EFFECT OF CONDENSATE FLOW RATE, SURFACE TENSION, DENSITY, AND VAPOR VELOCITY ON CONDENSATE RETENTION OF WIRE WRAPPED TUBES

by

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Simulated condensation has been conducted on three wire wrapped tubes having same root diameter but different fin spacing of 1.5 mm, 2 mm, and 2.5 mm. Different fluids (ethanol, ethylene-glycol, and water) are used for condensation by providing them to the tubes through tiny holes in inter-fin spacing on the top of the surface of tubes. The major parameters are to be controlled in this research are fin spacing, vapor velocity, condensate flow rate and ratio of surface tension density of the fluid. Obtained results show that flooding angle (calculated from the top of the tube to the level where fluid fills the fin) rises by increasing fin spacing. Also, retention angles increase by reducing ratio of surface tension density of fluid. Acute flooding angles at zero air velocity and zero flow rate, elevates by increasing air velocity. However, obtuse flooding angles at static conditions drop by reducing air velocity. An interesting result is obtained regarding retention angle which remains almost even for the higher condensation flow rates until the tube gets inundated with condensation. Moreover, critical flow rates for all the tubes against using different working fluids are measured. Results obtained for static conditions have good correspondence with already available authentic data for flooding angle. Pictures showing condensate retention angles have been included in this paper.

Key words: *wire wrapped tubes, heat transfer enhancement, condensate retention*

Introduction

In the applications of air conditioning, water vapors in the air condense over the coils of heat exchanger when the dew point temperature of air is higher than the surface temperature. This retained condensate applies significant effect on the efficiency of the heat exchangers. In condenser's, heat transfer performance is enhanced by increasing surface area by developing fins on the surface [1, 2]. However, using fins, the condensate retains in the fin spacing due to its surface tension and reduces rate of heat transfer. The retention condensation is depicted in terms of *retention angle* or *flooding angle*, fig. 1. This angle is calculated from top of the tube to the level where condensate fills the inter fin spaces [3].

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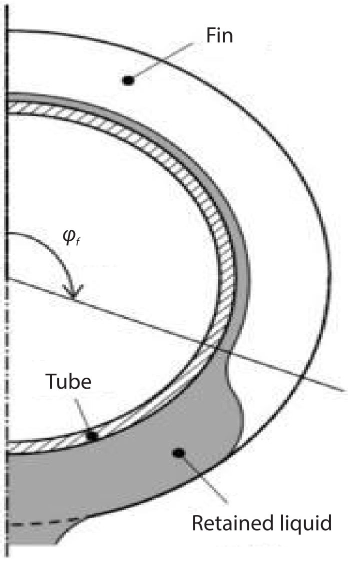


Figure 1. Retention angle

In order to measure retention angle, analytical model was produced by Honda *et al.* [3] for integral finned tubes for zero flow rate and zero air velocity:

$$\varphi_{\mathrm{f}} = \cos^{-1}\left(\frac{4\sigma}{\rho g s d_{\mathrm{o}}} - 1\right) \tag{1}$$

Owen *et al.* [4] investigated this model later. It was also validated by Rudy and Webb [5, 6]. Fitzgerald [7] got flooding angle with ethylene glycol, water and R113 and obtained a good agreement.

The heat transfer enhancement of 1.9 fold and 1.7 fold by the condensation of water and gasoline vapors with air content up to 6%, respectively, on vertical tubes having transverse annular groves on their outer surface and diaphragms on the inside surface [8]. A model was developed for the measurement of coefficient of heat transfer inside the horizontal tubes, which analyzed the effect of interfacial shear and gravity force on condensate film and stratified angle associated with condensate at the bottom of tube. The effect of these parameters was observed according to heat transfer performance of condensate film inside the horizontal tubes for turbulent and laminar range of water-vapor flow [9].

It was reported that condensate heat transfer of binary vapors of R113 and water is enhanced due to integral finned tubes [10]. An investigation has been done on pin finned tube to analyze that how array pins effects the heat transfer enhancement. The results showed that maximum heat transfer coefficient is 1.8 and 3.0 times greater for partially and full pin finned tip, respectively than that of smooth tip. Furthermore, 6% less heat transfer enhancement was reported for the tip having full pins array than that of partial pin-fins array [11]. It was reported that diameter and location of pin fin reduces heat transfer on the surface and cone shaped pin fin causes more heat transfer on the surface of pin fin [12].

