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Condensation Heat Transfer Coefficients and Enhancements of R134a in Smooth and Microfin Inclined Tubes

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Abstract

This paper presents the thermal performance of smooth and microfin tubes and the enhancement factors as they respond to inclination angle, mass flux and vapour quality in inclined tubes of 1.488 m long, 9.55 mm outer diameter during the convective condensation of R134a at the saturation temperature of 40°C. For the experiment, the quality was varied between 0.5 and 0.9, mass flux of 200 kg/m^{2}s to 400 kg/m^{2}s and inclination angle between -90° (vertically downward) and +90° (vertically upward) tube orientations. The result shows that inclination angle, mass flux and vapour quality significantly affect the heat transfer coefficient and enhancement factor. The enhancement factor varied between 0.98 and 2.0 depending on the operating variables. Higher enhancements were however obtained during the downward flow as compared with upward flow.

Keywords: Heat enhancement factor, heat transfer coefficient, convective condensation, microfin, smooth

1. Introduction

The scarcity of water, especially in the arid and remote areas, is encouraging the use of air-cooled A- and V-industrial condensers in such environments. Inclined heat exchangers are applicable also in aerospace during landing, banking and take-off of aeroplanes and in automobiles during navigation uphill and downhill. It is also relevant in a situation where there is a need for space and reduction in size and weight.

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Previous studies on condensation and evaporation have shown that microfin tubes enhanced heat transfer coefficient significantly. Most of the investigations have mainly addressed horizontal and vertical flows. Several comprehensive reviews have been done on heat transfer coefficients in smooth and microfin tubes [1-3]. To mention a few, Liebenberg and Meyer [4] in their study of the heat transfer coefficient and pressure drop in horizontal smooth and microfin tubes of an inner diameter of 8.9 mm obtained heat enhancement factor of two. Olivier et al. [5] compared the heat transfer coefficients in horizontal smooth, helical and herringbone microfin tubes for mass fluxes between 400 kg/m^{2}s and 800 kg/m^{2}s, inlet qualities between 0.85 and 0.95, outlet qualities between 0.05 and 0.15 at the saturation temperature of 40°C. They obtained, as compared with the smooth tube, a 70% higher thermal performance for the herringbone tube and a 40% higher for the helical microfin tube. Sapali and Patil [6] compared the heat transfer enhancements of R134a and R404a in horizontal smooth and microfin tubes and obtained enhancement factor of between 1.5 and 2.5 for R134a and between 1.3 and 2.0 for R404a.

The study of the response of the heat transfer enhancement factor to inclination angle is scarce in the literature, and it is, therefore, the focus of this investigation.

Nomenclature

A	heat transfer area (m^2)
d	diameter (m)
EF	enhancement factor
k	thermal conductivity (W/mK)
L	length of test section (m)
Q	heat transfer rate (W)
T	temperature (°C)
x	quality
Greek letters	
α	heat transfer coefficient (Wm^{-2}K^{-1})
Subscript	
w	wall
sat	saturation
Cu	copper
m	mean
i	inner

2. Experimental Facility and Methods

Fig. 1 shows the sketch of the test facility which has been used and validated by various researchers for condensation studies among whom are Meyer et al. [7-9]. Details of the test section can be found in the above studies.

The test condensers have the same length of 1.488 m, and inner diameters were 8.38 mm for smooth tube and 8.71 mm for the microfin tube. The working fluid, R134a passed through the inner tube at the saturation temperature of 40 °C and water was pumped through the annulus in a countercurrent arrangement providing heat flux of between 230 W and 270 W. The energy balance was maintained below 3.0% throughout the test. The test section was inclined between -90° (vertically downward) and +90° (vertically upward) with the aid of a high-pressure hose connected to the two ends of the condenser and the inclination angle was measured with the aid of a digital inclinometer. The summary of the geometry of the inner tubes and the operating conditions are presented in Tables 1 and 2.

