluids and tube geometries over a range of operating conditions of vapor velocity and pressure [30–32]. Heat transfer rate increased with increasing vapor velocity due to the effect of vapor sheer stress and turbulence in the condensate film. Briggs and Rose (2009) provided the empirical model to account for the vapor side heat transfer coefficient. The model relies on empirical constant and observed/calculated retention angles for forced convection condensation on finned tubes. Data for pure steam are predicted more accurately as compared to that of non-steam data [33,34]. More accurate model would require less dependency on empirical constants and accurate estimation of retention angle at higher vapor velocities. More recently, experimental data have been made available using simulated condensation on horizontal finned tubes in a vertical wind tunnel. Condensation was simulated using three liquids (water, ethylene glycol and R113) and eight different tube geometries [35]. This could be useful in the development of a fully predictive heat-transfer theory incorporating a method for calculating the retention angle.

Condensation of pure fluids on low finned tubes is fairly understood. Extensive experimental data are available for both condensation of pure fluids on finned tubes and that of steam-ethanol mixtures on flat surfaces/horizontal smooth tubes [36]. Moreover, for finned tubes, satisfactory predictive models are available with simplifying approximations. However, few data are available for condensation of mixtures in general and Marangoni condensation in particular over a range of operating conditions such as vapor-to-surface temperature difference, vapors pressure and velocity. The present work investigates the condensation of steam-ethanol mixtures on a horizontal low-finned tube in order to examine the combined effect of fins and Marangoni phenomenon due to condensation of steam-ethanol mixtures to obtain heat transfer enhancement.

2. Apparatus and procedure

The stainless-steel apparatus, as shown schematically in Fig. 1, consisted of a closed loop, with vapor generated in electrically-heated boilers (maximum power 45 kW) and passed through a 180° bend to flow vertically downward, through a calming section and then to the test section. Excess vapor condensed in the water cooled auxiliary condenser from which the condensate returned to the boilers by gravity.

The finned tube had a condensing length of 70 mm and a diameter at the fin root of 12.7 mm. The rectangular cross section fins had height 1.6 mm, thickness 0.5 mm and spacing between fins 1.0 mm. PTFE sleeves were inserted at both ends of the test tube