Pin fin heat transfer performance with unequal convective coefficient was reported. Pin fin length improves the heat transfer rate for subcritical conditions and reduces it for supercritical conditions [13]. The effect of component composition in condensation mixture on heat transfer performance was reported. Experiments were conducted by using ethyl acetate vapors and water as a condensing mixture and results were compared with available theoretical data [14]. The condensation was reviewed on integral-fin tubes especially considering effect of gravity, vapor shear and surface tension that improves the heat transfer coefficient [15].

For enhanced boiling surface, pool boiling performance was investigated by using R134a at different saturation temperatures. By wrapping wire mesh of copper or brass with 80, 100, or 120 mesh per inch and 42, 50, or 60 fins per inch around finned tube to make enhanced boiling surface having fin height of 0.2 mm or 0.4 mm and it was reported that best performance was observed for brass mesh surface of 100 mesh per inch having fin height of 0.4 mm with 60 fins per inch tube [16]. Flooding mechanism was analyzed on smooth and fluted tube (with or without twisted insert) with water and ethanol solution that was flowing over there against the direction of air. The effect of twisted insert on flooding was examined. It was reported that inclination angle of flooding did not affect the enhanced surface and the effect of twisted insert on flooding decreased as inclination angle changed from horizontal to vertical position. Flooding correlations as a function of inclination angle were developed for all tubes [17].

Heat transfer enhancement during condensation of R22 was investigated by using coiled wire inserts. Coiled wires were made by using different wire diameters and coil pitches and results showed that condensing heat transfer coefficients improve by using coiled wire [18]. Simulation was conducted for R134a, which results showed that micro finned tube geometries were more effective for in-tube condensation and evaporation [19]. For low finned tube, to optimize fin dimensions, theoretical study was made by keeping constant thickness at fin root but radius of curvature changes at fin tip. Calculations were conducted also for rectangular fin tube by using HCFC-123 and it was reported that heat transfer performance for proposed finned tubes is better than rectangular fin tube [20].

Another technique *wire wrapped tubes* also has been used to enhance the heat transfer rate and studies show that researchers have been reported many investigations on it. This method is not much expensive because no machining is required. Condensation of steam on horizontal wire wrapped tube was analyzed by changing wire diameter, pitch and coolant flow rates. Enhancement ratios up to about two were obtained [21]. Simulated condensation of steam was observed on a horizontal tube around which steel wire was wrapped. Experiments were conducted by changing the diameter of wire and spacing. It was found that wire of 0.5 mm diameter 3.6 mm pitch shows maximum heat transfer enhancement of 1.8 [22]. Condensation of steam was simulated on a tube over which the copper wire of different diameters of 0.71 mm, 1.5 mm, 0.3 mm, and by varying spacing from 7.5 mm to 30 mm was wrapped. The results showed that copper wire of 1.5 mm diameter with 7.5 mm pitch shows maximum heat transfer enhancement of 1.45 [23]. The experimental study has been performed on 85-rod bundle of wire wrapped tubes and results of heat transfer obtained by conducting experiments on these bundles in axial air-flow. Relative pitch of bundle packing and wire wrapping was $P/d = 1.23$ and $T/d = 14$, 28, and 69.8, respectively [24].

There is a very high vapor velocity and condensation rate in industries and from aforementioned survey, it has been understood that there is no theoretical and experimental model presented for wire wrapped tubes which shows the combined effect of variable condensation rate and vapor velocity. In this research work mutual effect of variable flow rates and vapor velocity on retention angle was investigated for wire wrapped tubes with three different fluids (ethylene-glycol, water, and ethanol) having distinct surface tension density ratio. Theoretical modal of Honda *et al.* [3] was used for validation the results for static conditions because there is no specific modal is available to validate the results for wire wrapped tubes.

