

A THEORETICAL INVESTIGATION ON THE EVAPORATIVE HEAT TRANSFER OF CO₂ IN SMOOTH AND MICROFIN TUBE

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ABSTRACT

Nowadays, global environmental events such as thinning of the ozone layer and climate changes are increasing. These types of events are not only affecting all creatures living on the Earth, but also decreasing the quality of life. For this reason, natural refrigerants which are not harmful to environment, have been preferred in cooling systems. In this study, heat transfer coefficient of CO₂ was investigated during the evaporation process in smooth tube and designed microfin tube. Features of the tube used in evaporator of these cooling systems directly affect to the heat transfer coefficient. The geometric parameters of the microfin tubes are an outer diameter of 9.52 mm, number of fins 50, apex angle of 38°, helix angle of 20° and fin height of 0.12 mm. Theoretical model was created on MATLAB environment. The heat transfer coefficient was investigated based on vapor quality. When theoretical results obtained for microfin tube were compared with experimental results, 6% approach was seen. A theoretical model was created for smooth and microfin tube by selecting heat flux as 10 kW/m² and mass flux as 380 kg/m²s and heat transfer coefficients in different evaporation temperatures were compared based on vapor quality. It has been concluded that heat transfer coefficients of microfin tube at 5°C, 0°C and -8°C were 52%, 44% and 34% higher than that of smooth tube, respectively.

Keywords: Carbon Dioxide, Evaporation, Smooth Tube, Microfin Tube, Heat Transfer Coefficient

INTRODUCTION

Conventional refrigerants such as CFC, HCFC and HFC refrigerants used in air conditioning systems, cause to depletion of ozone layer and global warming. For these effects are eliminated or kept in minimum degree, states attempted all around the world, signed varied protocols. When selecting of refrigerants for using air conditioning systems, the values of global warming potential (GWP) and ozone depletion potential (ODP) should be paid attention to be low. For these reasons, use of CO₂ which ODP is 0, GWP is 1, is becoming more common [1,2]. Geometry of tubes used in evaporators are important parameters which effect heat on transfer. Using of microfin tube instead of smooth tube in evaporators increases surface area in tube and turbulence characteristics of refrigerants and provides increasing of heat transfer [3]. Kaji et al. [4] examined the effect of geometries of microfin tube on the heat transfer performance experimentally by using CO₂. Smooth and two types of grooved tubes that are spiral and herringbone were used in a series of experiment. The experiments were carried out at mass flux 600 kg/m²s, with a evaporation temperature of 7°C and heat flux is 10 kW/m². As a result, the highest heat transfer coefficient of CO₂ was observed in the herringbone type tube. Cho et al. [5] investigated the heat transfer coefficient of CO₂ in smooth and microfin tube during boiling process. They concluded that the heat transfer coefficient of the microfin tube higher than smooth tube. In addition, the heat transfer coefficient in microfin tube of outer diameter 5 mm 13% higher than outer diameter of 9.52 microfin tube. Zhao and Bansal [6] conducted experiments on flow boiling of CO₂ in horizontal and microfin tube with an outer diameter of 7.94 mm. The experiments were carried out at mass fluxes from 100 to 250 kg/m²s, with evaporation temperature of -30 °C, heat fluxes from 10 to 25 kW/m². When results taken from experiments were compared to theoretical results, close to 50% difference between the results was seen. For this reason, for CO₂ microfin tube at low evaporation temperature, necessity to development of new correlations was stated. Onbasioglu et al. [7] investigated the CO₂ thermal capacity effect of using smooth tube and microfin tube in evaporator. They concluded that using microfin tube instead of smooth tube increases heat transfer capacity 3.24% by theoretical calculations and 1.3% by test conditions. Schael et al. [8] experimentally investigated the flow boiling heat transfer coefficient of CO₂