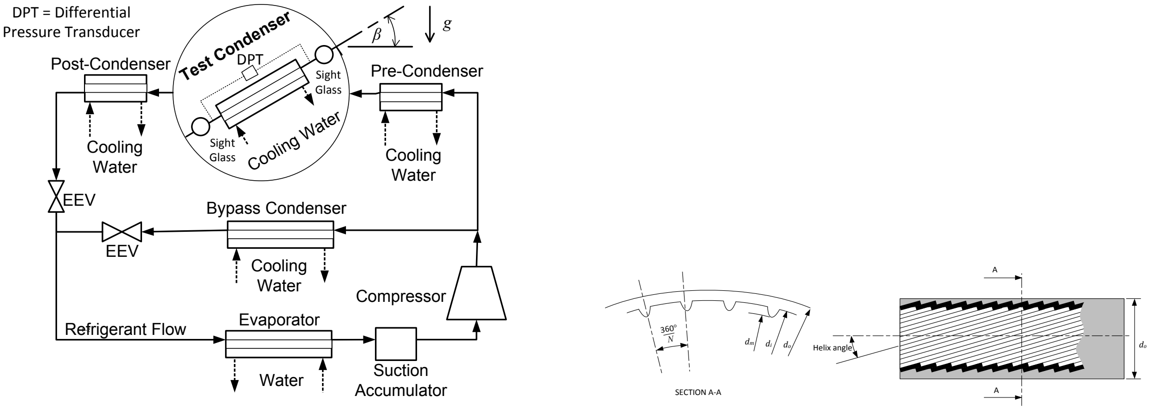

Fig. 1: The schematic diagram of the experimental setup and microfin tube geometry.

Table 1: Smooth and Microfin tube dimensions.

Description	Value	
	Microfin	Smooth
Outer diameter d_o [mm]	9.55	9.55
Inner diameter d_i [mm]	8.92	8.38
Mean inner diameter d_m [mm]	8.71	
Wall thickness [mm]	0.32	0.598
Fin height e [mm]	0.21	
Fin pitch [mm]	0.445	
Circumferential Fin number, N [-]	60	
Helix angle H [°]	14	
Roughness (e/d_i)	0.0235	

Table 2: Test parameters and range.

Parameter	Range	Band
T_{sat} [°C]	40	± 0.6
G [kg/m^{2}s]	200, 300, 400	± 5
x_m [-]	0.5 – 0.9 (for G = 400 kg/m^{2}s) 0.5 (for G = 200 - 400 kg/m^{2}s)	± 0.01
β [°]	0°, ±5°, ±10°, ±15°, ±30°, ±60°, ±90°	± 0.1
Q_{H2O} [W]	230 - 270	± 20
ΔP [kPa]	-2 to +12	±0.05

3. Data Reduction Strategy

The heat transfer coefficient can be expressed as

$$\alpha = \left| \frac{Q_{test}}{A(T_{sat} - \bar{T}_{w,i})} \right| \tag{1}$$

Where α is heat transfer coefficient, Q_{test} is heat transfer rate, T_{sat} saturation temperature, A is the heat transfer area and the average of the inner wall temperature can be expressed as, for microfin tube (Eq. 2a) and, for smooth tube (Eq. 2b)

$$\bar{T}_{w,i} = \bar{T}_{w,o} + \left| Q_{test} * {}^{ln\left({}^{d_o}/_{d_m}\right)}\Big/_{2\pi k_{cu} L} \right| \tag{2a}$$

$$\bar{T}_{w,i} = \bar{T}_{w,o} + \left| Q_{test} * {}^{ln\left({}^{d_o}/_{d_i}\right)}\Big/_{2\pi k_{cu} L} \right| \tag{2b}$$

The enhancement factor is expressed in Eq (3). The ratio of the heat transfer area of the microfin to smooth tube was 2.05.

$$EF = \frac{\alpha_{microfin}}{\alpha_{smooth}} \tag{3}$$

4. Validation

The validation study was conducted with our experimental data compared with well-established and trusted correlations for smooth and microfin tubes as shown in Fig. 2. For smooth tubes, among the correlations [10-13] considered, the model of Cavallini et al. [12] gave the best result within ±25%. For the microfin tube, the model of Akhavan-Behabadi et al. [14] was used to predict all the data while the others [15-17] predicted horizontal tube data. Within ±50%, the correlation of Cavallini et al. [17] gave the best result.

