CONDENSATION HEAT TRANSFER ENHANCEMENT USING STEAM ETHANOL MIXTURES ON A FINNED TUBE

H. Ali, F. Noor, M. S. Kamran, A. Hussain, S. Imranand F.Farukh*

Faculty of Mechanical Engineering, University of Engineering and Technology Lahore, Pakistan
*Wolfsan School of Mechanical and Manufacturing Engineering, Loughborough University, UK
Corresponding Author: hassan.ali@uet.edu.pk

ABSTRACT: Heat-transfer experiment was conducted for condensation of steam-ethanol mixtures in vertical down flow over two horizontal, water-cooled, low-finned copper tubes at atmospheric pressure. Tube had a fin height of 1.6 mm, root diameter of 12.7, thickness of 0.3 mm and spacing between fins of 0.5 mm. Tests were conducted at atmospheric pressure. Effects of ethanol concentration on both retention angle and heat transfer were measured. The retention angle was strongly dependent on ethanol concentration, upstream vapour velocity, temperature of the condensate at the interface and consequently the surface tension. Mass fractions of ethanol used to conduct tests were 0.025, 0.05, 0.1, 0.5 and 1.0percent. Range of vapour velocity at approach to the condenser tube was 0.78 to 7.5 m/s. For each composition and vapour velocity, measurements were recorded for a range of vapour to surface temperature difference. As a result of Marangoni phenomenon obtained by using steam ethanol mixture,a maximum sustainable heat transfer enhancement up to 3 times as compared to that of pure steam was obtained.

Keywords: Finned tube, Steam ethanol mixture condensation, Heat transfer enhancement, Marangoni condensation

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INTRODUCTION

Integral fin tubes have been used in industrial applications since 1940, due to their enhanced heat transfer characteristics (Rudy and Webb, 1985). The enhancement is primarily produced by providing excess area in the shape of fins. However, due to surface tension forces liquid film is retained on the lower parts of the finned tube. The retained liquid inhibits the heat transfer, thus reducing the heat transfer efficiency of the condenser. The level of retained liquid on finned tube in case of quiescent vapour was quantified by (Honda *et al*., 1983). However, in industrial condensers the velocity can be appreciably high up to 60 m/s.

Binary mixture condensation has been studied extensively (Belghazi *et al.,* 2002) focusingon the diffusion resistance of more volatile component of the condensing mixture (Rose, 2004). In certain cases the condensate appearance resembles to that of typical dropwise condensation of pure fluid on a hydrophobic surface. This type of condensation, known as Marangoni or pseudo-dropwise condensation, takes place when more volatile constituent has the lower surface tension such as steam-ethanol mixtures (Belghazi *et al.,* 2002). The pioneering studies, highlighting the fundamental aspects of the phenomenon have been conducted by (Mirkovich and Missen1961; Fujii *et al*. 1993, Utaka and Terachi, 1995;Utaka *et al*., 1998; Uataka and Wang, 2002, 2004; Utaka and Kobayashi, 2003).

The Marangoni effect is the mass-transfer of the fluids with different surface tension along the interface. It was first discovered by James Thomson as “tears of wine” (Thomson, 1855), later on it was named after Carlo Marangoni, who studied this for his doctoral research (Marangoni, 1865).

More recently, (Murase *et al*.2007) carried out experiments at atmospheric pressure on a smooth horizontal tube over a range of ethanol concentrations (0 to 1%) at a maximum vapor velocity of 0.75 m/s. Later on (Ali *et al*.2013) conducted experiments using same tube and a similar ethanol concentrations at vapor pressures of 101, 55 and 14 kPa at a maximum vapour velocity of 7.5 m/s. In both investigations maximum heat transfer enhancement of around 4 times as compared to that of pure steam was obtained.

A significant amount of experimental work has been done on Marangoni condensation using flat plates, horizontal and vertical tubes (Utaka and Terachi, 1995; Utaka*et al*., 1998; Utaka and Wang, 2002, 2004; Utaka and Kobayashi, 2003). In case of condensation of pure fluids on finned tubes, various fluids on different tube geometries have been investigated (Briggs, 2006; Briggs and Rose, 2009; Namasivayam and Briggs, 2005, 2006).

So far no data is available for Marangoni condensation (MC) of steam ethanol mixtures on finned tubes used in industrial condensers. This study was carried out to investigate the relationship of MC with ethanol concentration, retention angle, vapour velocity, temperature of the condensate and the heat transfer co-efficient.