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in a microfin tube with outer diameter 9.52 mm was much higher than that in a smooth tube. The boiling heat transfer coefficient increased markedly when mass flux increased from 75 to 250 kg/m²s, but decreased when mass flux increased to 500 kg/m²s. Yun et al. [9] studied the heat transfer coefficient during evaporation in microfin tube and correlations were developed. From technical literature, experimental data was taken such as evaporation temperature, mass flux, heat flux, fin height, fin number, helix angle and diameter of tube. By including non-dimensional parameters, developing correlations were compared with 13303 data for 5 different refrigerants. Average mean deviation was found as 20.5%. Yoon et al. [10] investigated the evaporation heat transfer characteristics and pressure drop of CO₂ in horizontal smooth tube. During evaporation flow characteristics of CO₂ was revealed. At the start of evaporation, heat transfer coefficient for nucleate boiling being dominant is high; with increasing vapor quality, because surface tension and viscosity decrease, liquid film layer spoils, it tends to decrease. When compared to theoretical and experimental data, 5% difference was seen. Yoon et al. [11] investigated the evaporation heat transfer coefficient of CO₂ at low temperature of -30 to -20°C in a horizontal smooth tube. When results were examined, it was seen that heat transfer coefficient was stable depending on vapor quality when the mass flux was 100 kg/m²s; heat transfer coefficient increased depending on increasing of vapor quality when the mass flux was 200 kg/m²s and 300 kg/m²s. Diani et al. [12] experimentally investigated the heat transfer coefficient of refrigerants in inside a mini microfin tube, with an inner diameter at the fin tip of 2.4 mm. Tests were run at 30°C of saturation temperature, with mass velocities ranging between 375 and 940 kg/m²s, heat fluxes from 10 to 50 kW/m², and vapor qualities from 0.1 to 0.99. Inoue et al. [13] investigated the heat transfer pressure drop in smooth and microfin tube. In experiment, outer diameter of 4 mm smooth tube and two different microfin geometries were tested. It has been observed that the fin height and fin geometry do not affect the low heat flux and mass flux conditions. Mancin et al. [14] conducted experiments on flow boiling of R134a in microfin tubes with an outer diameter of 3.04 mm. The experiments were carried out at mass fluxes from 190 to 755 kg/m²s, with a saturation temperature of 30 °C, heat fluxes from 25 to 50 kW/m². Experiment results showed that with increasing of mass flux heat transfer coefficient followed different characteristics.

In this study, the evaporative heat transfer coefficient of CO₂ was theoretically examined in smooth and microfin tubes. For smooth and microfin tubes, theoretical model on heat transfer coefficient of CO₂ was formed. For microfin tube, theoretical model results of this study and experimental results of the Cho et al.'s study were compared. Theoretical model and experimental results confirmed each other. In smooth and microfin tubes, heat transfer coefficients of CO₂ were compared, at different evaporation temperatures such as -8°C, 0°C and 5°C. In addition, the effect of different design parameters on heat transfer coefficient was investigated for microfin tube.

THEORETICAL ANALYSIS

Carbon dioxide among natural refrigerants has gained a considerable attention as an alternative refrigerant due to its excellent thermophysical properties. CO₂ has zero ozone depletion potential (ODP), and the majority of them have one global warming potential (GWP). For this reason, CO₂, which is not harmful to environment, have been preferred in this study.

Thermodynamic properties of CO₂ that is subject to this study are given in Table 1.

Table 1. Thermodynamic properties of CO₂ at evaporation temperatures -8°C, 0°C and 5°C [15]

Thermodynamic properties of CO ₂	Evaporation Temperatures (°C)		
	-8	0	5
Pressure [bar]	28.03	34.85	39.70
Density fluid [kg / m ³]	972.4	927.4	895.9
Density gas [kg / m ³]	75.83	97.65	114.7
Heat conductance fluid [10 ⁻³ (W/(m·K))]	120.7	111	104.95

Table 1. Thermodynamic properties of CO_2 at evaporation temperatures $-8^\circ C$, $0^\circ C$ and $5^\circ C$ [15] (Cont.)

Thermodynamic properties of CO_2	Evaporation Temperatures ($^\circ C$)		
	-8	0	5
Dynamic viscosity fluid [$10^{-6}(Pa \cdot s)$]	120	104.7	95.565
Dynamic viscosity gas [$10^{-6}(Pa \cdot s)$]	14	14.75	15.32
Prandtl-Number fluid :	2.33	2.39	2.48
Prandtl-Number gas :	1.223	1.352	1.471

In smooth and microfin tube, during evaporation of CO_2 two phase flow occurs. Two phase flow means that liquid and gas phase are together and move. In two phase flow, it is one of the most important topics which need to be argued on boiling. Although in two phase flow, there are many correlations created for determining the heat transfer, being prepared each one of them for refrigerants and not being formed it in a spacious working area made difficult to account of heat transfer. In this study, the correlations of Gungor and Winterton [16] were used for calculations of the smooth tube, the correlations of Cavallini [17] were used for calculations of the microfin tube.