Apparatus and procedure

Is this research work simulated condensation has been performed on three horizontal wire wrapped tubes having different geometrical parameters, in order to measure the mutual effect of variable condensate flow rate and vapor velocity on retention angle for various fluids having different physical properties (*e.g.* surface tension and density). Wire wrapped tube under observation was placed in the vertical wind tunnel and three different fluids (ethylene glycol, water, and ethanol) were provided to the tubes through tiny holes in inter-fin spacing along the top surface. A glass is attached, opposite the tube, in the wind tunnel wall so that retention angle could easily be measured by using photographic observations. Apparatus is shown in fig. 2.

Three tubes of same fin tip diameter of 16 mm were tested, which were wrapped by copper wire of diameter 0.7 mm with different fin spacing of 1.5 mm, 2 mm, and 2.5 mm. The 1 mm holes were drilled in inter-fin spacing of all tubes, shown in fig. 3.

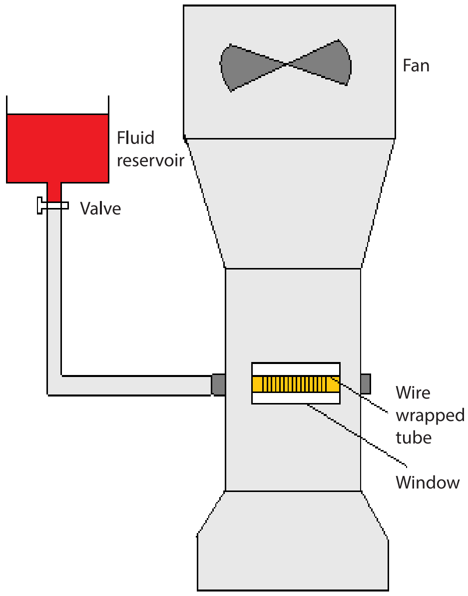


Figure 2. Schematic of the apparatus

Figure 3. Wire wrapped tubes A_1, A_2, and A_3 with 1.5 mm, 2 mm, and 2.5 mm fin spacing, respectively

Flexible pipe was used to connect one end of the wire wrapped tube with fluid reservoir and other side of tube was closed. In order to adjust the flow rate of fluid, a valve or stopper was attached with flexible pipe so that fluid spilled uniformly and smoothly over the test tube. On the top side of wind tunnel, a blower was attached there. In order to measure the velocity of air, an anemometer was used which was placed below the test tube but before taking photographs of test tube, it was removed earlier. Stopwatch was used to measure flow rate. Sodium bicarbonate solution was used to wash all the tubes before going to conduct experiments and observed to be fully flooded by fluid. In order to improve the visibility of retention level some quantity of food color was mixed in fluid. Readings at static conditions were almost mapped with theoretical modal of [3] and results showed that surface tension of fluid was not affected by adding some quantity of food color. Retention angles were measured firstly by taking photographs for all the tubes for zero flow rates and zero vapor velocity, by spraying a fluid on the tube. Then, retention angles were measured again by taking pictures after placing the tube in wind tunnel under the influence of variable flow rates and vapor velocity. Photographic method was used for each tube, in order to measure the retention angles for different fluids.

Image processing method

In this technique, the fluid spilled vertically downwards over the wire wrapped tubes and the tubes were located in a horizontal position. When flooding level on the tubes became constant, at that time photograph was captured by digital camera. By using image processing, retention angles were measured. The accuracy range for the results of this method was $\pm 0.05d$. This method was compared with calibrated ring method.

Calibrated ring method

This was another technique to measure retention angle other than aforementioned discussed method. In which calibrated ring having engraved angles on its periphery was affixed with wire-wrapped tubes, as shown in fig. 4. Just to slide the ring over the tube, its diameter was kept slightly more than tube diameter. Zero error was rectified by making the holes in line with zero degree position of ring. In order to measure retention angle by this ring, the reading of angle on ring was read which was in front of the flooded level.