MATERIALS AND METHOD

The present work was focused on determination of vapour side heat transfer co-efficient and retention angles on finned tube. The apparatus consisted of three boilers as shown in Fig-1. Initially boilers were filled with distilled water and various concentrations of ethanol (0.025, 0.05, 0.1, 0.5 and 1.0 %) were added. Three boilers were electrically heated with total power of 60 kW. Vapours produced in boilers travelled through 180° bend and flowed vertically downward on the horizontally mounted instrumented finned test tube. Excess vapours passed on the auxiliary condenser and condensed vapours for the boiler. Test tube and auxiliary condenser were supplied cooling water and was controlled by two variable aperture type flow meters. Vapour temperature was determined using thermocouple, located above the test tube. Cooling water temperature rise was measured using ten-junction thermopile. Heat flux was determined using cooling water temperature rise and corresponding flow rate. Wall temperature of finned test tube was determined using arithmetic mean of four embedded thermocouples (Fig-2 and 3). All K type thermocouples were calibrated in high precision constant temperature bath against platinum resistance thermometer, accurate to 0.005 K. Detailed explanations of apparatus, procedures, uncertainty analysis and equations were obtained following the studies of (Ali et al., 2013 and Fitzgerald, 2011).

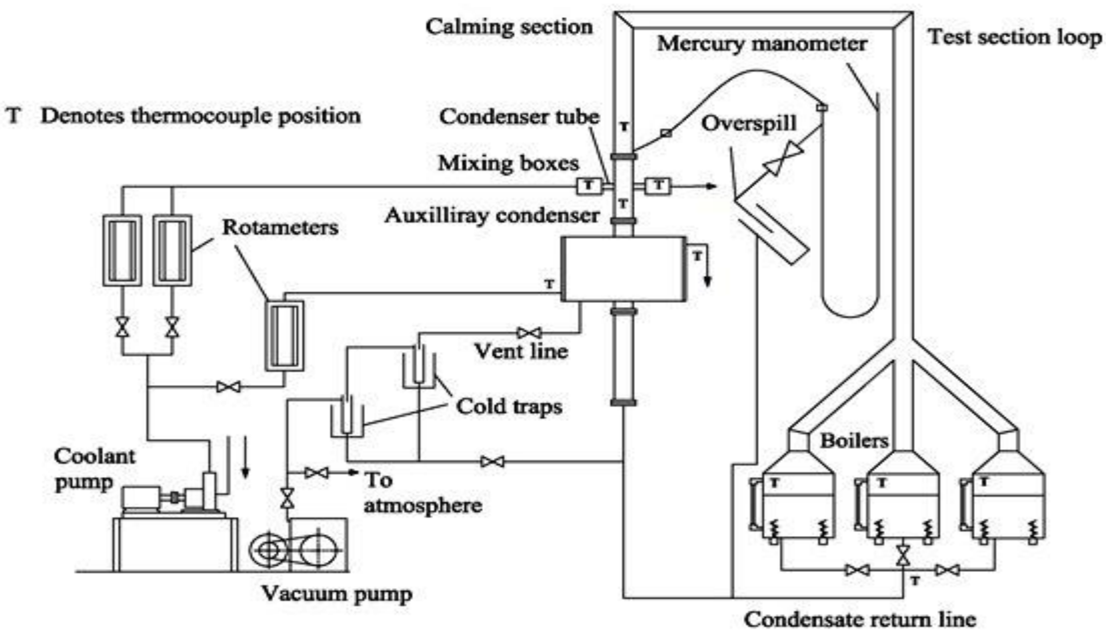


Fig-1:Showing schematic of apparatus used for condensation experiment of steam ethanol mixtures.

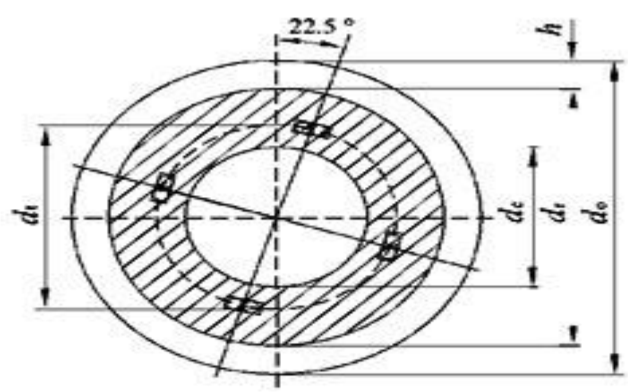


Fig-2:Showing arrangement of thermocouples in finned test tube wall (*h*- fin height, d_r- outside diameter of smooth test tube, fin root diameter of finned tube, d_c - inside diameter of test tube, d_o - diameter of test tube at fin tip, d_t-diameter of thermocouple position in test tubes)