Calculations of Heat Transfer Coefficient of Smooth Tube

In two phase boiling has two kinds of heat transfer mechanisms as nucleate and convective boiling. In nucleate boiling, bubbles starts to form at the edge of the wall and because of the axial flow, after a certain growth, it deflates. Convective boiling heat transfer shows heat transfer occurred with transfer between heated wall and liquid phase.

For calculating the heat transfer coefficient inside the smooth tubes, the equations of Gungor and Winterton [16] were used.

Two phase heat transfer coefficient:

$$h_{TP} = E \cdot h_{cv} + S \cdot h_{NB} \quad (1)$$

Two-phase convection multiplier E, as a function of the Martinelli number (X_{tt}) and the Boiling number (Bo);

$$E = 1 + 2400 \cdot Bo^{1.16} + 1.37 \left(\frac{1}{X_{tt}} \right)^{0.86} \quad (2)$$

Boiling number:

$$Bo = \frac{q}{h_{fg} G} \quad (3)$$

Martinelli parameter:

$$X_{tt} = \left(\frac{1-X}{X} \right)^{0.9} \left(\frac{\rho_v}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_v} \right)^{0.1} \quad (4)$$

Convection heat transfer coefficient:

$$h_{cv} = 0.0233 Re_l^{0.8} Pr_l^{0.4} \frac{k_l}{d} \quad (5)$$

Reynolds number:

$$Re_l = \frac{G(1-x)d}{\mu_l} \quad (6)$$

Nucleate pool boiling heat transfer coefficients:

$$h_{NB} = 55 \cdot P_r^{0.12} \cdot (-0.4343 \ln Pr)^{-0.55} \cdot M^{-0.5} \cdot q^{0.67} \quad (7)$$

Suppression factor:

$$S = \frac{1}{1 + 1.15 \cdot 10^{-6} E^2 Re_l^{1.17}} \quad (8)$$

Calculations of Heat Transfer Coefficient of Microfin Tube

In microfin tube, total of two phase heat transfer coefficient, the convection heat transfer coefficients and the nucleate boiling heat transfer coefficients were calculated with Cavallini [17] equation:

$$h_{TP} = h_{NB} + h_{CV} \quad (9)$$

Nucleate pool boiling heat transfer coefficients:

$$h_{NB} = 55 \cdot P_r^{0.12} (-\log P_r)^{-0.55} M^{-0.5} q^{2/3} S \cdot F_1 \quad (10)$$

Suppression factor:

$$S = A \cdot X_{tt}^B \text{ if } X_{tt} > 1 \text{ then } X_{tt} = 1 \quad (11)$$

Convection heat transfer coefficient:

$$h_{cv} = \left(\frac{k_l}{d_t}\right) \cdot Nu_{cvsmooth} \cdot R_X^D \cdot (BoFr)^T F_2 F_3 \quad (12)$$

Nusselt number for convection:

$$Nu_{cvsmooth} = [0.023 \left(\frac{Gd_t}{\mu_l}\right)^{0.8} Pr_l^{1/3}] [(1-x) + 2.63 \times \left(\frac{\rho_l}{\rho_v}\right)^{0.5}]^{0.8} \quad (13)$$

Bond Number:

$$Bo = \frac{g \rho_l f \pi d_t}{8 \sigma n_{groove}} \quad (14)$$

Froude Number:

$$Fr = \frac{G^2}{\rho_g^2 g d_t} \quad (15)$$

Geometry enhancement factor:

$$R_x = \frac{\frac{2fn_{groove} \left(1 - \sin\left(\frac{\alpha}{2}\right)\right)}{\pi d_t \cos\left(\frac{\alpha}{2}\right)} + 1}{\cos\beta} \quad (16)$$

$$F_1 = \left(\frac{d}{d_t}\right)^c \quad (17)$$

$$F_2 = \left(\frac{d}{d_t}\right)^v \quad (18)$$

$$F_3 = \left(\frac{100}{G}\right)^z \quad (19)$$

The constants of the equations 11, 12, 17, 18, 19 are given in Table 2.

