

## CONDENSATE RETENTION OF WATER-ETHANOL MIXTURE ON HORIZONTAL ENHANCED CONDENSING TUBES

by

**Muhammad ABUBAKER<sup>a</sup>, Hafiz Muhammad ALI<sup>b\*</sup>, Fahad NOOR<sup>c</sup>,  
Muhammad IMRAN<sup>c</sup>, and Tehmina AMBREEN<sup>a</sup>**

<sup>a</sup> Department of Mechanical Engineering, COMSATS Institute of Information and Technology,  
Sahiwal, Pakistan

<sup>b</sup> Mechanical Engineering Department, King Fahd University of Petroleum and Minerals,  
Dhahran, Saudi Arabia

<sup>c</sup> Department of Mechanical Engineering, University of Engineering and Technology,  
Lahore, Pakistan

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*Condensate retention has been found an important parameter for heat transfer on horizontal enhanced condensing tubes. In this research, five pin-fin (varying in circumferential pin spacing) and three integral-fin horizontal tubes are investigated for condensate retention angle (which is measured from the top of tooth to the fully flooded flank) using water-ethanol mixture. An attempt was made to find the optimum concentration of ethanol in water for maximum retention angle. Concentration of ethanol was varied in between 0.5% to 1.5% by weight. Data revealed the importance of integral-fin tube over pin-fin tube as significant increase in retention angle was observed for integral-fin tube ((having same longitudinal spacing, tooth thickness, tooth height, inner and outer diameter) while retention angle for pin-fin tubes remain unchanged. Optimum ethanol concentration was observed to be 0.75%.*

Key words: *condensate retention, pin-fin and integral-fin tubes, water-ethanol mixture, dropwise condensation, binary mixture*

### Introduction

#### *Film-wise condensation*

Researchers have found that the measurement of condensate retention during static condensation was in agreement found in real condensation [1-5]. Measurement of retention angle has been found to be an important parameter in order to understand the condensation heat transfer on enhanced tubes *i. e.* integral-fin and pin-fin.

Researchers have reported number of heat transfer models in which the key factor was retention angle [6-8]. Honda *et al.* [4] reported the model to predict the retention angle for free convection condensation on integral-fin tubes, see eq. (1). This model predicted the experimental data in good agreement [1-5, 9]. Recently, two new models [2, 10], see eqs. (2) and (3), have been reported which predict the retention angle in case of forced convection condensation on integral-fin tubes and free convection condensation on pin-fin tubes respectively. Both of these models show agreement to the already published data to within  $\pm 20\%$  [1, 2, 11].

\* Corresponding author, e-mail: hafiz.ali@kfupm.edu.sa

In past couple of decades, horizontal pin-fin tubes have shown superior performance over integral-fin tubes and many heat transfer investigations have been published [12-19]. Many researchers have proven the superiority of pin-fin tubes over integral-fin tubes in terms of less condensate retention [1, 10, 11, 20]. In all cases, retention angle,  $\varnothing_f$ , in case of pin-fin tube was found greater compared to equivalent integral-fin tubes:

$$\varnothing_f = \cos^{-1} \left[ \left( \frac{2\sigma \cos \theta}{\rho g s R_o} \right) - 1 \right] \quad \text{for } s < 2h \quad (1)$$

$$\varnothing_f = \left\{ \left[ A s \left( \frac{\sigma}{v^2 s \rho_c} \right)^a \left( \frac{sg}{v^2} \right)^b \left( \frac{\rho_a}{\rho_c} \right)^b \right] - 1 \right\} \quad (2)$$

$$\varnothing_f = \cos^{-1} \left[ \left( 1 - N \frac{s_c}{t_c} \right) \left( \frac{2\sigma}{\rho g s R_o} \right) - 1 \right] \quad \text{for } s < 2h \quad (3)$$

Recently Ali and Abubaker [1, 11] measured retention angle for the cases of pin-fin and integral-fin tubes during forced convection condensation. Wide range of vapour velocity was selected from free convection to 18 m/s. Geometrical parameters tested were circumferential pin spacing and circumferential tooth thickness for the case of pin-fin tubes. Three fluids water, ethylene glycol and R-141b were tested. Data showed less condensate retention on pin-fin tubes over integral-fin tubes at all vapour velocities.