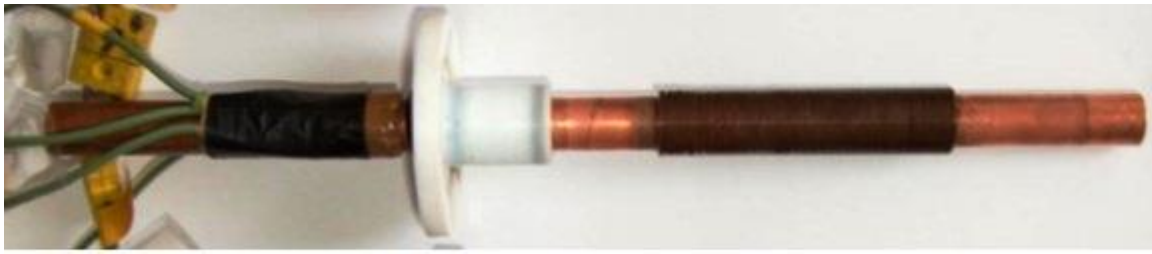


Fig-3:Showing finished Instrumented finned tube

RESULTS AND DISCUSSION

Condensation of pure steam: Great care was taken to make sure that the working fluid was avoided from any contamination and film wise mode of condensation was obtained in all experiments using pure steam.

Heat transfer results: Pure steam condensation on finned tube(Fig-4). Heat flux was plotted as a function of vapour-to-surface temperature difference. The lines for Eq. (1) of Rose (1984) are as under

$$\frac{Nu}{Re_{\mathrm{tp}}^{-1/2}} = \frac{0.9+0.728F^{1/2}}{\left(1+3.44F^{1/2}+F\right)^{1/4}} \tag{1}$$

Equation (1) approaches the Nusselt (1916) equation for $U_V \rightarrow 0$ and the Shekriladze and Gomelauri (1966) forced convection result for $U_V \rightarrow \infty$.

Addition of fins resulted in higher heat transfer as compared to that of smooth tube. The data of present experiment was in agreement with that of Fitzgerald (2012) under similar experimental conditions.

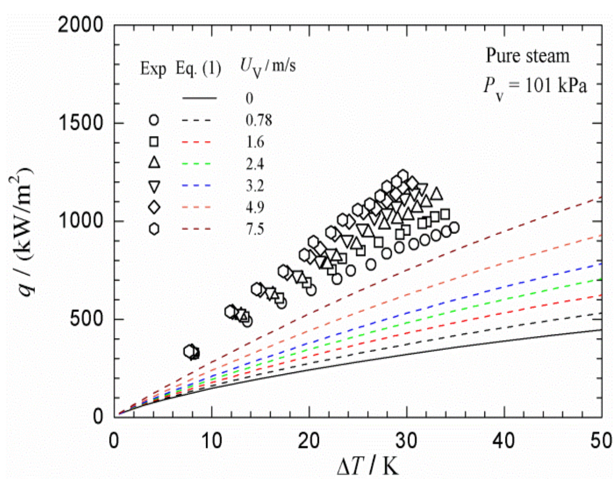


Fig-4:Showing heat flux versus vapour-to-surface temperature difference at different vapour approach velocities for pure steam condensation on finned tube –In comparison to Eq. (1) of Rose (1984). P_v = 101 kPa

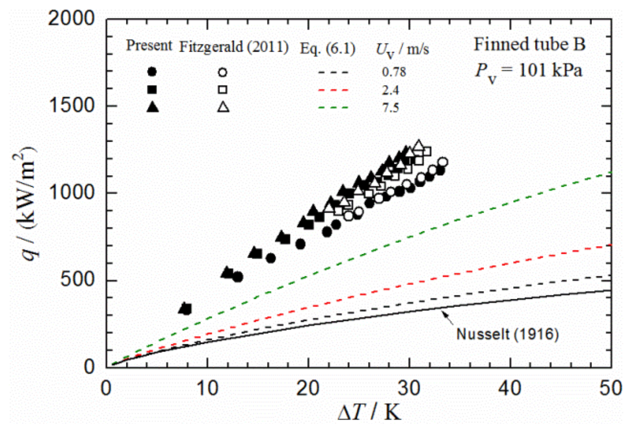


Fig-5:Showing heat flux versus vapour-to-surface temperature difference for different vapour approach velocities (P_V = 101 kPa) –In comparison to Fitzgerlad (2011).