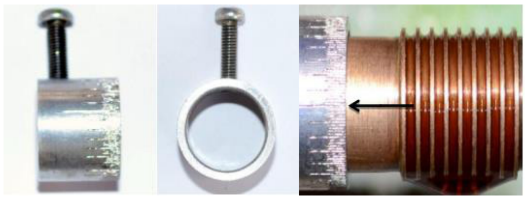


Figure 4. Calibrated ring and measurement of flooding angle by calibrated ring method

Results and discussion

Simulated condensation was performed and results were obtained by conducting experiments on three wire wrapped tubes, having a fin spacing of 1.5 mm, 2 mm, and 2.5 mm with water, ethylene glycol and ethanol as working fluids. Theoretical and mathematical model [3] given by eq. (1) was used for the validation of results at static conditions as shown in fig. 5.

Results indicated that fin spacing directly affect the retention angle and by enhancing fin spacing retention angle gradually rises up for same working fluid, as shown in fig. 6.

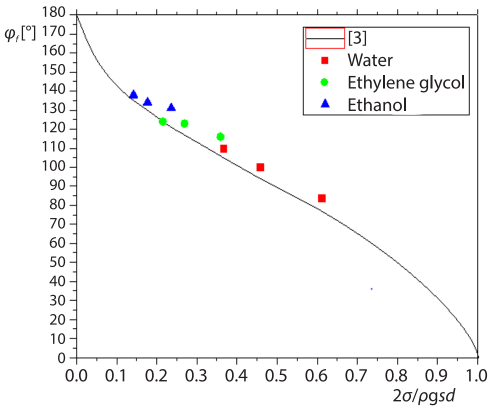


Figure 5. Comparison of theoretical model of [3] with current data

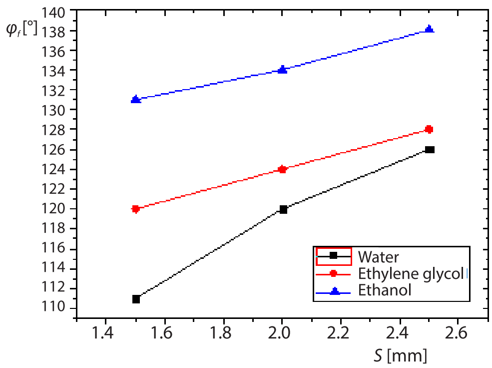


Figure 6. Relation of retention angles with fin spacing for ethanol, ethylene glycol and water

Results showed that flooding angle more than π/2 at zero air velocity and zero flow rates, decreases (retention level decreases) by increasing air velocity. Retention angles less than π/2 at static conditions, rises (retention level increases) by increase in air velocity. For all types of geometries and fluids it was noticed that retention angles appeared to approach the value of around 90°-110° with increasing air velocity and flow rates, fig. 7.

It was observed that physical properties of fluid affect the retention angle. Ratio of surface tension density for ethanol, ethylene glycol and water are 27, 42, and 72 μNm^2/kg, respectively. Results showed that retention angle rises up by lowering of surface tension density ratio, see fig. 8.

Critical flow rate was also observed for each tube that was maximum flow rate which inundates the tube completely. It was noticed that retention angles were independent of air velocity and remained almost constant by increasing flow rates until tube gets fully flooded, as shown in fig. 9.