Table 2. The constants of Cavallini equations

	A	B	C	D	T	V	Z
$G < 500 \text{ kg/m}^2\text{s}$	1.36	0.36	0.38	2.14	-0.15	0.59	0.36
$G > 500 \text{ kg/m}^2\text{s}$	1.23	0.36	0.38	2.14	-0.21	0.59	0.36

In industrial applications, available microfin tubes are generally manufactured from copper raw materials. The outer diameter of the tube was changed between 4 mm and 19 mm, its fin numbers were changed between 50 and 75, its helix angle was changed between 15° and 30°, its groove height was changed between 0,1 and 0,25 and its apex angle was changed between 25° and 90°.

Examining within this study, microfin geometry which was compared to smooth tube was given in Fig.1. Microfin tube features were also given in Table 3.

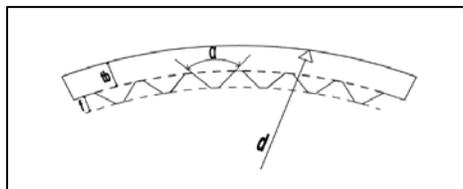


Figure 1. Microfin tube

Table 3. Geometrical parameters of tubes

Tube parameter	Smooth	Microfin
Outer diameter (mm)	9.52	9.52
Thickness (mm)	0.28	0.28
Fin-height (mm)	-	0.12
Apex angle (°)	-	38
Helix angle (°)	-	20
Number of fins	-	50

When microfin tube is used, attention should be paid about the geometrical parameters such as fin geometry, fin height, apex angle and helix angle. These geometrical parameters affect directly to the heat transfer coefficient and the pressure drop. In addition, refrigerant type is important to reach the maximum heat transfer values.

RESULTS AND DISCUSSION

The change of heat transfer coefficient depending on the vapor quality was theoretically modeled during CO₂ evaporation in microfin tube. Theoretical model results of this study and experimental results of the Cho et al.'s study were compared (5). Parameters used in this study were given in Table 4. The approach was calculated as 6% between theoretical model results and experimental results.

Table 4. Test Conditions

Parameter	Value
Mass flow rate (kg m ⁻² s ⁻¹)	424
Heat flux (kW m ⁻²)	12 and 20
Evaporation temperature (°C)	0

In Figure 2, the model results and test results are compared to some parameter values such as evaporation temperature (0 °C), heat fluxes (12 and 20 kW/m²) and mass flow rate (424 kg/m²s). It is seen that theoretical results are approximately 6% closer to the test results. It is concluded that there is more difference between heat transfer coefficients obtained theoretically and experimentally when vapor quality is below 0.4. Moreover, it is also observed that when vapor quality increases, heat transfer coefficient decreases. Its reason is that low vapor quality at the beginning of the process causes nucleate boiling and thus, high heat transfer coefficient is obtained. When the vapor quality increases, the heat transfer coefficient decreases due to decreasing of nucleate boiling. After that, boiling with convection is obtained at interface between liquid and steam. In addition to, during the CO₂ evaporation in horizontal tube, thickness of liquid film begins to decrease and eventually disappears.

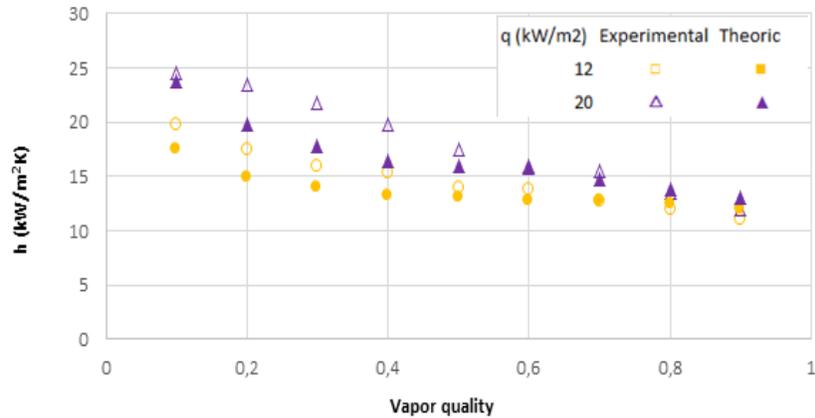


Figure 2. Effect of vapor quality on heat transfer coefficient of CO₂ in microfin tube at evaporation temperature 0°C (q=12 and 20kW/m², G=424 kg/m²s) [From Cho et al. [5], with permission from Elsevier]

The change of the heat transfer coefficients depending on vapor quality in designed microfin tube and the smooth tube was calculated with parameters given in Table 5. The calculated results were illustrated in Figures 3, 4 and 5.