Flooding angles: The flooding angle measured from the top of the tube to the point where interfin space was filled with retained condensate (Fig-6).

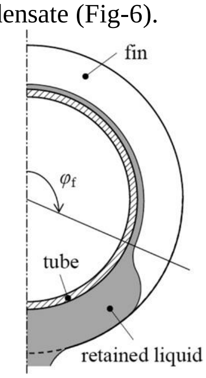


Fig-6:Showing retention Angle(Honda *etal*., 1983)

For quiescent vapours the flooding angle was calculated as per (Honda *et al*., 1983).

$$\varphi_f = \left(\frac{4\sigma\cos\beta}{\rho g s d_o} - 1\right)$$

Where σ was surface tension of the condensate, β was the half angle at the fin tip, ρ was density of the condensate, g was the specific force of gravity, s was the spacing between fins and d_o was the tube diameter at the fin tip. The fully flooded finned tube for pure steam condensation at atmospheric pressure and vapour velocity of 7.5 m/s (Fig. 7) and was in line with the results of (Honda *et al*., 1983).

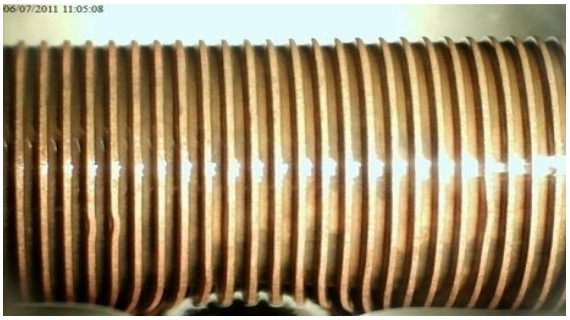


Fig-7:Showing fully flooded finned tube for condensation of pure steam(U_v = 7.5 m/s, P_v = 101 kPa, ΔT = 29.6 K, ε = 1.7, φ_f =0).

Condensation of steam-ethanol mixtures: For condensation of steam ethanol mixtures experiments were conducted at same conditions as that for pure steam experiments.

Heat transfer results: Condensation of steam-ethanol mixtures on finned tube with heat flux plotted against vapour-to-surface temperature difference for different vapour velocities and three pressures was calculated (Fig-8). Lines given for pure steam condensation on smooth tube were included. The heat flux increased monotonously with increasing vapour-to-surface temperature difference for the whole range of the data.