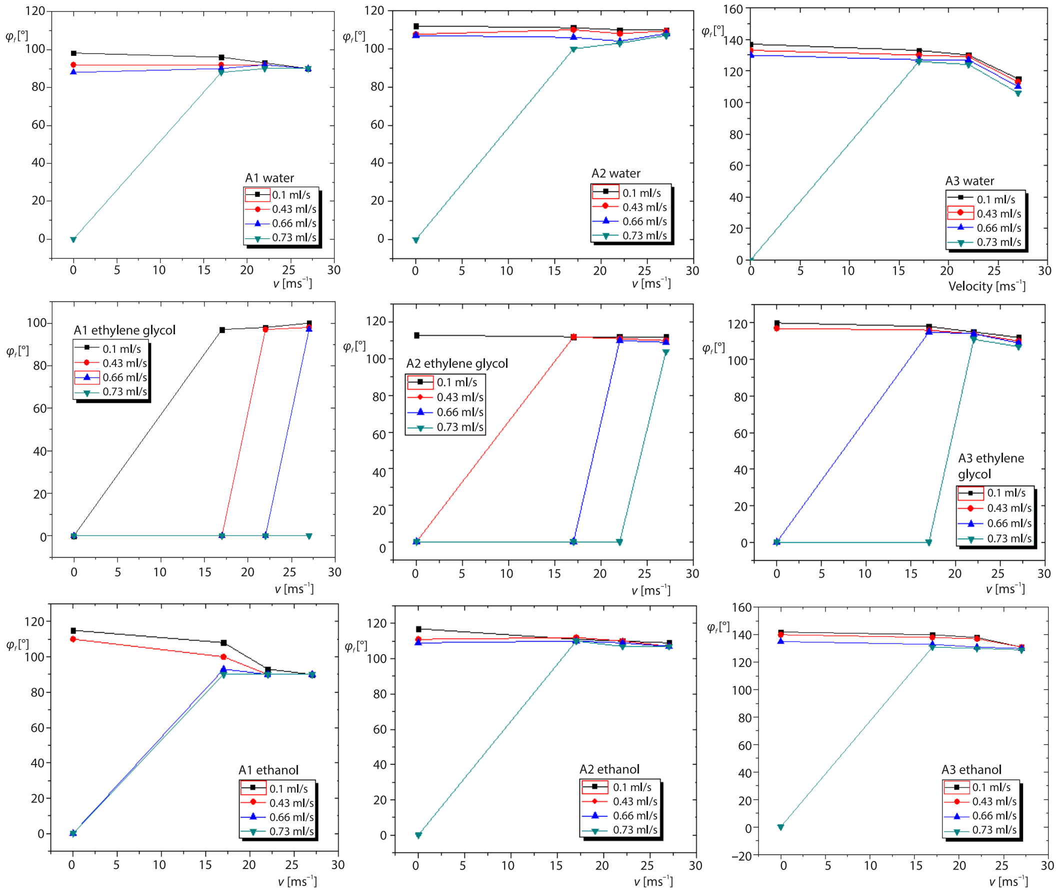
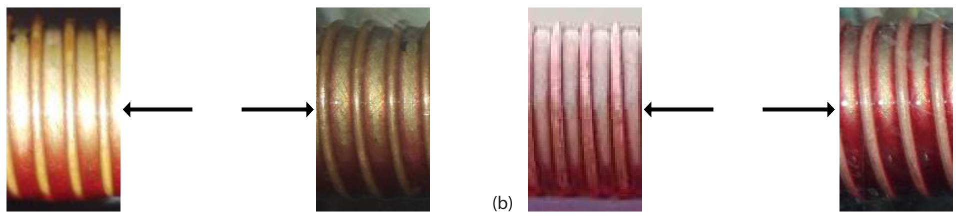


Figure 7. Variation of flooding angles with velocity at different condensate flow rates for ethylene glycol, water, and ethanol on all three tubes

(a) (b)



(c)

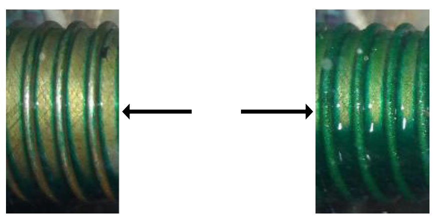


Figure 8. Flooding angles on A1 tube with variable vapor velocity and flow rates for ethylene glycol, water, and ethanol; (a) flow rate = 0 ml/s, v = 0 m/s φ_f = 111° and flow rate = 0.66 ml/s, v = 27 m/s, φ_f = 100 ° (water), (b) flow rate = 0 ml/s, v = 0 m/s, φ_f= 120° and flow rate = 0.66 ml/s, v = 27 m/s, φ_f = 90° (ethylene-glycol), and (c) flow rate = 0 ml/s, v = 0 m/s, φ_f = 131° and flow rate = 0.66 ml/s, v = 27 m/s, φ_f = 90° (ethanol); (a)-(c) show pictures of condensate water, ethylene glycol, and ethanol, respectively

