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An Investigation of Condensate Retention on Pin-Fin Tubes

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***Abstract*-Fifteen rectangular pin fin tubes are tested for retention angle measurements under static conditions (i.e. with no condensation). It was found that retention angles for the case of pin fin tubes were larger in a range of 5% to 60% when compared with the retention angles for integral fin tubes with same radial and axial dimensions. A semi empirical correlation is also presented to predict the retention angle for pin fin tubes; predicted values are in good agreement with measured values.**

***Keywords*—Condensate Flooding, Condensate Retention, Pin-Fin Tubes, Retention Angle**

I. Introduction

EXPERIMENTAL investigations performed for condensate retention on three dimensional pin fin tubes (see Figure 1 for a schematic of pin fin tube) have considerably shown deceasing trends in condensate retention when compared with integral fin tubes with equal dimension in radial and axial directions. Briggs [1] and Sukathme et al. [2] measured retention angles on geometrically enhanced pin fin tubes using R-113, water, ethylene-glycol and R-11 respectively, both reported less liquid retention on lower part of tubes (i.e. larger condensate retention angles) for pin fin tubes when compared with integral fin tubes of equal dimensions.

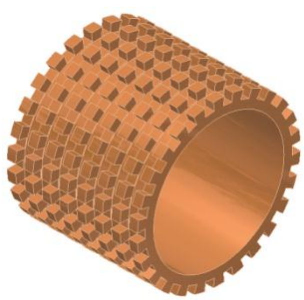

Figure 1. A Representation of Three Dimensional Pin Fin Tube

In this investigation liquid retention measurements are reported and an empirical correlation has been presented for predicting retention angle on three dimensional pin fin tubes.

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II. Measurement Of Flooding Angle On Three Dimensional Tubes

In the present investigation, static (no condensation) retention angle measurements are made on 15 rectangular pin-fin tubes. Table I shows the dimensions of the pin-fin tubes. Water, ethylene glycol and R-113 are used as test fluids. Table I also shows the dimensions of a special pin-fin tube (S1) tested by Sukathme et al. [2] using R-11 and it will be used here for comparison purpose.

TABLE I
DIMENSIONS OF PIN-FIN TUBES (MM)

Tubes	*t*	s_c	*s*	$t_{c\ root}$ *	$t_{c\ tip}$ *	$t_{c\ mean}$ *	*h*	*d*
P1	0.5	1.0	1.1	0.4	0.6	0.5	0.9	12.7
P2	0.5	1.0	1.1	0.4	0.7	0.55	1.6	12.7
P3	0.5	0.5	0.5	0.7	0.8	0.75	0.9	12.7
P4	0.5	0.5	0.5	0.7	0.9	0.8	1.6	12.7
P5	0.5	0.5	0.5	0.4	0.5	0.45	0.9	12.7
P6	0.5	0.5	0.5	0.4	0.6	0.5	1.6	12.7
P7	0.5	0.5	1.5	0.4	0.6	0.5	1.6	12.7
P8	0.5	1.0	1.5	0.3	0.7	0.5	1.6	12.7
P10	0.5	0.5	1.5	0.8	1.2	1.0	1.6	12.7
P11	0.5	1.0	1.5	0.8	1.2	1.0	1.6	12.7
P12	0.5	1.5	1.5	0.7	1.3	1.0	1.6	12.7
P1 *Brass*	0.5	1.0	1.1	0.4	0.6	0.5	0.9	12.7
P2 *Brass*	0.5	1.0	1.1	0.4	0.7	0.55	1.6	12.7
P1 *Bronze*	0.5	1.0	1.1	0.4	0.6	0.5	0.9	12.7
P2 *Bronze*	0.5	1.0	1.1	0.4	0.7	0.55	1.6	12.7
S1	0.305	0.315	0.405	0.9	0.47	0.689	1.22	12.7