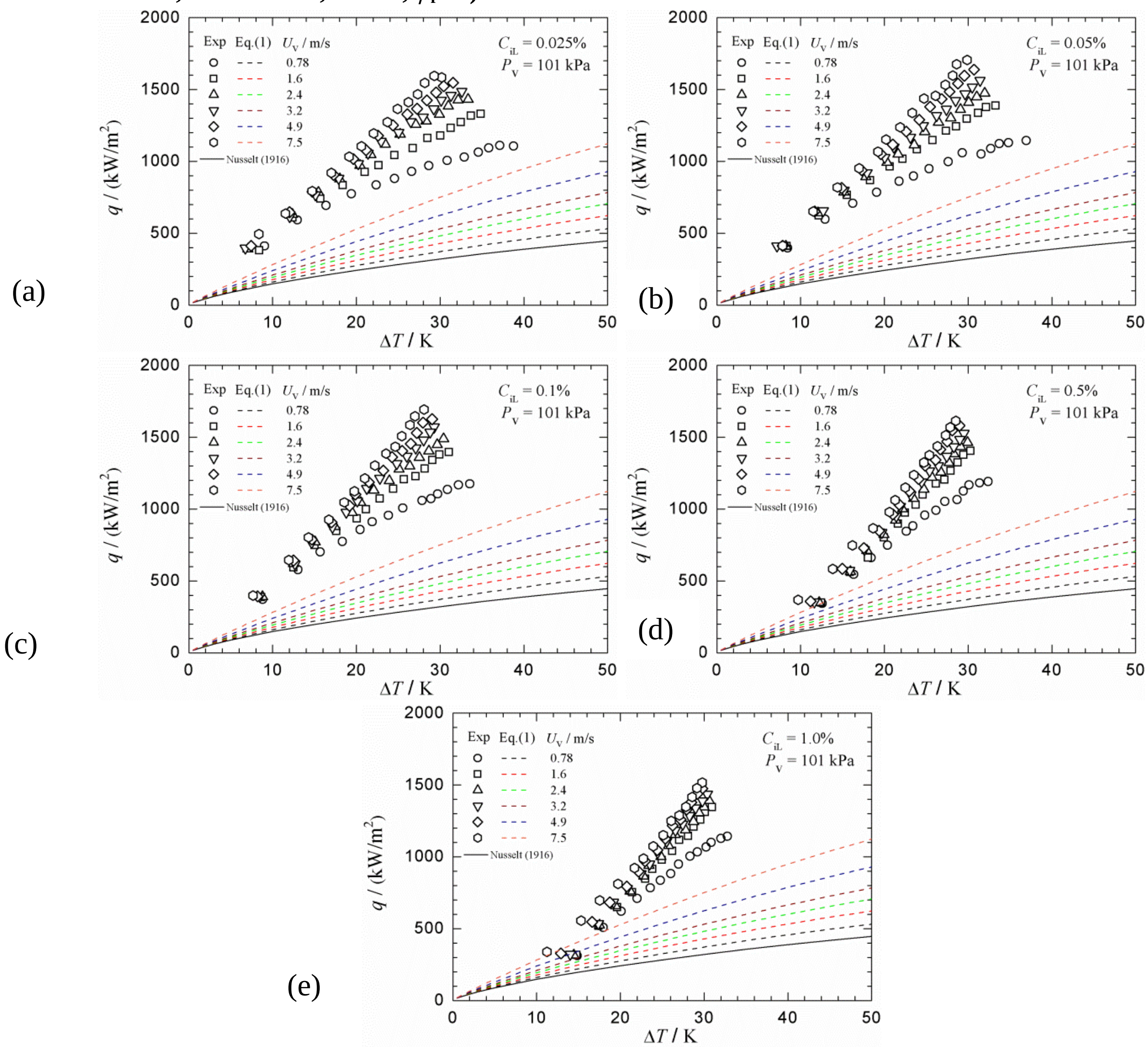


Fig-8:Showing heat flux versus vapour-to-surface temperature difference for different vapour approach velocities for finned tube B (P_V = 101 kPa). (a) C_{iL} = 0.025%, (b) C_{iL} = 0.05%, (c) C_{iL} = 0.1%, (d) C_{iL} = 0.5% (e) C_{iL} = 1.0%.

Flooding angles: Retention angles during condensation of steam-ethanol mixtures under various conditions were calculated (Fig-9). The typical appearance of Marangoni condensation was hardly seen with the naked eye compared with that in the case of smooth tube seen inFig-9. However, a noticeable increase in the flooding angle was observed with increasing ethanol concentration.

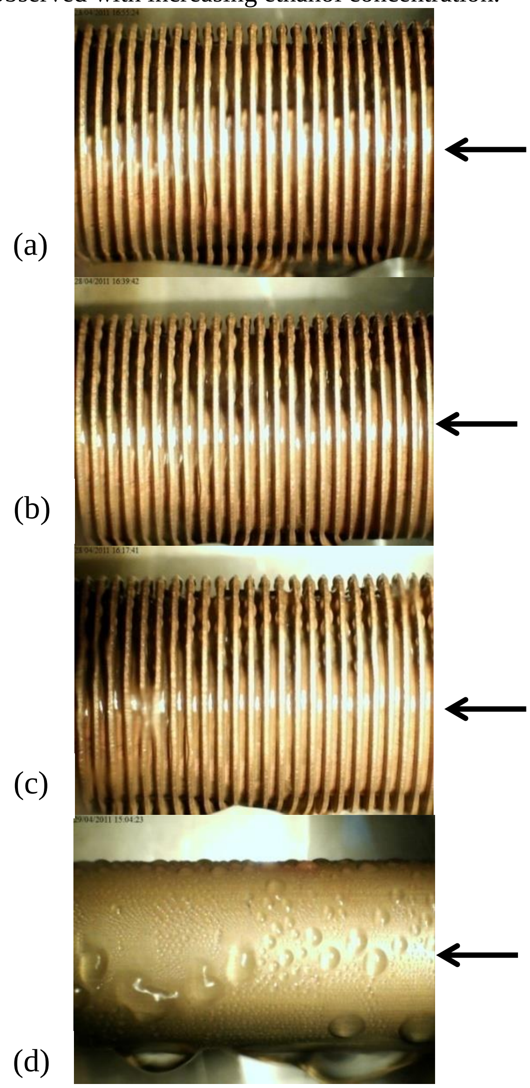


Fig-9:Snowing photographs of finned tube B for condensation of steam-ethanol mixtures. C_{iL} = 1.0 % (arrows indicate retention angle).