Effect of mass-flow rate on condensate retention on eight finned tubes was reported by Ali *et al.* [21] using eight finned tubes with same root diameter and different spacing. Interesting results were obtained as condensing tubes were found unaffected by the variation of mass-flow rate. An extensive literature review on condensate retention on enhanced tubes has also been reported by Ali [22].

### Drop-wise condensation

Non-film wise or pseudo-drop wise condensation of a binary vapor mixture of a positive system (mixture in which more volatile component contains low surface tension and vice versa) resulting from uneven surface tension distribution on condensate surface, is known as Marangoni condensation phenomena. Marangoni condensation phenomena is predominantly stimulated by concentration and/or temperature gradients recognized as Marangoni effect [23, 24]. The Marangoni condensation of binary mixtures attained massive attention in past decade when experimental results of Utaka and Terachi [25, 26] revealed significantly enhanced heat transfer characteristics as compared to pure steam.

Mirkovich and Missen [27] are pioneer researchers who discovered non-film wise phenomenon of condensation for binary vapors and calculated heat transfer coefficients for condensation of the numerous types of binary vapors [28]. Fujii *et al.* [29] observed condensation of ethanol-water vapor mixtures on a horizontal tube and categorized five different modes of the Marangoni condensation mechanism, including drop, streak, ring, smooth film and wavy film, respectively. The results showed reduced heat transfer coefficients as compared to pure steam. Similar heat transfer trends were observed in other works too [29-31]. The first investigation that publicized enhanced heat transfer characteristics as compared to the pure steam was conducted on a vertical plate by Utaka and Terachi [25, 26]. Results stated that by increasing vapor to surface temperature difference, the heat transfer coefficient inhibited non-linear characteristics with extreme values, and the heat transfer was boosted approximately two to eight

times. Since then a considerable amount of literature has been published validating enhanced heat transfer characteristics of Marangoni condensation mechanism on both horizontal/vertical plates [32-37] and conventional condensing tubes [31, 36, 38-45]. Morrison and Deano [38] demonstrated that at very low ammonia mass fraction of vapor mixtures, heat transfer was enhanced up to 13-30%. Kim *et al.*[39] experimental results exposed similar results with enhanced heat transfer rate up to 30% for 2-ethyl-1-hexanol.

In further researches of Utaka and Wang [32, 33] reported that at very low ethanol mass fractions of 0.5-1%, enhancement of condensation heat transfer was up to eight times when compared to pure steam. Later on, study of vapor velocity effect on Marangoni condensation for ethanol-water vapor mixtures [34] and measurement of thin condensate film thickness during the solutal Marangoni drop wise condensation phenomenon were performed [46]. The results of Philpott and Deans [40] addressed approximate enhancement of average and local condensation heat transfer rate up to 14% and 34% with inlet ammonia concentrations of 0.2-0.9% and 0.2-2%, respectively. Theoretical and experimental results of Vemuri *et al.* [41] presented that condensation heat transfer coefficient could be enhanced approximately 1.47 times by using 2-ethoxyethanol additives when compared to film wise condensation. Murase *et al.*, [42] achieved high heat transfer enhancement for experimentation on a horizontal tube.

A semi empirical model was also presented by Li *et al.* [47] to explain heat transfer characteristics of Marangoni condensation for ethanol-water vapor mixtures.

To the best of authors knowledge, insufficient literature exists to report the retention angle of water-ethanol on horizontal enhanced tubes except the recent publication of Ali *et al.* [48]. Their results showed strong dependence of retention angle on ethanol concentration, upstream vapor velocity, condensate temperature at the interface and consequently the surface tension. However, their work does not provide a systematic geometric effect along with water-ethanol concentration on retention angle. In the present investigation, static (no condensation) retention angle measurements are made on five rectangular pin-fin tubes and three integral fin tubes by systematically varying their geometries to get the effect of water-ethanol concentration and of tube geometry on retention angle.