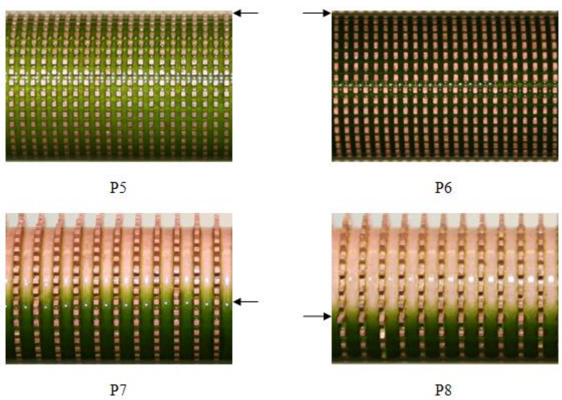
* The pins were produced by making rectangular slots in the axial direction of the tube. All pins have slightly larger pin thickness than tip in circumferential direction.

Two methods are used here to measure the extent of condensate flooding on pin-fin tubes,

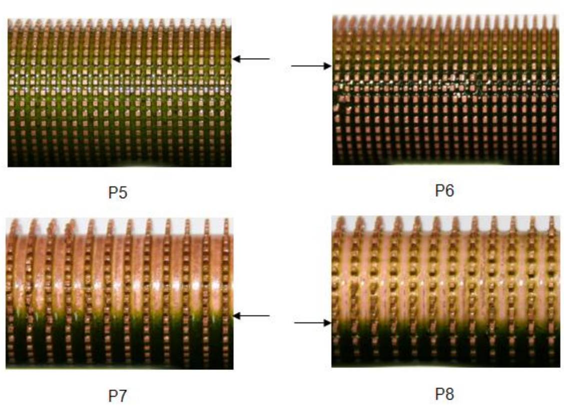
- Photographic Method
- Pin Counting Method

A. Photographic Method

In this method, tubes were mounted horizontally and test fluid was sprayed flowing vertically downward using a fine spray. A small amount of green dye was added into the working fluid to help pick out the flooding angle. The tube was loaded with the fluid up to the point where flooding level on the tube becomes constant, and a photograph taken using a digital camera. A few sample photographs of condensate flooding on pin-fin tubes using water and ethylene glycol are shown in Figure 2 a and b respectively and an arrow is placed on each photograph to highlight flooding point where the pin flanks become fully flooded. Photographs were enhanced electronically and retention angles were then calculated. The accuracy of photographic method, however, seems to be within ± 0.05d for very small or very large flooding angles. As no dye was dissolvable into R-113 to more clearly identify the flooding point, it was not possible to pick out flooding point of transparent R-113 on pin-fin tubes using the photographic method.



(a) Water



(b) Ethylene Glycol

Figure 2.Condensate Flooding on Pin-Fin Tubes

B. Pin Counting Method

The pins were counted in the direction of circumference for the region above the condensate flooding (i.e. the region that contains no liquid or condensate) and then by dividing with the total number of pins per circumference, and then flooding angle was obtained. This method could be used to find the flooded angle for all fluids tested. For tubes with higher number of pins around the circumference, however, the pin counting method is thought to be only good to ± 1 pin pitch.

TABLE II
MEASURED RETENTION ANGLES

	Water			*Ethylene Glycol*			*R-113*
Tubes	Φ_f/π Photo	Φ_f/π Pin Count	Φ_f/π Mean	Φ_f/π Photo	Φ_f/π Pin Count	Φ_f/π Mean	Φ_f/π Pin Count
P1	0.58	0.58	0.58	0.73	0.76	0.745	0.93
P2	0.54	0.54	0.54	0.71	0.67	0.69	0.9
P3	0	0	0	0.29	0.28	0.285	0.69
P4	0	0	0	0.32	0.28	0.3	0.708
P5	0	0	0	0.29	0.36	0.325	0.777
P6	0	0	0	0.36	0.34	0.35	0.733
P7	0.51	0.49	0.5	0.67	0.65	0.66	0.8
P8	0.61	0.61	0.61	0.76	0.72	0.74	0.9
P10	0.46	0.46	0.46	0.66	0.6	0.63	0.8
P11	0.58	0.54	0.56	0.73	0.63	0.68	0.864
P12	0.61	0.61	0.61	0.74	0.66	0.7	0.861
P1 $_{Brass}$	0.58	0.56	0.57	0.67	0.69	0.68	0.9
P2 $_{Brass}$	0.62	0.6	0.61	0.7	0.72	0.71	0.916
P1 $_{Bronze}$	0.57	0.57	0.57	0.67	0.69	0.68	0.9
P2 $_{Bronze}$	0.59	0.53	0.56	0.71	0.71	0.71	0.9