(a) U_v = 7.5 m/s, ΔT = 29.6K, ε = 2.0, φ_f = 74°
(b) U_v = 4.9 m/s, ΔT = 29.5K, ε = 2.4, φ_f = 72°
(c) U_v = 2.4 m/s, ΔT = 30.6K, ε = 2.8, φ_f = 39°
(d) U_V = 4.9 m/s, ΔT = 10.9 K, ε = 1.3(Ali *et al.*, 2013)

Flooding angle was plotted against vapour Reynolds number during condensation of steam-ethanol mixtures on finned tube (Fig. 10).The bands represented the fluctuation of liquid levels in the interfin space. The finned tube was fully flooded in all cases except at initial ethanol liquid concentration (1.0%).

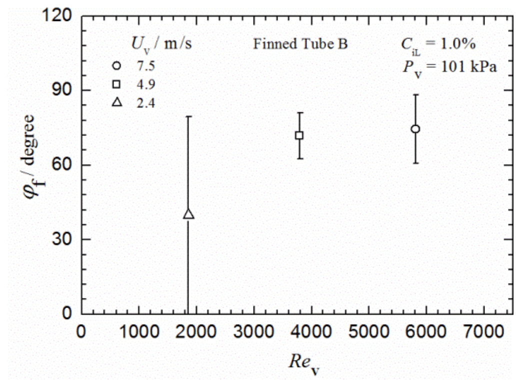


Fig-10:Showing flooding angle versus vapour Reynolds number for finned tube at different approach velocities and initial ethanol concentration of 1.0%.

The effect of vapour shear on retention angle had been reported by Namasivayam and Briggs (2005, 2006) and Fitzgerald (2012). The effect of ethanol on retention angle has not been previously reported. In the present case, ethanol lowered the surface tension of the mixture and reduced flooding. The concentration of ethanol in the boiler at start up was never greater than 1%. Assuming equilibrium conditions this would result in about 10% ethanol in the vapour but again, assuming equilibrium, this would again be 1% in the condensate which would have a negligible effect on the surface tension. A marked increase in the retention angle (i.e. reduction in condensate flooding) would have a big effect on the heat transfer and hence the enhancement ratio.

Enhancement ratio: In order to better quantify the effects of fins and Marangoni condensation it was useful to evaluate an enhancement ratio, defined as the heat-transfer coefficient for a given condition (plain or finned tube, pure steam or ethanol-steam mixture) divided by the corresponding value for pure steam on a smooth tube as given by Eq. (1), at the same vapour-to-surface temperature difference and vapour velocity.

$$\varepsilon = \left[\frac{\alpha_{Exp}}{\alpha_{\mathrm{Eq.1}}}\right]_{\text{same } \Delta T \text{ and } U_V}$$