### Experimental set-up

A simple apparatus was designed to measure the retention angle of water-ethanol mixture, as shown in fig. 1. Separating funnel (with adjustable valve) was used to provide the water-ethanol mixture towards the test tubes. One end of test tubes, see figs. 2 and 3 for tested tubes, was kept open to ensure the continuous flow of condensate along the circumference through small holes provided on the upper side. Specifications of these tubes are given in tab. 1. In order to validate the experimental set-up, data with pure water was compared with already published data [1, 2] and a good agreement can be seen in fig. 4.

### Methodology

Retention angle provides the criteria to see the extent of flooding on test tubes and can be characterized as the angle measured between the fully flooded finflank to the top of tube. Previously, two methods have been used

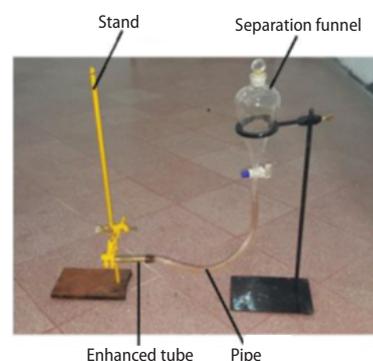


Figure 1. Experimental set-up

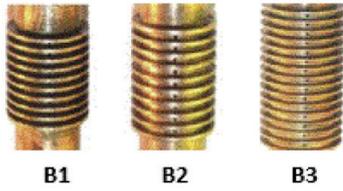


Figure 2. Integral-fin tubes in present investigation

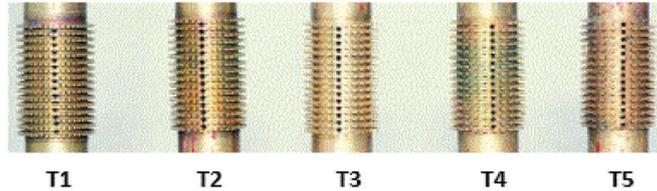


Figure 3. Pin-fin tubes used in present investigation

Table 1. Specification of test tubes used in present investigation

Tubes	$t_c$ (root)	$t_c$ (tip)	$s_c$	$t$	$s$	$h$	$d_r$	$d_0$
T0	0.4	0.62	0.5	0.5	1	1.6	12.7	15.9
T1	0.36	0.62	0.75	0.5	1	1.6	12.7	15.9
T2	0.33	0.64	1.0	0.5	1	1.6	12.7	15.9
T3	0.28	0.65	1.25	0.5	1	1.6	12.7	15.9
T4	0.23	0.64	1.5	0.5	1	1.6	12.7	15.9
T5	0.22	0.74	2	0.5	1	1.6	12.7	15.9
B1	-	-	-	0.5	0.6	1.6	12.7	15.9
B2	-	-	-	0.5	1	1.6	12.7	15.9
B3	-	-	-	0.5	1.5	1.6	12.7	15.9

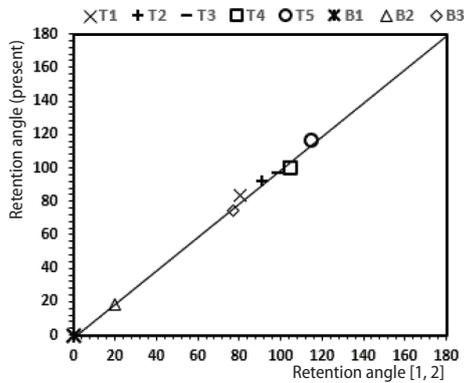


Figure 4. Comparison of present data with already published data [1, 2]

[1, 10, 20] for measurement of retention angle, namely pin counting method and the photographic method. It has been shown that these two methods agreed to each other within  $\pm 10\%$ . Pi-counting method has been found to be effective in calculating very small and very large angles. However, for intermediate angles, as observed in this investigation, photographic method is convenient to use with good accuracy.