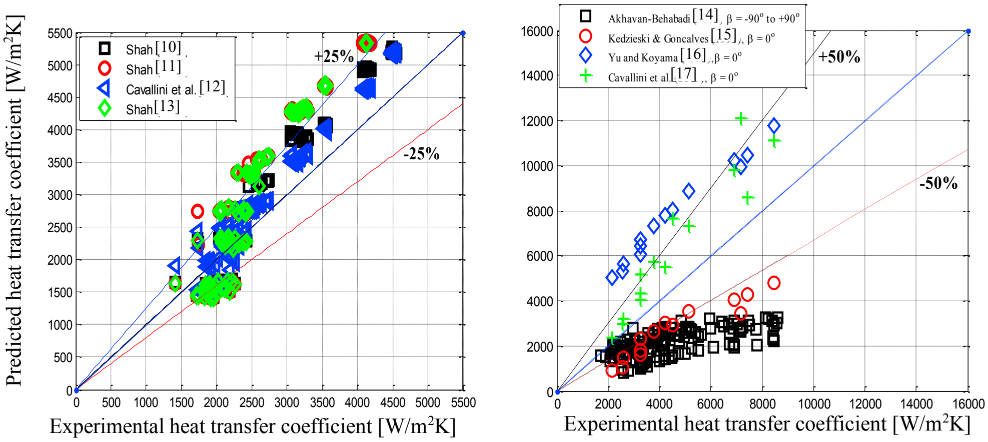

Fig. 2: Comparison of experimental data with some predictive models for a) smooth tube, and, b) microfin tube.

5. Results

5.1. The response of heat transfer coefficient to inclination

Fig. 3 represents the result for both smooth and microfin tubes at the saturation temperature of 40 °C, for a) different vapour qualities for the mass flux of 400 kg/m^{2}s, and, b) different mass fluxes for vapour quality of 50%. Results show that heat transfer coefficient is significantly higher for the microfin tube than for the smooth tube. The exception to this is that at an inclination angle of +60°, quality of 50% and mass flux of 400 kg/m^{2}s the smooth tube has superior thermal performance.

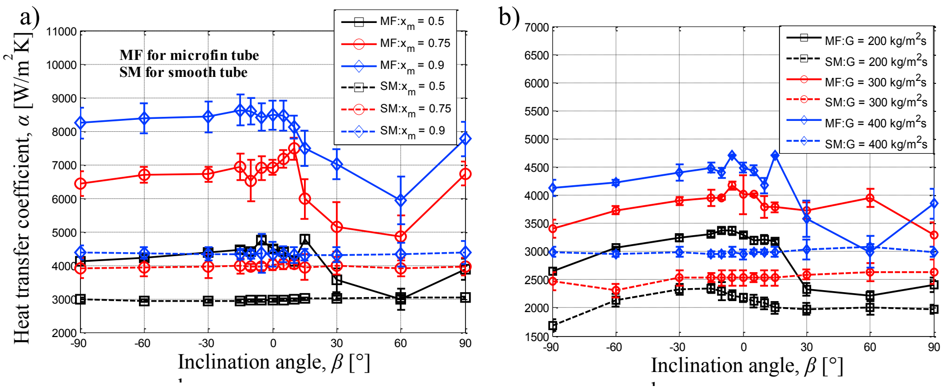

Fig. 3: Comparison between heat transfer coefficient in smooth and microfin tubes for a) different vapour qualities for G = 400 kg/m^{2}s, b) different mass fluxes for x_m = 50%.

5.2. The response of heat transfer enhancement factor to inclination

The variation of the enhancement factor with inclination angle for a) different qualities for the mass flux of 400 kg/m^{2}s, and, b) different mass fluxes for vapour quality of 50% are presented in Fig. 4. The result shows that the enhancement factor increases with increasing vepour quality and varies between 0.98 and 2.0. In most of the cases the downward, horizontal or slightly upward inclined flow performed better due to the low liquid thickness coupled with the turbulence induced by the fins hence less thermal barrier. The flow patterns in these cases are annular, annular-wavy or stratified-wavy. The highest value of enhancement was recorded for quality of 90%, mass flux of 400 kg/m^{2}s and inclination of -15° while the lowest was obtained for the quality of 50%, mass flux of 400 kg/m^{2}s and inclination of +60°. For vapour quality of 50%, the microfin tube performed best for mass flux of 300 kg/m^{2}s for most of the orientations. Fig. 5a shows that for a mass flux of 400 kg/m^{2}s and vapour qualities of 75% and 90%, the best performance was obtained for downward flow of -15°; and for 50% quality during the upward flow of 15°. The worst performance was obtained for upward flow of +60°. In Fig. 5b, for vapour quality of 50%, the highest enhancement factors were obtained for inclination angle of 15° for mass fluxes of 200 kg/m^{2}s and 400 kg/m^{2}s but it was obtained for inclination angle of -60° for mass flux of 300 kg/m^{2}s. The worse performance was obtained during the upward flow, +60°, for mass flux of 200 kg/m^{2}s and 400 kg/m^{2}s and +90° for mass flux of 300 kg/m^{2}s.