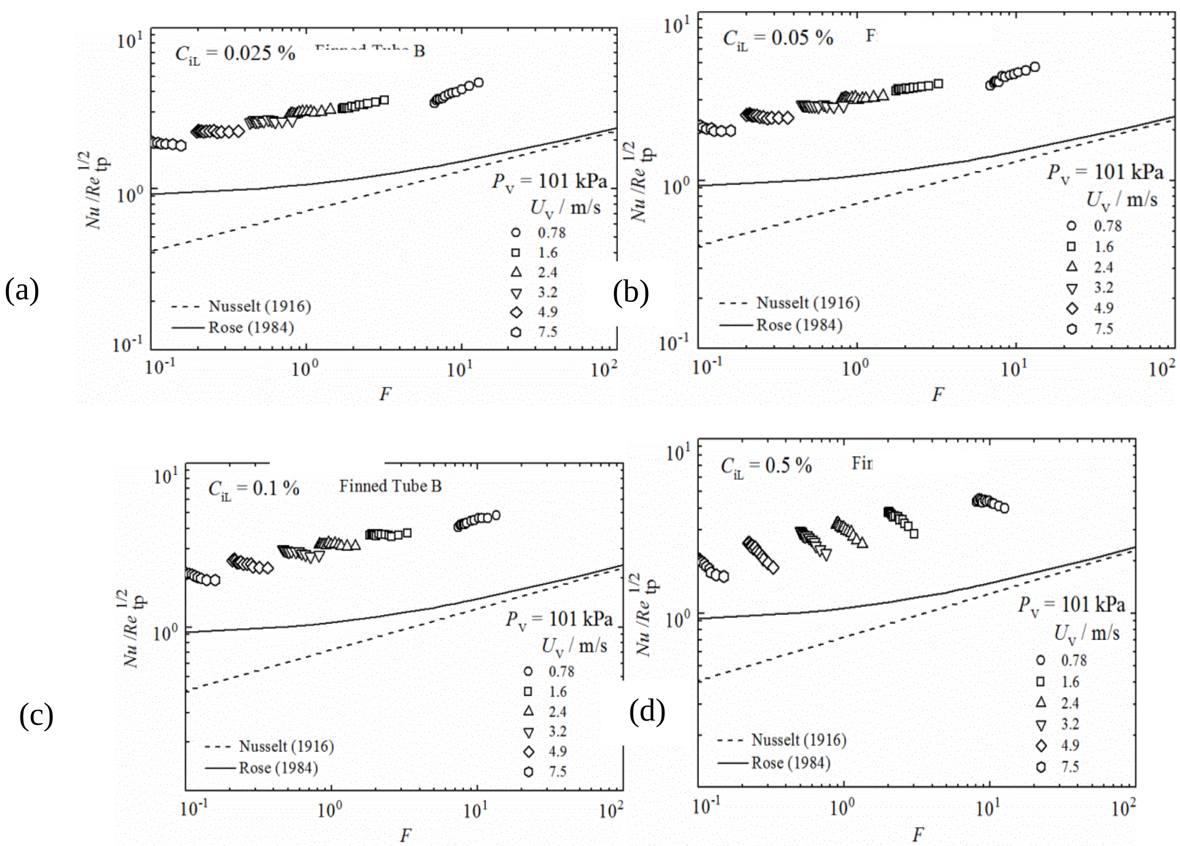
Table1 Experimental conditions and maximum values of vapour-to-surface temperature difference, heat flux, heat-transfer coefficient and heat- transfer enhancement ratio for finned tube are presented in table 1.

Enhancement ratio of around two was observed for pure steam condensation on the finned tube. This was independent of vapour-side temperature difference but a fairly strong function of vapour velocity. Higher vapour velocity giving lower enhancement ratio, indicate that the effect of vapour shear on enhancing the heat transfer was weaker on the finned tube than on the smooth one. This was in agreement with the findings of Namasivayam and Briggs (2005, 2006).

For condensation of steam-ethanol mixtures on the finned tube, enhancement ratio of around three was observed, i.e. a further increase in the heat-transfer coefficient of about 50% over that for pure steam on a finned tube. Enhancement ratio was fairly independent of vapour-to-surface temperature difference for lower ethanol concentrations but increase with higher vapour-to-surface temperature difference for higher ethanol concentrations of 1.0%. This can be attributed to the inherent diffusion resistance in the case of binary mixture condensation. It was interesting to note that, assuming equilibrium conditions in the test section, the ethanol concentration in the vapour was at least more than 10 times than in the liquid (Table 1).

Table 1:Showing values of vapour-to-surface temperature difference, heat flux and heat transfer enhancement in finned tube.

C_{iL} / %		0.025				0.05				0.1				0.5				1.0			
U_V m/s	Re_{tp} /10^3	ΔT_{max} K	q_{max} kW/m^2	α_{max} kW/m^{2}K	ε_{max}	ΔT_{max} K	q_{max} kW/m^2	α_{max} kW/m^{2}K	ε_{max}	ΔT_{max} K	q_{max} kW/m^2	α_{max} kW/m^{2}K	ε_{max}	ΔT_{max} K	q_{max} kW/m^2	α_{max} kW/m^{2}K	ε_{max}	ΔT_{max} K	q_{max} kW/m^2	α_{max} kW/m^{2}K	ε_{max}
										P_V = 101 kPa											
		C_V = 1.2 %, T_V = 373 K				C_V = 1.3 %, T_V = 373 K				C_V = 1.9 %, T_V = 373 K				C_V = 6.1 %, T_V = 373 K				C_V = 10.6 %, T_V = 372 K			
0.78	31.6	38.8	1106	42	3.0	35.7	1145	43	3.0	33.5	1175	45	3.0	32.4	1191	39	3.1	32.7	1141	35	2.9
1.6	65.7	34.9	1329	47	2.9	33.3	1387	49	3.0	31.0	1396	50	3.2	30.3	1404	47	3.2	31.0	1343	43	3.0
2.4	99.7	33.3	1431	51	2.8	32.0	1475	52	2.9	30.4	1489	51	3.0	29.9	1462	49	3.0	30.6	1389	45	2.8
3.2	134.1	32.6	1486	51	2.7	31.4	1562	53	2.8	29.3	1570	54	2.9	29.5	1526	52	2.9	30.4	1435	47	2.7
4.9	203.2	31.6	1547	54	2.4	30.1	1638	55	2.6	29.0	1625	57	2.7	29.0	1581	55	2.6	29.8	1474	49	2.4
7.5	311.7	30.1	1585	55	2.2	29.9	1706	59	2.3	28.0	1693	61	2.4	28.5	1613	57	2.2	29.8	1517	51	2.0