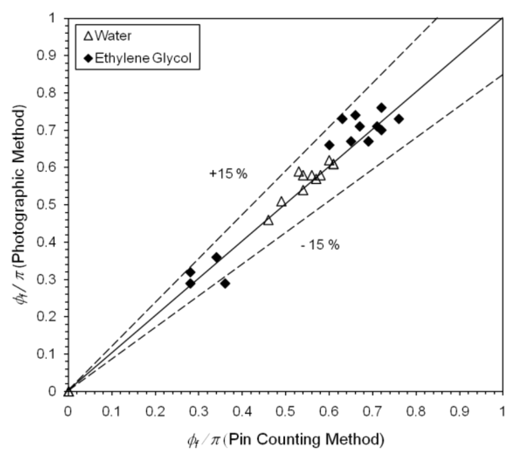


Figure 3. Comparison of Results of Two Methods of Measuring Retention Angle

Flooding angles obtained by using both methods on all pin-fin tubes are listed in Table II. Figure 3 gives a comparison of the results of the two methods of measuring retention angle for water and ethylene glycol. The methods agree with each other to within 15 %, so for water and ethylene glycol a mean value of two results is thought to be more reasonable to use.

TABLE III
EXPERIMENTAL RETENTION ANGLES REPORTED BY BRIGGS [1] AND SUKHETME ET AL. [2]

	Briggs [1]			Sukathme et al. [2]
Tubes	Φ_f/π (Water)	Φ_f/π (Glycol)	Φ_f/π (R-113)	Φ_f/π (R-11)
P1	0.58	0.75	0.93	
P2	0.59	0.64	0.93	
P3	0	0.33	0.78	
P4	0	0.44	0.75	
P5	0	0.4	0.8	
P6	0	0.36	0.8	
P7	0.48	0.61	0.84	
P8	0.59	0.66	0.9	
P10	0.47	0.63	0.88	
P11	0.53	0.63	0.91	
P12	0.59	0.61	0.92	
S1				0.79

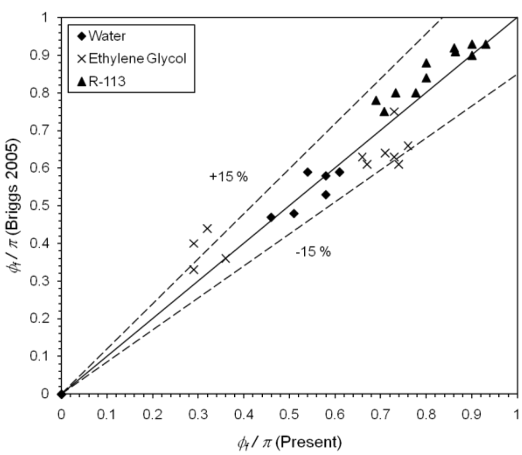


Figure 4. Comparison of Present Measured Retention Angles with those of Briggs [1]

Table III lists the retention angle measurements obtained by Briggs [1] on a set of tubes (eleven copper pin fin) which are used in the current investigation and also retention angle measurement obtained by Sukathme et al. [2] on a copper pin-fin tube using R-11. Figure 4compares the present retention angle measurements made on copper pin-fin tubes (P1 to P12) with those of Briggs [1] retention angles, almost all the data show agreement to within 15 %.