Table 5. Test Condition

Parameter	Value
Mass flow rate (kg m ⁻² s ⁻¹)	380
Heat flux (kW m ⁻²)	10,15,20
Evaporation temperature (°C)	5, 0, -8

For evaporation temperature of 5°C, the change in the heat transfer coefficients of CO₂ depending on vapor quality is shown in Figure 3. It is shown that heat transfer coefficient decreases with the decrease in surface tension and viscosity. It also decreases with deterioration of liquid layer when vapor quality reaches the maximum value. It is also observed that the heat transfer coefficient of microfin tube is higher than the smooth tube is in average 52%. The reasons for this situation are that microfin tube has larger surface area than smooth tube and it has turbulence flow.

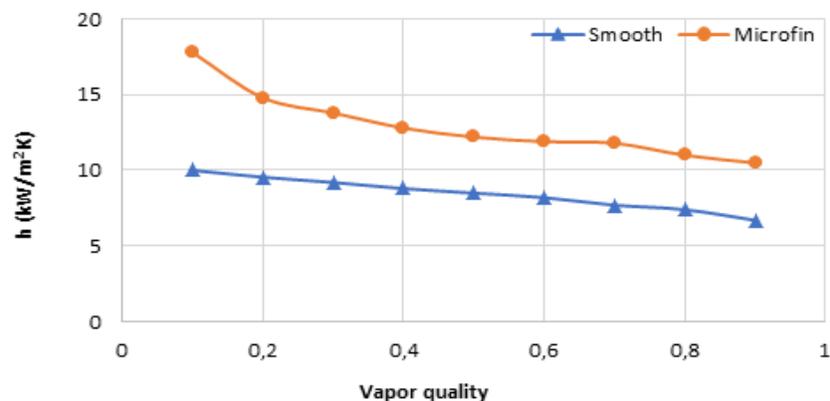


Figure 3. Effect of vapor quality on heat transfer coefficient of CO₂ at the evaporation temperature 5°C (q=10 kW/m², G=380 kg/m²s)

For evaporation temperature of 0°C, the change in the heat transfer coefficients of CO₂ depending on vapor quality is observed in Figure 4. It is revealed that the heat transfer coefficients decreases with increasing of vapor quality both smooth tube and microfin tube. The heat transfer coefficient of the microfin tube was observed to be 44% higher than the smooth tube. The difference between the heat transfer coefficients of smooth tube and microfin tube is more at low vapor quality values while it is smaller at high vapor quality values.

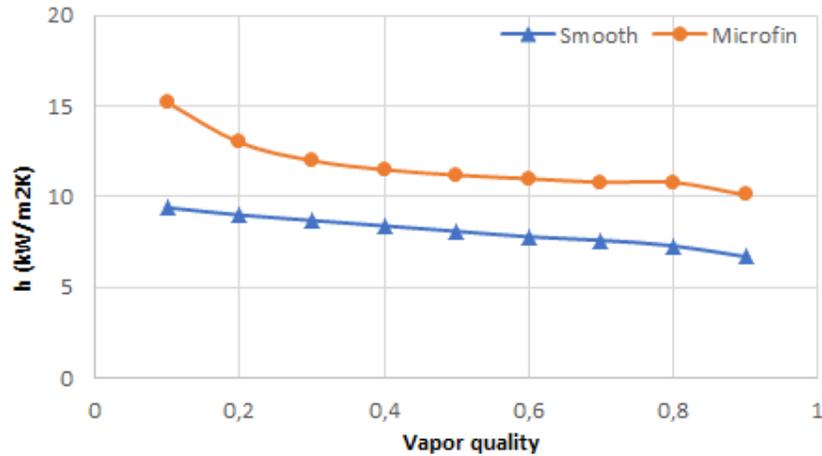


Figure 4. Effect of vapor quality on heat transfer coefficient of CO₂ at the evaporation temperature 0°C (q= 10 kW/m², G=380 kg/m²s)

For evaporation temperature of -8 °C, the variation in the heat transfer coefficients of CO₂ depending on vapor quality is given in Figure 5. It is observed that the heat transfer coefficient in the microfin tube is almost 34% higher than the smooth tube.