Tubes were placed horizontally on the stand and loaded with test fluid. The extent of retention was measured by the following formula. Pictures were captured from both sides of test tubes to get maximum accuracy in results. These photographs were then analyzed to calculate the retention angle as presented in result and discussion section:

$$\cos \varnothing_f = \left( 2 \frac{L_{\varnothing}}{d_0} - 1 \right) \tag{4}$$

**Results and discussion**

Figures 5 and 6 shows sample of photographs with arrows pointing the extent of retention. Ethanol concentration vs. retention angle are plotted in figs. 7 and 8. For both types of tubes tested, ethanol addition considerably increases the retention angle when compared with pure water.

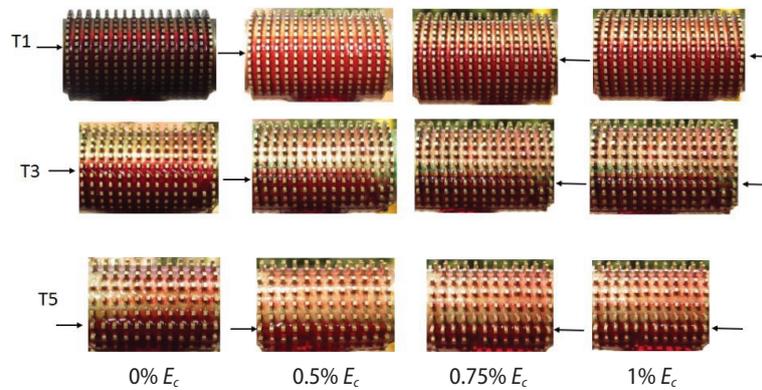


Figure 5. Flooding on pin-fin tubes

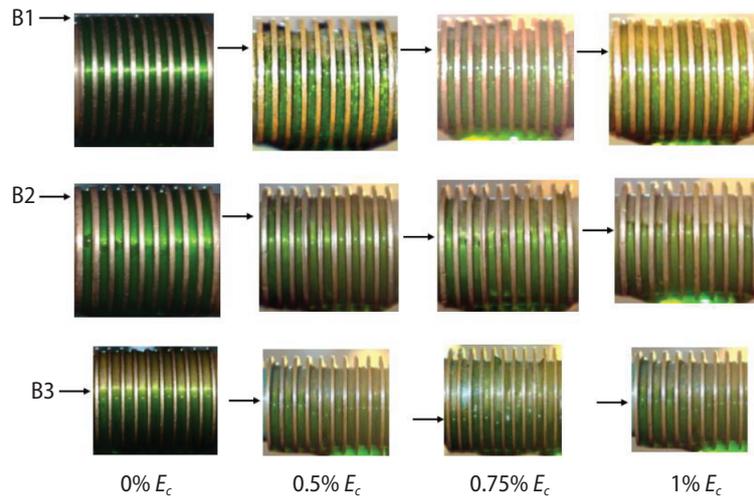


Figure 6. Flooding on integral-fin tube B2

In case of pin-fin tubes, the maximum of  $8^\circ$  increase in  $\varnothing_f$  was observed for tube T2 ( $s_c = 0.75$  mm). However, change in ethanol concentration showed almost no effect on retention angle for these pin-fin tubes. Circumferential pin spacing was found to be an important parameter as retention angle increased with the increase of circumferential pin spacing and vice versa.

For integral fin tube B2 (having same dimensions as that of pin-fin tubes), the effect on retention angle with ethanol concentration was remarkable. With pure water as test fluid,  $\varnothing_f$  was measured to be  $18^\circ$  which reaches to  $82^\circ$  at 0.75% ethanol concentration. Further increase in ethanol concentration caused  $\varnothing_f$  to decrease to  $67^\circ$  at 1.5% ethanol concentration.

