

**Discussions on Prediction Methods of Evaporation Heat transfer of CO₂-oil Mixtures
in a Horizontal Smooth Tube**

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ABSTRACT

Experiments on flow boiling heat transfer of pure CO₂ and CO₂-oil(PAG) mixtures in a horizontal smooth tube have been carried out. The test tube is a stainless steel smooth tube, which is 3.76 mm in inner diameter and 1 m in length. Experiments were carried out at mass velocities from 100 to 400 kg/(m²s), a saturation temperature of 10 °C, heat fluxes from 10 to 30 kW/m², and the oil circulation ratios from 0 to 1.01 mass%. The flow patterns were observed and the results were compared with the flow pattern map developed by Cheng et al., and the measured local heat transfer coefficients were compared with the prediction correlations proposed by Cheng et al.

As the results, it was found that there is a discrepancy between the observations and the flow pattern map. On flow boiling heat transfer of pure CO₂, the heat transfer coefficients estimated using the prediction method agreed with 91% of the experimental data within ±30% by modifying the flow pattern map. In case of CO₂-oil mixtures, the heat transfer coefficients estimated using the prediction method agreed with 81% of experimental data within ±30% by modifying the nucleate boiling suppression factor.

NOMENCLATURE

G	mass velocity	[kg/(m ² s)]
q	heat flux	[W/m ²]
S	nucleate boiling suppression factor	[-]
T_s	saturation temperature	[K]
T_w	inner wall temperature	[K]
y	oil circulation ratio	[mass%]

Greek symbol

α	heat transfer coefficient	[W/(m ² K)]
θ_{dry}	dry angle of tube perimeter	[rad]

Subscripts

cal	calculated
cb	convective boiling
exp	experimental
nb	nucleate boiling
v	vapor
wet	wet perimeter

INTRODUCTION

Recently, carbon dioxide(CO₂) is regarded as environmentally-friendly refrigerant, and used in automobile air conditioners and heat pump systems. In Japan, in order to reduce the CO₂ emissions for the purpose of preventing global warming, a CO₂ heat pump system for residential hot water heater was developed in 2001, and the spread of the system broke through a million and half units in 2008. Therefore, the improvement in performance of the system is urgent research task. Many researchers have reported about the cycle and heat exchanger performance of the CO₂ heat pump system.

On flow boiling in smooth tubes of CO₂, Cheng et al. [1][2] have proposed a new flow pattern map and prediction model for flow boiling heat transfer. In their reports, they showed that the heat transfer coefficients estimated using their prediction method agreed with 83.2% of the experimental database (a total of 773 data points) within ±30% at pre-dryout region. However, their

flow pattern map was only compared with the observed flow pattern data obtained by Gashe [3] for a 0.8 mm equivalent diameter rectangular channel. And, the flow boiling heat transfer experimental data in their database were obtained for the tubes of the inner diameter of less than 3 mm or greater than 6 mm. Therefore, the research on flow patterns and flow boiling heat transfer of CO₂ are still insufficient for the tubes of the inner diameter of 3~6 mm.

In this report, experiments on flow patterns and flow boiling heat transfer of pure CO₂ and CO₂-oil (PAG) mixtures in a horizontal smooth tube of 3.76 mm in inner diameter have been carried out. The results were compared with those proposed by Cheng et al., and the appropriateness of the prediction correlations was discussed. In case of CO₂-oil mixtures, a new prediction method was proposed for flow boiling heat transfer by modifying the prediction model proposed by Cheng et al.

EXPERIMENTAL APPARATUS

The experimental apparatus used in the present research is shown in Figure 1. It is a heat pump system consisting of a two-stage compressor(1), an oil-separator(2), two gas-coolers(4,5), two expansion valves(11), a pre-heater(12), a test section(14), an auxiliary evaporator(16), and an accumulator(17). The test tube is a stainless steel smooth tube, which is 3.76 mm in inner diameter and 1 m in length, and it was heated using direct heating method. The outside wall temperatures were measured using 12 T-type thermocouples, 0.1 mm in wire diameter, of 150 mm interval at the top and the bottom of the test tube. The thermocouples used in this experiment were calibrated with a precision of ± 0.05 K. A 1 m Ω ($\pm 0.01\%$) standard resistance was used to measure DC current for heating.