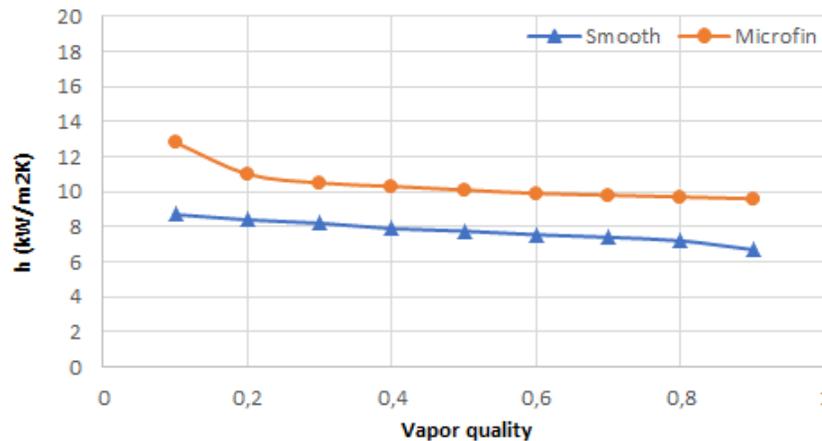


Figure 5. Effect of vapor quality on heat transfer coefficient of CO₂ at the evaporation temperature -8°C (q= 10 kW/m², G=380 kg/m²s)

Figure 6 shows the effect of vapor quality on heat transfer coefficient at the evaporation temperatures 5°C, 0°C and -8°C. It is concluded that heat transfer coefficients of CO₂ increases while the evaporation temperatures increases from -8 °C to 5 °C.

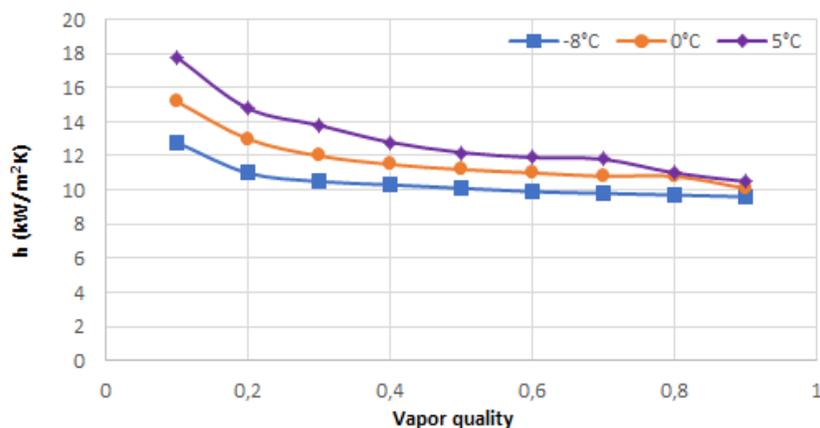


Figure 6. Effect of vapor quality on heat transfer coefficient of CO₂ in microfin tube at the evaporation temperatures 5°C, 0°C and -8°C ($q=10 \text{ kW/m}^2$, $G=380 \text{ kg/m}^2\text{s}$)

In Figure 7, the effect of vapor quality on the heat transfer coefficients is investigated and compared for different heat fluxes (10, 15 and 20 kW/m²). During these calculations, the evaporation temperature and mass flux are kept constant at -8 °C and 380 kg/m²s respectively. It is clear that the heat transfer coefficients increase with increasing heat fluxes. Furthermore, it was also concluded that the nucleate boiling was more dominant in higher heat flux values.