III. COMPARISON OF MEASURED RETENTION ANGLES FOR PIN-FIN TUBES WITH THE MODEL OF HONDA ET AL. [3]

Condensate retention was analyzed by Honda et al. [3] on trapezoidal integral fin tubes and they proposed the following theoretical equation for the retention angle,

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

Excellent agreement of Eqn. 1 with measured retention angles on integral-fin tubes for a range of fluids has been reported by many investigators (see for reference Honda et al. [3] and Yau et al. [4]).

To analyze the increase in retention angle (or reduction in condensate flooding) for three dimensional pin tubes from integral fin tubes of equal dimensions, the measured retention angles on pin-fin tubes are compared with Eqn. 1. Figure 5 compares the measured retention angles of the present investigation, Briggs [1] and Sukathme et al. [2] with Eqn. 1, it can be seen that theory under predicts the measured retention angles on pin-fin tubes in a range of 5% to 60 %. Retention angles, however, decrease with increasing values of $\sigma/\rho g s R_o$, indicating that this is an important parameter for both three dimensional pin fin and integral fin tubes.

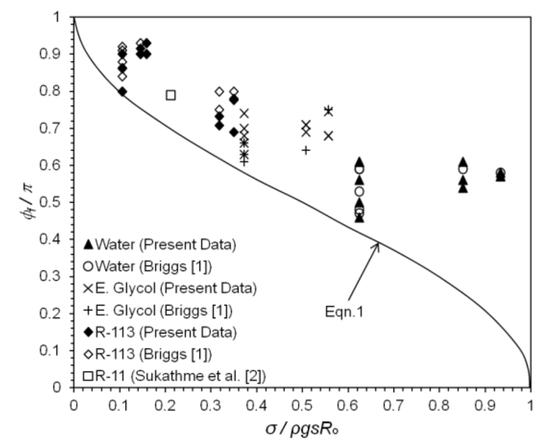


Figure 5Comparison of Measured Retention Angles for Pin-Fin Tubes with Honda et al. [3] Theory

IV. SEMI-EMPIRICAL EXPRESSION FOR CONDENSATE RETENTION ANGLE ON PIN-FIN TUBES

For developing a reasonable model to predict heat transfer for pin fin tubes, it is extremely important to come up with a correlation for retention angle for pin tubes.

Yau et al. [4] observed a decrease in condensate retention on the lower part of integral fin tubes when attached drainage strips. They proposed that by reducing the constant 2.0 in Honda et al. [3] Eqn. 1 to 0.83, it could be possible to calculate larger condensate retention angles that were measured using strips.

It has been shown in Figure 5 that all pin-fin tube and fluid combinations have larger retention angles compared to Eqn. 1, so it is quite possible to predict these larger angles by reducing the constant in Eqn. 1 using the same approach as used by Yau et al. [4]. The case of pin-fin tubes is different from that of integral-fin tubes with drainage strips, as however there are two variables involved namely circumferential pin spacing and thickness, affecting the behavior of condensate retention, so it would not be realistic to replace the constant in Eqn. 1 with a single fixed value to predict the larger retention angles. For each pin-fin tube and fluid combination, the extent of increase in retention angle compared to equivalent integral-fin tube is different, so it is important to include the effect of circumferential pin spacing and thickness in any modification of the model. A general observation from the measured retention angles show that retention angle decreases to some extent with an increase in circumferential pin thickness and increases with an increase in circumferential pin spacing when all other geometric parameters are kept constant.

The dependence of retention angle on circumferential pin thickness and spacing is shown in Figures 6 and 7 respectively. The following expression incorporating the effects of circumferential pin spacing and thickness is proposed to predict the retention angle on pin-fin tubes,

$$\emptyset_f = \cos^{-1}\left[\left(1 - C \times \frac{s_c}{t_c}\right)\left(\frac{2\sigma}{\rho g s R_o}\right) - 1\right] \quad for\ s < 2h \qquad (2)$$

Where, C is a constant in Eqn. 2 and found empirically for each fluid separately.