The mass flow rates were measured using two Coriolis type mass flow meters(7), for the total mass flow rate and that flowing through the test section. The precisions of the mass flow rate meters are $\pm 0.25\%$ full-scale(Full-scale: 100 kg/h). The pressures and bulk temperatures at mixing chambers prepared before the expansion valve and the outlet of the test section were measured using two pressure transducers and two sheathed thermo-couples. The precisions of the pressure transducers and sheathed thermocouples are ± 0.01 MPa and ± 0.05 K, respectively. The pressure drop over the test section was measured using a pressure difference transducer(13) with a precision of ± 0.2 kPa. The

purity of CO₂ used in the present research is 99.95 mass%. The kinetic viscosity of the PAG oil is 100 mm²/s at temperature of 40 °C. The circulation ratio of the oil was adjusted by the oil-control valve(3). The oil circulation ratio was measured using the visual methods [4][5]. The thermophysical properties of CO₂ were calculated using software package PROPATH [6]. The experimental conditions are shown in Table 1.

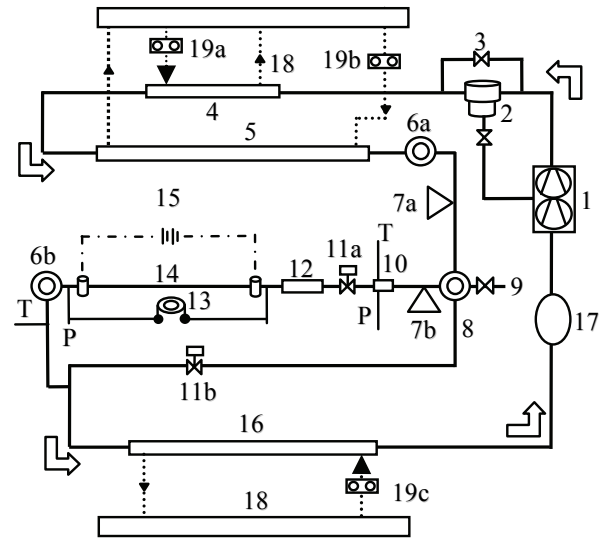


Figure 1
Schematic of experimental apparatus

Table 1
Experimental Conditions

Mass velocity, kg/(m ² s)	100 ~ 400
Pressure, MPa	4.5
Heat flux, kW/m ²	10 ~ 30
Inlet vapor quality, -	0.11 ~ 0.91
Oil circulation ratio, mass%	0, 0.08, 0.11, 0.32, 0.53, 1.01

DETA REDUCTION

The flow patterns were observed at the outlet of the test section using the sight-glass(6b). The flow patterns were recorded for 20 seconds for each condition with a high definition video camera (HDV1080i system). For these experiments, no heat was applied to the test section to let the two-phase flow developed over a sufficient adiabatic length. Figure 2 shows a snapshot of annular-wavy flow observed at the outlet of the test section. The flow direction is from left to right.

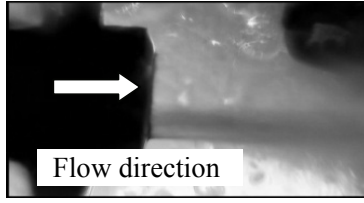


Figure 2
A snapshot of (annular)-wavy flow

The measured local heat transfer coefficients are defined as follows

$$\alpha_{\text{exp}} = q / (T_w - T_s) \quad (1)$$

Where q is the heat flux applied to the test section, T_w is the inside wall temperature of the test section and T_s is the saturation temperature of the refrigerant, which is calculated from the inlet pressure and the pressure drop of the test section. The saturation temperature of pure CO₂ was used in Eq.(1) even in case of CO₂-oil mixtures.