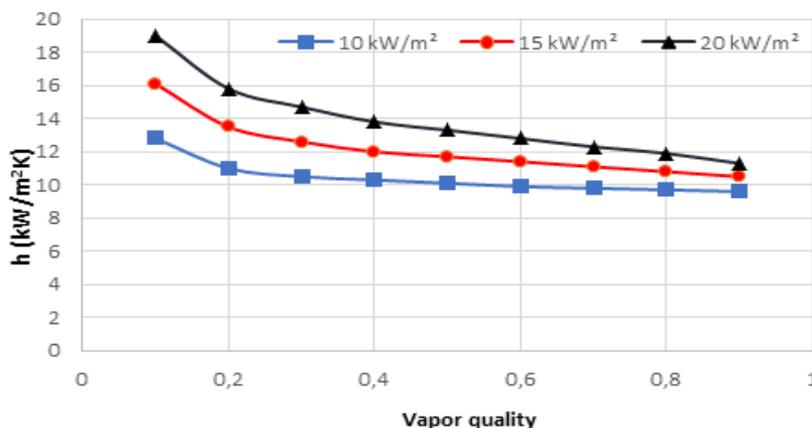


Figure 7. Effect of vapor quality on the heat transfer coefficients of CO₂ in microfin tube for different heat fluxes (10, 15 and 20 kW/m²) (Evaporation temperature of -8°C, $G=380 \text{ kg/m}^2\text{s}$)

CONCLUSIONS

In this paper, the change in the heat transfer coefficient of CO₂ depending on vapor quality was theoretically investigated in microfin and smooth tube. At the end of the study, the following implications are concluded by the authors:

- The heat transfer coefficients in different evaporation temperatures were compared based on vapor quality. It has been concluded that heat transfer coefficients of microfin tube at 5°C, 0°C and -8°C were 52%, 44% and 34% higher than that of smooth tube, respectively. The reason of this, having more surface area of microfin tube provides turbulent flow of fins and increasing heat transfer with accelerating nucleate boiling on surface.

- The heat transfer coefficients of CO₂ increases while the evaporation temperatures increases from -8 °C to 5 °C.
- At the beginning of the process low vapor quality causes nucleate boiling. Thus, high heat transfer coefficient is obtained. When the vapor quality increases, heat transfer coefficient decreases due to the decreasing in nucleate boiling. After that, boiling with convection is obtained at interface between liquid and steam. In addition to this, during CO₂ evaporation in horizontal tube, heat transfer coefficient tends to decrease due to its local break-down of liquid layer caused by smaller surface tension and viscosity.
- The effect of heat flux on the evaporation heat transfer coefficient of CO₂ was investigated. The data showed that the evaporation heat transfer coefficients for microfin tubes had similar trend with those for smooth tubes which increased with heat flux.

NOMENCLATURE

Bo	Boiling number
B_o	Bond number
d	Diameter, m
dt	Diameter of a microfin tube at fin root, m
E	Two-phase convection multiplier
Fr	Froude number
f	Fin height, m
G	Mass flow rate, $\text{kg}/\text{m}^2\text{s}$
g	Gravitational acceleration, m^2/s
h	Heat transfer coefficient, $\text{W}/\text{m}^2\text{K}$
h_{cv}	Convection heat transfer coefficient
h_{fg}	Latent heat of vaporization, kJ/kg
h_L	Liquid heat transfer coefficient, $\text{W}/\text{m}^2\text{K}$
h_{NB}	Nucleate boiling heat transfer coefficient, $\text{W}/\text{m}^2\text{K}$
h_{TP}	Two phase heat transfer coefficient, $\text{W}/\text{m}^2\text{K}$
k_L	Heat conductance fluid, W/mK
M	Molecular weight, kg/kmol
n	Number of grooves
Nu_{CV}	Nusselt number for convection
P_r	Reduced pressure
Pr_l	Prandtl number
q	Heat flux, W/m^2
Re_l	Reynolds number for liquid phase
R_X	Geometry enhancement factor
S	Suppression factor
T_b	Wall thickness
X_{tt}	Martinelli parameter
x	Vapor vapor quality
α	apex angle of microfin, °
β	Helix angle of microfin, °
μ_l	Dynamic viscosity fluid, kg/ms
μ_v	Dynamic viscosity gas, kg/ms
ρ_l	Density fluid, kg/m^3
ρ_v	Density gas, kg/m^3
σ	Surface tension, N/m

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