A least square method i.e. minimizing the sum of squares of residuals was used to find out the best value of C for each of the three fluids tested. Present experimental data and data of Briggs [1] were used in the minimization process.

Table IV lists the best values of C i.e. that gave the minimum value of sum of squares for each fluid used in Eqn. 2. Figure 8 compares the experimental retention angles used in the minimization process of the present investigation and Briggs [1] with predictions of Eqn. 2. It can be seen that more than 90% of the measured values are within the range of 15% of predicted or calculated values. There are some measured angles for pin-fin tubes P3 and P4 using ethylene glycol fall beyond the range of ± 15 %, however, it should be noted that these retention angles are comparatively small and a small difference (measured minus calculated) can lead to a big value of percentage error. For example, a difference of 0.1 (measured minus calculated retention angle ratio) for a measured angle of 0.9 will give 11 % error, but the same difference of 0.1 for a measured angle of 0.2 will lead up to 50 % error. As an overall, data showed a relative standard deviation of 11.7 %.

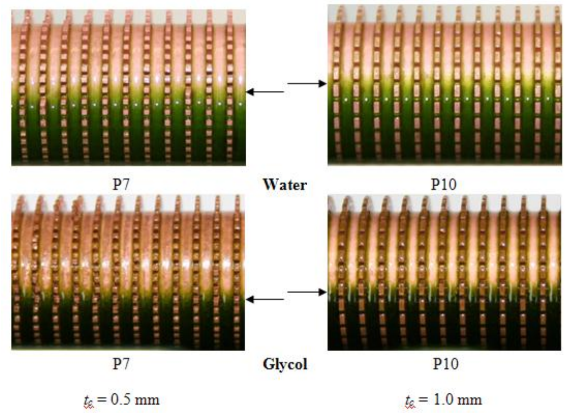


Figure 6. Effect of Circumferential Pin Thickness on Retention Angle for Pin Fin Tubes

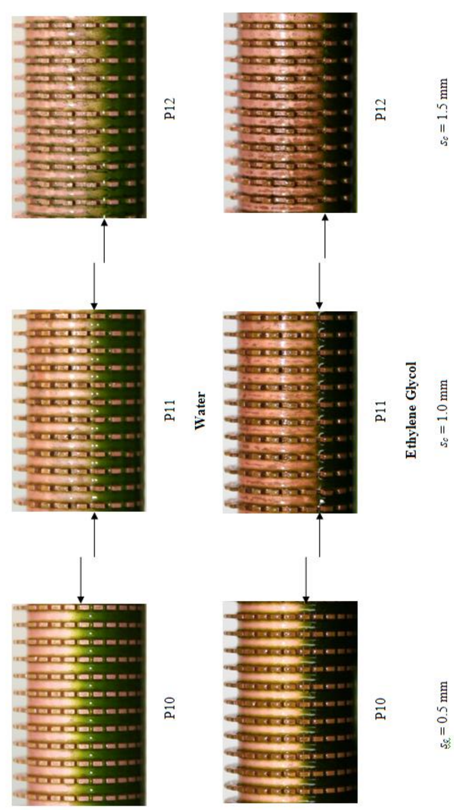


Figure 7.Dependence of Retention Angle on Circumferential Pin Spacing

From Figure 9, it will be interesting to note that empirical constant C in Eqn. 2 exhibits a reciprocal relation with $\sigma/\rho R^2 g$which is a unit-less parameter. This suggests that value of constant C in Eqn. 2 may be estimated for any fluid without finding it empirically from the following approximation,

$$C = 0.4919 - 1.306\,(\sigma / \rho R^2 g) \qquad (3)$$

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TABLE IV
EMPIRICAL CONSTANTS AND STANDARD DEVIATION

Fluid	*C*	Std_{rel} *
Water	0.25	0.0546
Ethylene Glycol	0.35	0.1877
R-113	0.45	0.0535
Overall		0.1170