The heat transfer coefficients at pre-dryout region were calculated with Eq.(2), which is proposed by Cheng et al. for bubble, intermittent and annular flows.

$$\alpha_{\text{cal}} = [(S\alpha_{\text{nb}})^3 + \alpha_{\text{cb}}^3]^{1/3} \quad (2)$$

where S is the nucleate boiling suppression factor, α_{nb} is the nucleate boiling heat transfer coefficient and α_{cb} is the convective boiling heat transfer coefficient.

The heat transfer coefficients at pre-dryout region for separated flows (wavy, stratified-wavy and stratified flows) were calculated with Eq.(3).

$$\alpha_{\text{cal}} = \frac{\alpha_v \theta_{\text{dry}} + (2\pi - \theta_{\text{dry}}) \alpha_{\text{wet}}}{2\pi} \quad (3)$$

where θ_{dry} is the dry angle, α_v is the vapor phase heat transfer coefficient on dry perimeter and α_{wet} is the heat transfer coefficient on wet perimeter calculated with Eq.(2).

RESULTS AND DISCUSSION

In case of pure CO₂: Figure 3 shows the influence of mass velocity on local heat transfer coefficients at heat flux q of 10 kW/m². The symbols show the experimental results and the lines

show the predicted values calculated with Eqs.(2) and (3). The experimental results agree well with the predicted values at mass velocity G of 380 kg/(m²s), but disagree with the predicted values for G of 100 and 190 kg/(m²s). The measured local heat transfer coefficients at the top and bottom of the tube are about the same values for G of 380 kg/(m²s), while those at the bottom of tube are higher than those at the top of the tube for G of 100 and 190 kg/(m²s). For this reason, it is considered that the flow patterns are separated flows for G of 100 and 190 kg/(m²s), and are intermittent or annular flows for G of 380 kg/(m²s).

Figure 4 shows the influence of heat flux on local heat transfer coefficients for G of 380 kg/(m²s). The symbols and lines are the same as those in Figure 3. The measured local heat transfer coefficients show a strong dependence on heat flux. It is considered that the flow boiling heat transfer in this case is dominated by nucleate boiling. The predicted values show this tendency as well and agree well with the experimental results at q of 10 kW/m². However, the predicted values are lower than the experimental results at q of 20 and 30 kW/m². It is considered due to the effects of the surface roughness of the test tube. On the other hand, the local heat transfer coefficients at the top of tube decrease significantly compared with those at the bottom of the tube at vapor quality x from 0.3 to 0.7 for $q = 20$ and 30 kW/m². This tendency is similar to that as shown in Figure 3 for G of 100 and 190 kg/(m²s). Although the flow patterns are considered to be intermittent or annular flows ($G = 380$ kg/(m²s) and $q = 10$ kW/m²), this trend can be explained by the liquid film at the top of the tube was very thin and partial dryouts occurred at q of 20 and 30 kW/m².

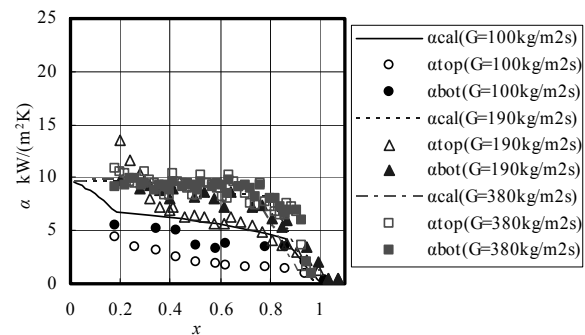


Figure 3
Influence of mass velocity on local heat transfer coefficients and comparison with the prediction model presented by Cheng et al.
($q = 10$ kW/m², $y = 0$ mass%)