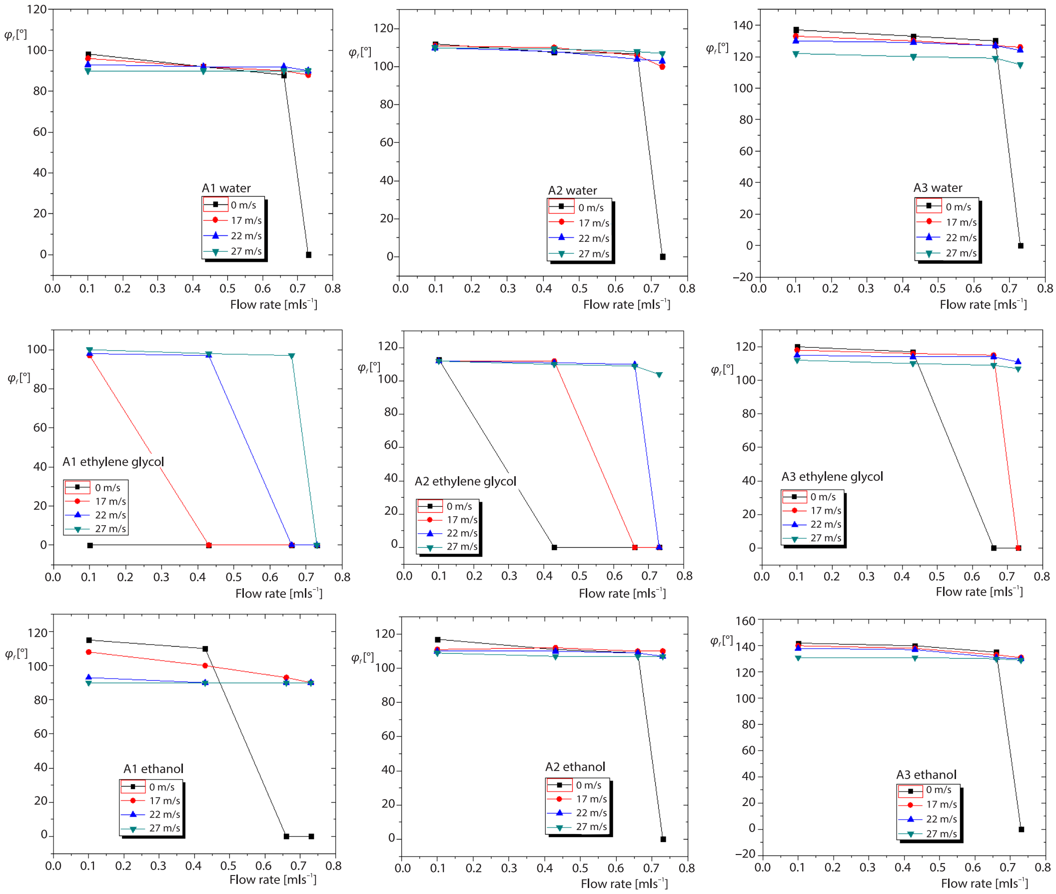


Figure 9. Variation of retention angle with condensate flow rates at high velocities for water, ethylene glycol, and ethanol on tubes A1, A2, and A3

Conclusion

Fin spacing has been made an important parameter to increase the rate of heat transfer amongst the researchers, for many last decades in different applications of refrigeration and air conditioning. It has been understood from previous research that fin density applies direct effect on the heat transfer performance with un-flooded conditions. But it has been observed that by increasing fin density, condensate retention level rises so it degrades the heat transfer performance. In industries vapor velocity and condensate rates are normally high. Higher rates enhance the flooding level, which reduces the heat transfer rate. Therefore, in this paper, effect of vapor velocity and condensate rates on retention angles was discussed and substantial experimental data is available in it, which will be helpful in future studies on wire wrapped tubes. Critical flow rates were also mentioned for different spacing to control liquid over loading rate, because no significant heat transfer is obtained beyond this flow rate in heat transfer and air-conditioning applications.

Nomenclature

d_o – fin tip diameter of tube, [mm]
g – force of gravity, [ms^{-2}]
s – fin spacing, [mm]
v – air velocity, [ms^{-1}]

Greek symbols

ρ – condensate density, [kgm^{-3}]
σ – surface tension, [mNm^{-1}]
φ_f – retention angle/flooding angle, [°]

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