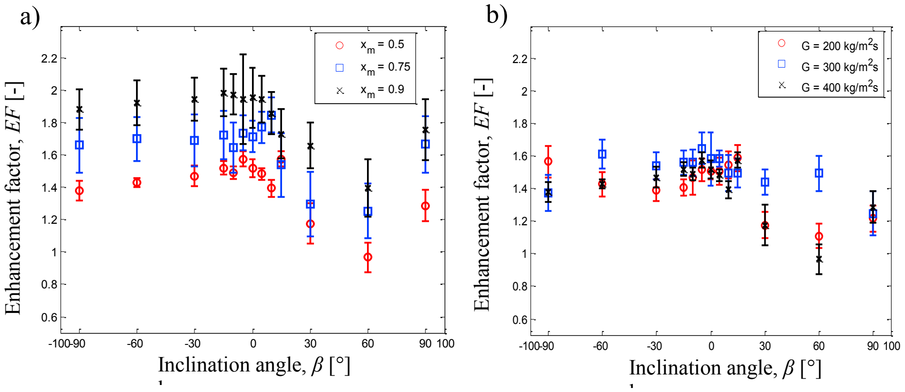

Fig. 4: Variation of enhancement factor with inclination angle for different a) vapour qualities for mass flux of 400 kg/m^{2}s, b) mass fluxes for vapour quality of 50%.

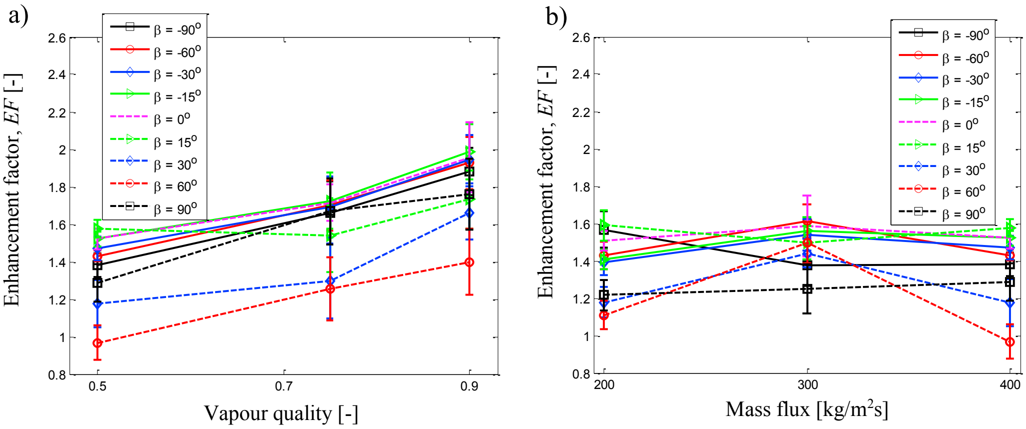

Fig. 5: Variation of enhancement factor with a) mean vapour quality for mass flux of 400 kg/m^{2}s, and, b) mass flux for quality of 50% for different inclination angles.

6. Conclusion

This paper presents the effects of quality, mass flux and inclination angle on the heat transfer coefficient in smooth and helically grooved microfin tubes and heat enhancement factor for tubes with an outer diameter of 9.55 mm and 1.488 m long. The vapour quality was varied between 50% and 90%, mass flux of 200 kg/m^{2}s to 400 kg/m^{2}s, the inclination angle between -90° (vertically downward) and +90° (vertically upward) for a saturation temperature of 40°C. The heat enhancement factor was between 0.98 and 2.0 and increased with increasing vapour quality. The highest value was obtained for the inclination angle of -15°, quality of 90%, mass flux of 400 kg/m^{2}s and the lowest for inclination angle of +60°, quality of 50% for the same mass flux.

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