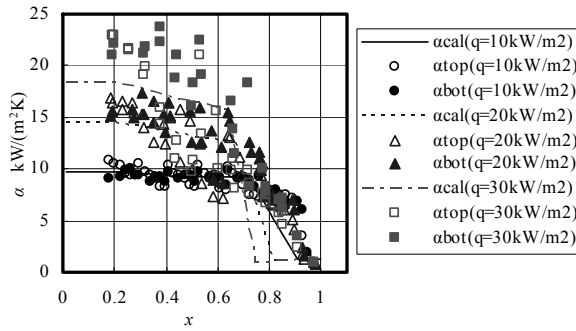


Figure 4

Influence of heat flux on local heat transfer coefficients and comparison with the prediction model presented by Cheng et al.
($G = 380 \text{ kg/(m}^2\text{s)}$, $y = 0 \text{ mass\%}$)

Figure 5 shows the observed flow patterns (symbols) and comparison with the flow pattern map developed by Cheng et al. In the flow pattern map, I, A, SW, SLUG and S indicate intermittent flow, annular flow, stratified-wavy flow, slug flow and stratified flow, respectively. As shown in the figure, there is a large discrepancy between the observed flow patterns and the flow pattern map. When $G \geq 150 \text{ kg/(m}^2\text{s)}$ and $0.2 < x < 0.8$, the flow pattern map shows a large region of annular flow, while the observed results are slug, wavy and annular-wavy flows. On the other hand, the observed flow patterns agree well with those obtained from Figures 3 and 4. For G of 200 $\text{kg/(m}^2\text{s)}$, the observed flow patterns are slug, wavy and stratified-wavy flows. These observation results agree well with that mentioned as above: the flow pattern is a separated flow for G of 190 $\text{kg/(m}^2\text{s)}$. And, for G of 400 $\text{kg/(m}^2\text{s)}$, slug, annular-wavy and annular flows were observed. These observation results agree well with that: the flow patterns are intermittent or annular flows which have a thin liquid film at the top of the tube for G of 380 $\text{kg/(m}^2\text{s)}$.

For this reason, it is considered that the transition from stratified-wavy flow to annular flow occurs at higher mass velocity region than the flow pattern map. But, there is a weak point in the present observation method: it is difficult to find a very thin liquid film at the top of the tube compared with other observation methods. Therefore, the authors modified the flow pattern map to conform the predicted local heat transfer coefficients and the experimental results. In Figure 5, arrow 1 and arrow 2 show the modification of transition boundary of stratified-wavy flow to annular flow and stratified

flow to stratified-wavy flow, respectively. In addition, in case of CO_2 -oil mixtures, there is little change in the flow pattern compared with pure CO_2 except that the times of the slug occurrence within 20 seconds increased.

Figure 6 shows the influence of mass velocity on local heat transfer coefficients and the comparison with the prediction model based on the modified flow pattern map at q of 10 kW/m^2 . The symbols show the experimental results and the lines show the predicted values calculated using Eqs.(2) and (3) based on the modified flow pattern map. As shown in the figure, the predicted values agree well with the experimental results for G of 100 and 190 $\text{kg/(m}^2\text{s)}$.

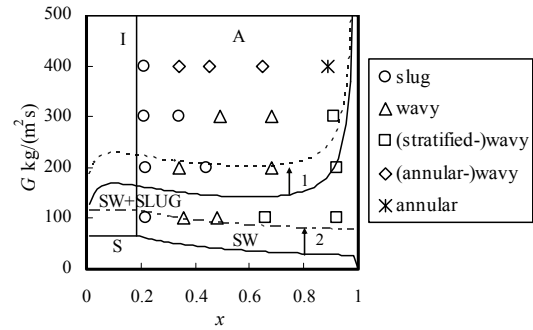


Figure 5

Observed flow patterns and comparison with the flow pattern map presented by Cheng et al.