* Relative standard deviation

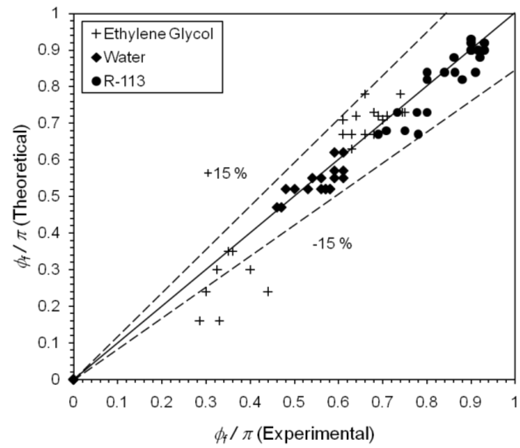

Figure 8. Comparisons of Experimental Retention Measurements with Present Theory

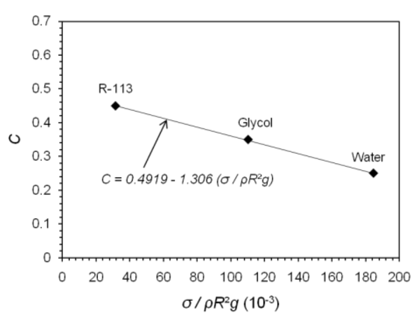

Figure 9.Relation of Constant *C* in Eqn. 2

Figure 10, plotted non dimensionally, compares the measured retention angles of the present investigation, Briggs [1] and Sukathme et al. [2] with Eqn. 2, measured values of angles are in reasonable agreement with the predicted valus. Retention angle exhibits a decrease with increasing value of non-dimensional parameter, it shows that axial fin spacing and spacing and thickness in circumferential direction along with surface tension to density ratio are important factors for liquid retention in the case of pin-fin tubes.

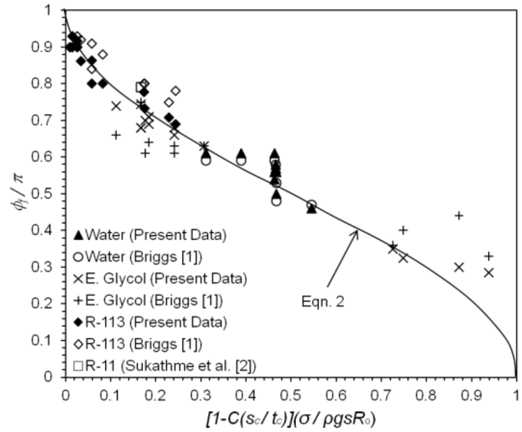

Figure 10. Measured Retention Angle for Pin-Fin Tubes (Comparison with Eqn. 2)

V. CONCLUSIONS

Fifteen three dimensional pin fin tubes are tested with ethylene glycol, water and refrigerant 113 under the static condition of simulated condensation. It was found that liquid retention on the lower part of all tubes was considerably lower than the integral fin tubes of similar geometries. The need to develop an accurate heat transfer model for pin tubes requires a correlation for calculating retention angle, a semi empirical correlation basing on the Honda et al. [3] was presented here to meet the requirement. The predicted values showed a reasonable agreement with measured retention angle data (about within 15%).

NOMENCLATURE

C	*const. defined in eqn. 3*	s_c	*circumferential pin spacing*
d	*pin root diameter*	t	*longitudinal pin thickness*
g	*gravitational acceleration*	t_c	*circumferential pin thickness*
h	*pin height*	ρ	*density*
R_o	*pin tip radius*	σ	*surface tension*
s	*longitudinal pin spacing*	$\emptyset_f$	*retention angle*

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Brief Description: A few typos and grammatical mistakes are fixed in the paper. Also, the author’s profiles are updated.