Integral-fin tubes B1 ( $s_c = 0.5$  mm) and B3 ( $s_c = 1.5$  mm) were also tested to ensure the potential of these tubes in case of binary mixtures. Again  $\varnothing_f$  was found to have strong dependence on ethanol concentration. At 0% ethanol concentration,  $\varnothing_f$  was observed to be fully flooded in case of tube B1 which increases to  $62^\circ$  at 0.75% ethanol concentration and then decreases to  $44^\circ$  at 1.5% ethanol concentration. Similar trend can also be observed for Test tube

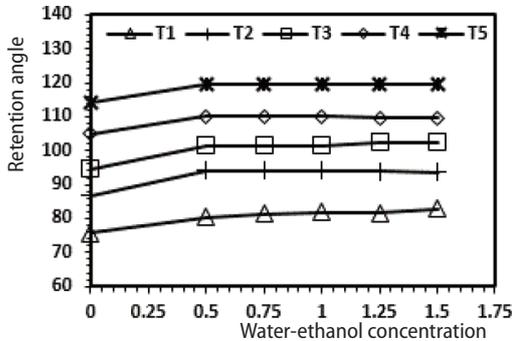


Figure 7. Measurement of retention angle on pin-fin tubes

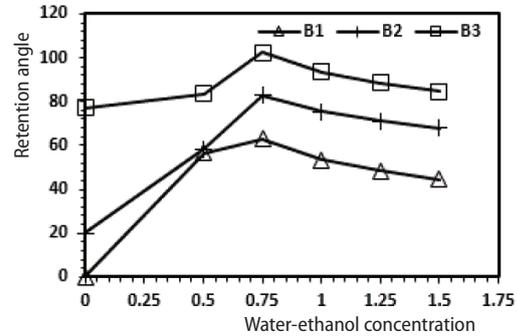


Figure 8. Measurement of retention angle on integral-fin tubes

B3 where  $\theta_f$  changes from  $77^\circ$  at 0% ethanol concentration to  $102^\circ$  at 0.75% ethanol concentration. The graphs also show the importance of longitudinal fin spacing at all ethanol concentrations. Data also shows the strong potential of integral-fin tubes compared to pin-fin tubes when binary mixture is used.

## Conclusion

Effect of water-ethanol concentration was studied on enhanced tubes and following important results were deduced.

Ethanol addition influences retention angle for both sets of tubes, however, a strong effect was measured for integral-fin tubes. In case of pin-fin tubes, the maximum increase in retention angle was measured to be  $8^\circ$ , for tube T2 with ( $s_c = 0.75$  mm) when compared with pure water. As already discussed, integral-fin tubes showed tremendous increase in retention angle and maximum of  $65^\circ$  increase in retention angle was measured for test tube B2 ( $s = 1.0$  mm).

It was also observed that change in ethanol concentration had least effect on pin-fin tubes while an optimum of 0.75% ethanol concentration was measured for all integral-fin tubes. Above and below this concentration, retention angle decreased.

Circumferential pin spacing (in case of pin-fin tubes) and longitudinal fin spacing (in case of integral-fin tubes) appeared to be important geometric parameters affecting the retention angle.

Earlier investigations have proved the superiority of pin-fin tubes over integral-fin tubes during free and forced convection. However, present investigation findings draw attention towards integral-fin tubes when binary mixture is dealt with.

## Nomenclature

$A, N, a, b, c$  – constants

$d_0$  – outer diameter

$d_r$  – root diameter

$E_c$  – Ethanol concentration

$g$  – gravitational constant

$h$  – pin or fin height

$L_\phi$  – flooding length

$s$  – longitudinal pin or fin spacing

$s_c$  – circumferential pin spacing

$t$  – pin or fin thickness

$t_c$  – circumferential tooth thickness

$v$  – vapour velocity

### Greek symbols

$\rho$  – density of condensate

$\rho_a$  – density of air

$\rho_c$  – density of condensate

$\sigma$  – surface tension

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