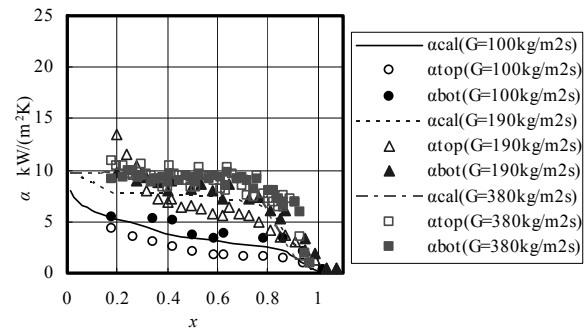


Figure 6

Influence of mass velocity on local heat transfer coefficients and comparison with the prediction model based on the modified flow pattern map
($q = 10 \text{ kW/m}^2$, $y = 0 \text{ mass\%}$)

Figure 7 shows a comparison of the experimental results and predicted values calculated using Eqs.(2) and (3) based on the modified flow pattern map at pre-dryout region. The predicted values agree with 91% of the experimental data within $\pm 30\%$.

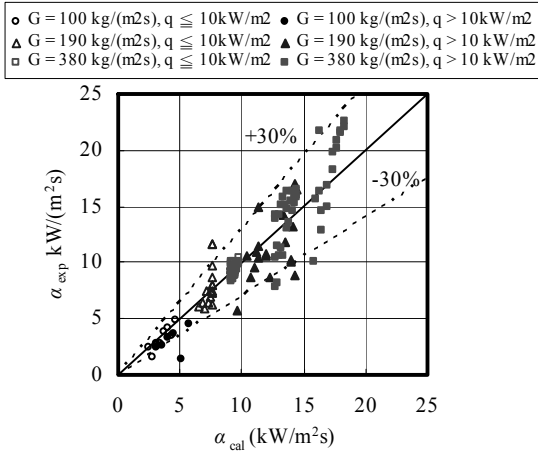


Figure 7

Comparison of the experimental results and the prediction model based on the modified flow pattern map at pre-dryout region ($y = 0$ mass%)

In case of CO₂-oil mixtures: Figure 8 shows the influence of heat flux on local heat transfer coefficients in case of CO₂-oil mixtures for $G = 380$ kg/(m²s). As shown in the figure, the experimental results (symbols) decrease significantly compared with those of pure CO₂ as shown in Figure 4. And, there is almost no effect of heat flux on local heat transfer coefficients when $0.4 < x < 0.8$. Gao and Honda [4][5] reported that the decrease in the local heat transfer coefficient is considered due to the nucleate boiling being suppressed by the oil film in case of CO₂-oil mixtures. However, the local heat transfer coefficients show a slight dependence on heat flux at x less than 0.4. It is considered that the nucleate boiling partially occurred (incomplete suppression of nucleate boiling) due to the low oil concentration in the liquid phase at the low vapor quality region. Therefore, in case of CO₂-oil mixtures, the authors proposed a new prediction method based on the modified flow pattern map and a modified nucleate boiling suppression factor S' to take into account the effect of the oil film.

$$S' = \begin{cases} S \times (-0.5x + 0.35) & (x \leq 0.7) \\ 0 & (x > 0.7) \end{cases} \quad (4)$$

The modified nucleate boiling suppression factor S' is used in Eqs.(2) and (3) instead of S in the new prediction method.

The lines in Figure 8 show the predicted values calculated using the new prediction method. The predicted values agree well with the experimental results when $x < 0.4$.

Figure 9 shows the influence of mass velocity on local heat transfer coefficients and the comparison with the new prediction method in case of CO₂-oil mixtures at heat flux q of 10 kW/m². The symbols and lines are the same as those in Figure 8. The measured local heat transfer coefficients increase with the increase in mass velocity. This fact means that the flow boiling heat transfer changed to convective evaporation dominated regime. However, the predicted values are higher than the experimental results for G of 190 and 380 kg/(m²s). And, the difference between the predicted values and experimental results increases with the increase in vapor quality. It is considered that the oil film thickness which acts as a thermal resistance increases with the increase in vapor quality.