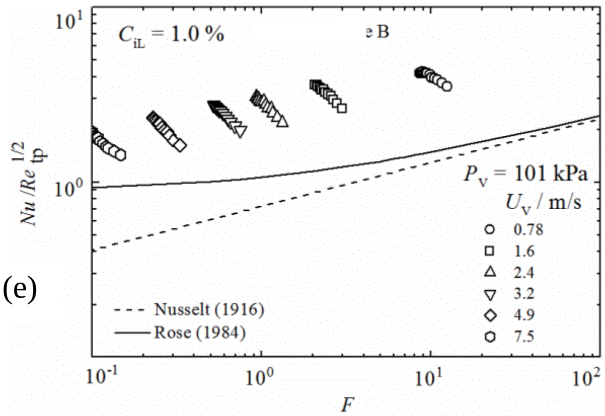


Fig-11:Showing comparison of present steam-ethanol data for finned tube with Eq. of Nusselt (1916) and Eq. (1) of Rose (1984) (P_V = 101 kPa). (a) C_{iL} = 0.025%, (b) C_{iL} = 0.05%, (c) C_{iL} = 0.1%, (d) C_{iL} = 0.5%, (e) C_{iL} = 1.0%.

Conclusion: Experimental data of heat transfer and condensate retention have been obtained for condensation of steam-ethanol mixtures over a range of vapour velocities on a finned tube. The condensate retention between fins was found lower, compared with that of pure steam condensation, resulting from lower surface tension due to the addition of ethanol. For pure steam condensation the vapour-side enhancement ratio due to the fins alone was fairly uniform at about 2 for the whole range of vapour velocities and vapour-to-surface temperature differences tested. When ethanol was added to the vapour it resulted in vapour-side enhancement around 3, a further 50% enhancement of the heat transfer over most of the range of data, the exception being at relatively high ethanol concentrations (C_{iL} = 1.0%) and low vapour-to-surface temperature differences. This could result in compact condensers, useful in applications where reductions in size and cost could be beneficial such as aerospace and offshore applications. However, larger fin spacing (lower level condensate retention between fins) and fin height (larger temperature gradients) may provide higher heat-transfer enhancement. Further investigation is needed for maximum heat transfer.

Nomenclature

C_{iL} concentration of ethanol (initial in liquid at room temperature)
C_v equilibrium concentration of ethanol in vapour
d_r outside diameter of smooth test tube, fin root diameter of finned tube
d_c inside diameter of test tube
d_o diameter of test tube at fin tip
d_t diameter of thermocouple position in test tubes
F dimensionless parameter, $\rho g d h_{fg}/kU_v^2\Delta T$
g specific force of gravity
h fin height
h_{fg} latent heat of vaporization
k thermal conductivity of condensate
Nu Nusselt number based on outside diameter of smooth tube, $\alpha d / k$
P_v vapour pressure
q heat flux
Re two phase Reynolds number, $\rho U_v d/\mu$
Re_v vapor Reynolds number
s fin spacing
T_{wo} mean outside wall temperature of test tube
T_v vapour temperature
U_v upstream vapour velocity based on cross sectional area of test section

Greek symbols

α vapour-side, heat-transfer coefficient, $q/\Delta T$
β half angle at the fin tip
σ surface tension
ε heat-transfer enhancement ratio
ΔT vapour-to-surface temperature difference, $T_v - T_{wo}$
ρ density of saturated liquid
μ dynamic viscosity of condensate at saturation condition
φ_f condensate retention angle or flooding angle measured from the top of a horizontal low-finned tube to the position at which the inter-fin space becomes full of condensate

Subscripts

Exp experimental
max maximum

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