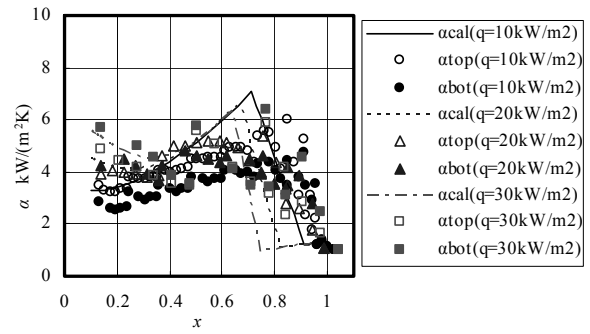


Figure 8

Influence of heat flux on local heat transfer coefficients and comparison with the new prediction method ($G = 380$ kg/(m²s), $y = 1.01$ mass%)

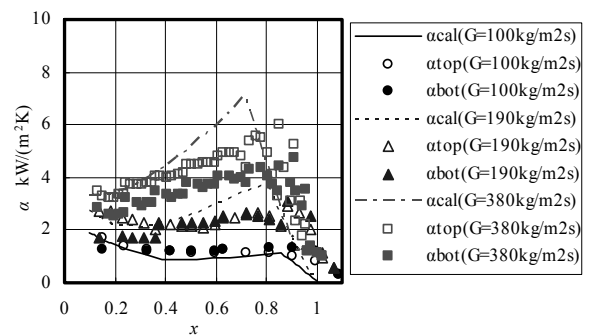


Figure 9

Influence of mass velocity on local heat transfer coefficients and comparison with the new prediction method ($q = 10$ kW/m², $y = 1.01$ mass%)

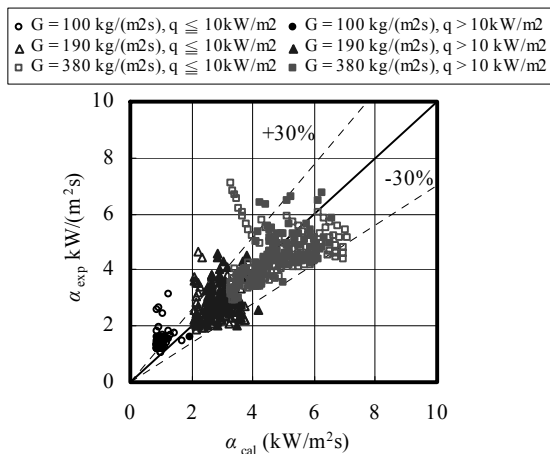


Figure 10

Comparison of the experimental results and the new prediction method at pre-dryout region ($\gamma = 0.08 \sim 1.01$ mass%)

Figure 10 shows comparisons of the experimental results and the new prediction method at pre-dryout region in case of CO₂-oil mixtures (at the oil circulation ratios γ from 0.08 to 1.01 mass%). The heat transfer coefficients estimated using the new prediction method agree with 81% of experimental results within $\pm 30\%$. In the figure, most of the experimental results, which are over 30% higher than the predicted values, are those obtained at the low oil circulation ratio of 0.08 mass%.

CONCLUSIONS

Experiments on flow patterns and flow boiling heat transfer of CO₂ and CO₂-oil mixtures inside a horizontal smooth tube of 3.76 mm in inner diameter were conducted, and the experimental results were compared with the predicted model proposed by Cheng et al. The following results were obtained.

- (1) It is found that there is discrepancy between the observed flow patterns and the flow pattern map proposed by Cheng et al. it is considered that the transition of stratified-wavy flow to annular flow occurs at higher mass velocity conditions.
- (2) In case of pure CO₂, the experimental results agree well with the predicted values by modifying the flow pattern map proposed by Cheng et al., and the heat transfer coefficients estimated using the modified prediction method agree with 91% of the experimental data within $\pm 30\%$ at pre-dryout region.
- (3) In case of CO₂-oil mixtures, the heat transfer coefficients estimated using the new prediction

method agree with 81% of experimental results within $\pm 30\%$ by modifying the nucleate boiling suppression factor.

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